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Decarbonising Healthcare

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Abstract

At COP26, thirty-six countries committed to develop low-carbon health systems, with a further fourteen countries setting a target of net-zero healthcare by 2050. There is currently little information available, however, on the carbon footprint of most healthcare activities, nor is there any recognised way for carbon emissions to be included in the clinical decision-making process. This research explores how healthcare can rapidly reduce its carbon footprint while not adversely affecting patient health. It does so in three parts: methodology, measurement, and mitigation.

Methodology explores how to incorporate carbon footprints, calculated from environmental life cycle assessment (LCA), into health technology assessments (HTAs) including cost-effectiveness analysis and cost-benefit analysis, or as one criterion in a multi-criteria decision analysis. There are no technical impediments to stop the incorporation of carbon emissions into HTAs. Rather, the main barrier is that unlike other sectors of the economy, currently few LCAs have been undertaken in healthcare to quantify carbon emissions.

Measurement examined the consequential and attributional life cycle carbon emissions of pathology blood tests (full blood examination, coagulation profile, urea and electrolytes, C-reactive protein, and arterial blood gases); the attributional life cycle carbon emissions of urinalysis; and the consequential and attributional life cycle carbon emissions of diagnostic imaging (magnetic resonance imaging (MRI), computerised tomography (CT), chest X-ray (CXR), mobile chest X-ray (MCXR), and ultrasound(US)).

The consequential LCA of pathology testing showed the greatest source of carbon emissions originated from phlebotomy, which can be reduced by only ordering tests when necessary. The attributional LCA additionally showed the impacts of standby power usage, which can be reduced by moving to renewable energy and ensuring analysers are highly utilised. For diagnostic imaging for both attributional and consequential analysis, X-rays and US have lesser carbon emissions compared to MRI and CT, and therefore should be preferentially used wherever possible. The attributional LCA showed that MRIs and CTs have a carbon footprint similar to the known carbon hotspot of anaesthesia. These carbon emissions can be similarly reduced by moving to renewable energy and ensuring the high utilisation rates of scanners.

Mitigation shows how an intervention to reduce unnecessary pathology testing by the Department of Medicine at St George Hospital, Sydney, led to 10% reduction in pathology tests over the six-month intervention period. The reduction resulted in a saving of 132kg carbon dioxide equivalent (CO₂e) and A\$53,573, with no change in adverse patient outcomes. The second part of Mitigation investigated the prevalence of unnecessary routine preoperative testing at Western Health. It found virtually no unnecessary testing, with the odds of potentially receiving an unnecessary preoperative test being 0.017.

This thesis highlights that there are large research areas to be undertaken for healthcare to decarbonise, especially in performing LCAs of healthcare consumables, devices, and interventions. Additionally, the thesis shows that low-value care, such as the overutilisation of testing, should be an initial focus towards healthcare's decarbonisation, as reducing low-value care reduces carbon emissions while not adversely affecting patient health.

Declaration

This is to certify that

- I. the thesis comprises only my original work towards the PhD except where indicated in the preface
- II. due acknowledgment has been made in the text to all other materials used; and
- III. the thesis is less than 100,000 words in length, exclusive of tables, maps, bibliographies and appendices

Signature

Preface

Publications forming part of this thesis

Chapter 3

Incorporating carbon into healthcare's future: adding carbon emissions to health technology assessments

S. McAlister, R. Morton, A. Barratt

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Overall, the candidate contributed approximately 75% to the preparation of the work for this paper, and was responsible for project administration, methodology, formal analysis, and the writing of the original draft.

Chapter 4

The carbon footprint of pathology testing

S. McAlister, A. Barratt, K. Bell, F. McGain

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Overall, the candidate contributed approximately 85% to the preparation of the work for this paper, and was responsible for project administration, methodology, data collection, data analysis, and the writing of the original draft.

The carbon footprint of pathology testing – letter

S. McAlister, A. Barratt, F. McGain

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An LCA of hospital pathology

S. McAlister, T. Grant, F. McGain

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Chapter 5

The carbon footprint of diagnostic imaging

S. McAlister, F. McGain, M. Petersen, D. Story, K. Charlesworth, G. Ison, A. Barratt
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S. McAlister

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Carbon footprint for general, regional, and combined anaesthesia for total knee replacements

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Anesthesiology (2021), 135: 976 – 991

Converting gas-driven ventilators from oxygen to air: environmental implications

M.W. Court, S. McAlister, J.M.T Pierce, R. Sutton
Anaesthesia (2021), 76:285 – 286

The carbon footprint of Australian health care

A. Malik, M. Lenzen, S. McAlister, F. McGain
Lancet Planetary Health (2018), 2(1):27 –35.

The carbon footprint of treating patients with septic shock in the intensive care unit

F. McGain, J.P. Burnham, R. Lau, L. Aye, M.H Kollef, S. McAlister
Critical Care and Resuscitation (2018), 20(4):304 – 312.

Financial and environmental costs of reusable and single-use anaesthetic equipment

F. McGain, D. Story, T. Lim, S. McAlister
British Journal of Anaesthesia (2017), 118(6):862 – 869

The Environmental footprint of morphine: a life cycle assessment from opium poppy farming to the packaged drug

S. McAlister, Y. Ou, E Neff, K. Hapgood, D. Story, P. Mealey, F. McGain
BMJ Open (2016), 6(10):e013302

A life cycle assessment of reusable and single-use central venous catheter insertion kits

F. McGain, S. McAlister, A. McGavin, D. Story D
Anesthesia and Analgesia (2012) 114(5):1073 – 1080

Sustainable cardiac services—From the catheterization laboratory to the operating room and beyond

F. McGain, N.R. Cox, S.S. Cecchin, S. McAlister, P.R. Barach
Progress in Pediatric Cardiology (2012), 33(1):81 – 84.

Workplace sustainability: the “cradle to grave” view of what we do

F. McGain, D. Story, E. Kayak, Y. Kashima, S. McAlister
Anesthesia and Analgesia (2012) 114(5):1134 – 1139.

The Financial and Environmental Costs of Reusable and Single-Use Plastic Anaesthetic Drug Trays

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Abbreviations

ABG	Arterial blood gas
ALCA	Attributional LCA
ASA	American Society of Anesthesiologists Physical Status
AusLCI	The Australian LCI database
C-Rp	C-reactive protein
CBA	Cost benefit analysis
CCA	Cost consequence analysis
CEA	Cost effectiveness analysis
CLCA	Consequential LCA
CO ₂ e	Carbon dioxide equivalents
CRP	C-reactive protein
CT	Computerised tomography
CUA	Cost utility analysis
CUE	Creatinine, urea, and electrolytes
CV	Contingent valuation
CXR	Chest X-ray
DALY	Disability adjusted life year
DoM	Department of Medicine
ED	Emergency department
EIO	Environmental input-output
FBE	Full blood examination
GT	Gigaton, 10 ⁹ tons
HTA	Health technology assessment
HVAC	Heating, ventilation, and air conditioning
IAM	Integrated assessment model
ICER	Incremental cost-effectiveness ratio
ICU	Intensive care unit
IPCC	International Panel on Climate Change
ISO	International Organization for Standardization
KT	Kiloton, 10 ³ tons
kWh	Kilowatt hour
LBP	Lower back pain
LCA	Life cycle assessment
LOS	Length of stay
MAC	Marginal abatement cost
MBS	Medicare Benefits Scheme
MCDA	Multi criteria decision analysis
MCXR	Mobile chest X-ray

MRI	Magnetic resonance imaging
MRIO	Multi-regional input output
MT	Megaton, 10^6 tons
NICE	National Institute for Care Excellence (UK)
NWAU19	National weighted activity unit
P-LCA	Process LCA
PM _{2.5}	Fine particulate matter (<2.5 mm)
QALY	Quality adjusted life year
SC	Stated choice
SESLHD	South Eastern Sydney Local Health District
SSC	Social cost of carbon
U+E	Urea and electrolytes
US	Ultrasound
VSL	Value of a statistical life
Wh	Watt hour
WHO	World Health Organisation
WTA	Willingness to accept
WTP	Willingness to pay

Chapter 1 Introduction

“Climate change is the biggest global health threat of the 21st Century”

Lancet and University College London Institute for Global Health Commission 2009¹

1.1 Background

Since this statement by the Lancet in 2009, atmospheric carbon dioxide (CO₂) levels have increased from 387.4 parts per million to 414², causing global temperatures to increase from 0.65°C to 0.98°C above the 20th century average.³ The 10-year average for sea ice since 2009 compared to the decade preceding it has decreased by 19% in the Arctic and by 3% in the Antarctic^{4,5}, causing a 30mm increase in sea level.⁶ The 10-year average economic loss caused by extreme weather events such as cyclones, flooding, wildfire and drought rose from US\$151 billion for the ten years preceding 2009 to US\$259 billion for the ten years after, although not all of this loss can be attributed to climate change.⁷

These extreme weather events also have an impact on human health and wellbeing. For example using key health indicators from the 2021 *Lancet* Countdown on health and climate change, the decade after 2009 has seen the proportion of land surface area being in drought conditions in any given month rise to 22%, in comparison to the 13% seen between 1950-99.⁸ In conjunction with decrease in yields compared to 1981-2010 of staple crops such as maize, winter wheat and soybeans and rice comparison due to rising temperatures⁸, this has contributed to a decrease in food security and an increase in undernutrition.⁹ For heatwave exposure, compared to the 1986-2005 annual average baseline in 2020 there was a record 3.1 billion more person-days exposure for people older than 65, and 626 million person-days

for people less than 1.⁸ Additionally since 2009 there has been an increase in favourable environmental conditions for the transmission of malaria, dengue virus, Zika virus and cholera.⁸

Paradoxically, healthcare is a major contributor to global greenhouse gas (carbon) emissions. Globally, healthcare is responsible for 4.4% (2.4 Gt CO₂) of annual emissions.¹⁰ Individual countries have higher emissions than this global average, including the United Kingdom (5%)¹¹, Australia (7%)¹², and the United States (10%).¹³ Treating patients today, therefore, results in adverse health impacts in the future. Importantly, many of these impacts will fall on peoples living in countries with a low and medium human development index (HDI), leading to further global inequality.¹⁴

The world has seen a major global political shift towards the goal of a carbon-neutral world by 2050 since the Lancet's 2009 report. Much of that shift has, however, only occurred since 2018¹⁵, which was the year that the Intergovernmental Panel on Climate Change (IPCC) released a special report. This report prosecuted the importance of keeping global average temperatures to within 1.5°C relative to pre-industrial levels, and importantly, it established the need for a 50% reduction in carbon emissions by 2030, and net-zero by 2050, if this was to be achieved.¹⁶

Up to 2020 in Australia, there was little formal discussion about the need for healthcare to decarbonise beyond individual doctors and advocacy groups such as Doctors for the Environment Australia and the Climate and Health Alliance. This changed, however, in late 2019 and early 2020 when bushfires saw approximately 19 million hectares, predominantly

along the south-east of Australia, being burnt.¹⁷ Approximately three billion animals were impacted¹⁸, with the estimated economic damage costs being between A\$100 – 230 billion.¹⁹ Thirty-three people lost their lives directly due to these fires, with a further estimated additional 417 deaths attributable to bushfire smoke.²⁰ This bushfire smoke blanketed the major cities of Sydney and Melbourne, resulting in a 25-30% increase in people calling ambulances or presenting to hospital emergency departments due to respiratory difficulties.²¹ Beyond the visceral impact of bushfire smoke for people living in those cities, the national media was extensively reporting on stories such as whole towns of people being forced to huddle together on beaches during New Year's Eve to escape the bushfires.²² Although the increasing extent and intensity of bushfires due to climate change had been predicated since the 1990s²³, the 2019/20 bushfires clearly demonstrated to Australians that rather than climate change being something that was going to happen sometime in the future, it was instead happening now.²⁴

Highlighting the 2019/20 bushfires, in an unprecedented action, peak medical groups including the Australian Medical Association and multiple Australasian Medical Colleges united in 2020 to call climate change a public health emergency, and on the Australian government to reduce emissions.^{25,26} In 2021, the Australian Medical Association and Doctors for the Environment went further, emulating the aims of the UK's National Health Service (NHS) to call for healthcare to become net-zero by 2040, with an interim target of an 80% reduction by 2030.²⁷

When I began this thesis at the beginning of 2018, the original topic was “The environmental and economic impacts of unnecessary routine preoperative testing”. This topic came about based on my previous work investigating the life cycle environmental impacts and financial costs of medical items, pharmaceuticals, and modes of care. When investigating the environmental impacts of modes of care, there was a lack of any information surrounding the impacts of pathology testing, which given their ubiquity in all aspects of healthcare, was a large gap in knowledge. Furthermore, the original topic focusses on unnecessary preoperative testing, due to both the literature suggesting that the incidence was high, and that the UK’s National Institute for Health and Care Excellence (NICE) had guidelines for routine preoperative testing that could be used for determining whether a test was necessary or not.

A number of things occurred that caused the aims of the thesis to shift. Firstly, whilst undertaking the literature review around how to calculate the economic and environmental impacts of unnecessary preoperative testing, a broader question arose; that instead of having economic and environmental metrics disaggregated into individual items, was there instead a way of integrating them together? This new question was prompted largely by my previous experience in undertaking environmental healthcare assessments, in that once published they primarily sat as stand-alone items rather than helping guide changes in clinical practice. Undertaking the literature review meant that I gained an understanding of the modelling principles around Health Technology Assessments (HTAs), and hence saw a way that outputs from environmental Life Cycle Assessment (LCA) could be incorporated into HTA models.

Secondly, in late 2019 upon performing preliminary data analysis of patients undergoing routine preoperative testing from Western Health in Melbourne, I discovered that the incidence of unnecessary routine testing was almost non-existent. My proposed research into the environmental and economic costs of unnecessary testing, alongside determining whether factors such as the age or sex of the patient or the procedure being undertaken lead to unnecessary testing, had to therefore be reconsidered.

In the first half of 2020, I was approached by South Eastern Sydney Local Health District (SESLHD) to see whether they could fund me to undertake a retrospective study investigating the environmental and financial benefits resulting from reduced pathology testing at St George Hospital. This project came about because clinicians employed by the SESLHD understood that climate change impacted on public health, and that due to my recently published paper on the carbon footprint of pathology testing in the Medical Journal of Australia, that healthcare itself contributed to the problem.

Additionally, because SESLHD had additional funding available, they subsequently asked whether there were other sustainability areas I would be interested in studying. My previous experience investigating the environmental impacts of clinical modes of care had also identified diagnostic imaging as an area where there was a big gap in knowledge. A previous attempt in 2018 to measure the power consumption of imaging equipment at Western Health was not possible due to the manufacturers of their imaging equipment refusing to allow power loggers to be attached to the incoming electricity feeds of the scanners. By contrast, both the head of radiology at St George Hospital and the manufacturers of their imaging equipment were supportive of the study. In maybe another indication of the shift in

thinking around sustainability and healthcare, when the radiology department at Western Health was subsequently approached to measure the electricity consumption of their MRI scanner, due a logger error at St George Hospital, the imaging equipment manufacturers this time agreed.

These changes, including the evolving recognition from peak medical bodies that healthcare needs to reduce its carbon emissions, came together for me to develop a new aim.

1.2 Aims

This thesis aims to explore how healthcare can make reductions in its carbon footprint whilst not adversely effecting patient health. This carbon footprint includes all the greenhouse gases, including healthcare specific greenhouse gases such as the gaseous anaesthetics, converted to the reference unit of carbon dioxide equivalents (CO₂e) based on their respective global warming potentials. It does so in three parts; methodology, measurement, and mitigation.

1.3 Objectives

1. Methodology: Determining how to incorporate carbon footprints into HTAs, as guide clinical practice and policy, and help lock in future carbon impacts.
2. Measurement: Calculate the carbon footprint of pathology testing and diagnostic imaging.
3. Mitigation: Calculate the carbon benefit from reducing unnecessary pathology testing.

1.4 Research questions

1.4.1 Methodology: How to integrate carbon footprints in carbon dioxide equivalents (CO₂e) calculated through LCA with HTAs.

For the LCA component of methodology, the thesis aims to explore, while following the ISO 14040 LCA standard, how to model the CO₂e emissions of the multiple economic costs that are typically included within HTAs, ensuring the system boundaries of economic impacts and the LCA align; how to model the CO₂e emissions of multi-year health technology assessments, given LCA traditionally aggregates all emissions temporally; and how to monetise CO₂e emissions so that they can be used as an economic cost in an HTA.

For the HTA component, the thesis aims to investigate how to include CO₂e emissions in the typically used HTA methods of cost-effectiveness, cost-benefit, and cost-consequence analysis, or alternatively as a stand-alone alternative cost within HTA models or as a decision modifier; and to consider how to discount both CO₂e emissions, and monetised CO₂e emissions within an HTA.

1.4.2 Measurement: Measure the carbon footprint of commonly used pathology tests and diagnostic imaging

For pathology tests, the thesis aims to quantify the attributional and consequential life cycle CO₂e emissions, using ISO 14040, of the following commonly used tests: full blood examination (FBE); creatinine, urea and electrolytes (CUE); coagulation profiles; C-reactive protein (C-Rp); arterial blood gas (ABG); and urinalysis

Similarly for diagnostic imaging, the thesis aims to quantify the attributional and consequential life cycle CO₂e emissions, using ISO 14040, of the following commonly used imaging modalities: chest X-ray (CXR); mobile chest X-ray (MCXR); computerised tomography (CT); magnetic resonance imaging (MRI); and ultrasound (US).

1.4.3 Mitigation: Examine opportunities for reducing carbon emissions by reducing unnecessary testing

Mitigation has two research questions. Firstly, to quantify the environmental and financial benefits of reduced pathology testing at St George Hospital, Sydney, Secondly, to determine the CO₂e emissions due to unnecessary routine preoperative testing at Western Health, Melbourne.

1.5 Research strategies

A number of research strategies are used within this thesis.

1. For the integration of LCA and HTA:

Collaboration with a health economist, and the use of HTA software (TreeAge®)

2. For the LCA of pathology testing and diagnostic imaging:

Collaboration with pathology lab staff at Western Health and Austin Health, and radiographers at St George Hospital and Western Health. LCAs were undertaken using LCA software (SimaPro®) and data inventories (ecoinvent® and AusLCI®).

3. *For the reduction in carbon emissions due to unnecessary testing:*

Working with clinicians from the Department of Medicine at St George Hospital, where the intervention took place, and with statisticians to analyse the characteristics of pathology testing and patient admissions.

All the hospitals used for determining the footprint of pathology testing and diagnostic imaging, and for the potential reductions in carbon emissions due to unnecessary testing, (Western Health, Austin Hospital and St George Hospital) are average sized metropolitan hospitals.

1.6 Overview

Chapter 2 is the literature review of the carbon impacts of healthcare, and more specifically, how to quantify carbon emissions, methods of HTA, and overutilisation of testing. Chapter 3 investigates the challenges involved towards integrating LCA with HTA, especially due to the paucity of life cycle data/inventories around medical devices, pharmaceuticals, and clinical practices; and that there is currently no unified global method to undertake health technology assessments.

Chapters 4 through 6 aim to help address the lack of life cycle information of common healthcare procedures by providing both the attributional and consequential carbon impacts of the most commonly used pathology tests and diagnostic imaging modalities. In all these papers, suggestions are made for clinicians and healthcare administrators to reduce carbon emissions.

Chapter 7 reports on a retrospective study investigating the reduction in carbon emissions due to the Department of Medicine at St George Hospital reducing unnecessary testing. Discussed within the paper is an estimation of potential carbon reductions if this intervention was carried out nationally, alongside a discussion on the opportunities for greater carbon reductions due to reducing unnecessary testing.

Chapter 8 investigates the incidence of unnecessary routine preoperative testing at Western Health, as a potential area to reduce emissions. Chapter 9 ends the thesis with a discussion on what the thesis has achieved, the significance of the research, and a future research agenda.

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Chapter 2 Literature review

2.1 Introduction

This chapter begins with a brief history of both the science surrounding the discovery of anthropogenic climate change, and the main international political responses to mitigating greenhouse gas (carbon) emissions. It then discusses the economic and health impacts arising from climate change, so as to provide a context on the need to reduce carbon emissions.

The remaining literature review is then split into three distinct parts. The first part examines Life Cycle Assessment (LCA), the method to best quantify carbon emissions. Further, the review identifies LCAs that have been undertaken in healthcare. The second part focuses on economics, reviewing the main methods that are used to perform health technology assessments. Additionally, this second part examines ways to monetise carbon emissions, so they can be included in economic analysis. The last part of the review first looks broadly at overdiagnosis before focussing on the extent of overtesting of both pathology and diagnostic imaging, as a reduction in unnecessary care should result in both reduced environmental and economic impact whilst not adversely impacting patient care.

2.2 Anthropogenic climate change

Anthropogenic climate change was first hypothesised in 1896 when the Swedish chemist, Svante Arrhenius, calculated that if atmospheric carbon dioxide (CO₂) doubled due to the industrial revolution's burning of coal, then the Earth's temperature would be raised by 5-

6°C.¹ This hypothesis of anthropogenic climate change did not gain much scientific traction until the 1950's, in part because the impact on the climate up until that point was too small to notice.² In the second half of the 1950's the physicist Gliberth Plass calculated that a doubling in CO₂ would lead to a 3-4°C increase in global temperatures³, and the geochemist Charles David Keeling detected a rise in atmospheric CO₂ in only a two-year period instead of the expected decades.^{2,4}

During the 60's and early 70's, however, climate scientists still overwhelmingly believed that changes in climate were due to natural cycles. Studies, such as the 1965 US President's Scientific Advisory Committee's report stating that by 2000 rising CO₂ levels "could be deleterious from the point of view of human beings"⁵, and a 1970 Massachusetts Institute of Technology study that determined that anthropogenic warming would result in droughts and rising sea levels⁶, gained little traction.

This changed in the late 1970's and early 80's. In 1979, the US National Academy of Science's Charney Panel confirmed that doubling atmospheric CO₂ levels would increase global temperatures by 1.5-4.5°C.⁷ More importantly, in the following year NASA determined that other greenhouse gases such as methane, nitrous oxide, and ozone had a global warming potential, that their global warming potentials were higher than CO₂, and that combined they would contribute as much to global warming as CO₂.⁸ Previous modelling, based purely on atmospheric CO₂ levels and showing that the impacts of climate change would only be seen in the late 21st century, were now suddenly out of date.

In the 1980's, a range of studies from multiple disciplines were indicating that anthropogenic climate change needed to be acted on. Ice core studies showed the link between atmospheric CO₂ and global temperatures⁹; statistical studies showed that global temperatures were increasing¹⁰; and increasingly sophisticated computer modelling was showing projections of the impacts of climate change, and in particular to agriculture and fisheries.¹¹ In one of the first mentions about the health impacts of climate change, a US Academy study in 1983 estimated that global warming would cause deaths and illness due to heat waves and potential changes in the habitats of disease vectors.¹²

Studies such as these resulted in the Toronto Conference in 1988 stating that anthropogenic climate change was “a major threat to international security and are already having harmful consequences over many parts of the globe.”¹³ Governments started to take note, with the UK's Prime Minister Margaret Thatcher in 1988 being the first major leader to declare global warming was an issue, stating that due to the use of fossil fuels “... concentrated into such a short period of time, we have unwittingly begun a massive experiment with the system of this planet itself.”¹⁴

2.3 International Panel on Climate Change

The International Panel on Climate Change (IPCC) was established in 1990 by the United Nations Environment Programme and the World Meteorological Organization to advise governments on policy to regulate emissions. Their first report in that year concluded that the world had been warming due to human activity, and that a reduction of CO₂ emissions by 60% would be needed to stabilise concentrations at their current levels.¹⁵ The second report

in 1995 determined that anthropogenic climate change had the potential to alter the Earth's climate, and that these changes may be irreversible.¹⁶ This was followed by the two further IPCC reports, from 2001 - 2014, which stated that the warming of the atmosphere was unequivocal; that it was *extremely likely* (95-100% probability) that human influence was the dominant cause; that this would result in rising sea levels and in the frequency of heat waves; and that developing countries and poor persons were the most vulnerable to climate change.^{17,18}

The second IPCC report led in 1997 to the Kyoto Protocol, in which the 192 signatories, dependent on their stage of economic development, pledged to reduce their carbon emissions.¹⁹ To be put into effect, however, the Protocol required ratification by countries that contributed more than 55% of the world's emissions. The ratification was therefore delayed in 2001 when the incoming American President, George W. Bush publicly renounced the Kyoto Protocol.²⁰ It was only in 2005 that the Protocol came into effect, with 141 signatories.²¹

The Paris Agreement, the first legally binding international treaty on climate change, was adopted on December 12, 2015 by 195 signatories, and came into force on November 4, 2016, superseding the Kyoto Protocol. The goal of the Agreement was to limit global warming compared to pre-industrial levels to well below 2°C, and preferably to 1.5°C.²² Whilst USA President Trump officially removed the USA from the Paris Agreement on November 4, 2020²³, his successor, President Biden, officially re-joined the USA to the Paris Agreement on February 19 2021, on his first day in office.²⁴

The first Working Group of the Sixth Assessment Report of for the IPCC released its findings on the physical science basis of climate change in August of 2021.²⁵ Apart from stating that it is now unequivocal that humans caused global warming, the report also stated that

“Human-induced climate change is already affecting many weather and climate extremes in every region across the globe”,

and that expected changes to the climate system would include:

“...increases in the frequency and intensity of hot extremes, marine heatwaves, and heavy precipitation, agricultural and ecological droughts in some regions, and proportion of intense tropical cyclones, as well as reductions in Arctic sea ice, snow cover and permafrost.”

These changes to the climate have a range of potential economic and health impacts. It should be noted, however, that there are inherent levels of uncertainty when modelling the impacts of climate change. Firstly, there is uncertainty surrounding the interaction of anthropogenic influences and natural internal variability in the climate, thereby placing limits on the ability to accurately model changes going into the future.²⁶ As stated by Deser (2020), “anthropogenic climate change is what you expect; anthropogenic climate change and natural climate variability is what you get”.²⁶ This uncertainty is exacerbated by the short observational period we have of the impacts of climate change, in contrast to the long period of time we have been developing and improving weather forecasting models.²⁷ Furthermore, there is uncertainty in the modelled physical and economic damages from climate change, often resulting in wide discrepancies between models.^{28,29} This uncertainty can be addressed

through modelling techniques such as sensitivity analysis and Monte Carlo simulations to calculate probability distributions, although there is also criticism there is often no actual economic basis for determining a given parameter's probability distribution.³⁰ It is important to recognise, therefore, that this level of imperfect information exists when investigating the impacts of climate change, especially when studies attribute past and future events to climate change, and determine the resultant physical, economic and health damages.

2.3.1 Economic impacts of climate change

There are a wide range of economic impacts resulting from climate change. For example, agricultural yields are decreasing due to variations in precipitation patterns, increasing temperatures, storms, floods, droughts, and insect pests.^{31–34} The impacts of these reductions are exacerbated by reduced labour productivity due to heat stress in workers subject to outdoor temperatures.^{35,36} Energy systems are requiring increased peak supply and transmission capabilities due to an increased use of air conditioning^{37,38}, which may see increases to electricity prices.^{39,40} Sea level rise has resulted in losses in real-estate market values.^{41,42} Overall, Burke et al (2015) found that all economic productivity (agricultural and non-agricultural) in both rich and poor countries, reduces in line with global temperatures.⁴³

In addition to structural impacts to the economy from climate change, the frequency of extreme weather events such as heatwaves, heavy precipitation events resulting in flooding and major (Category 3-5) tropical cyclones, along with the frequency of fire weather that promotes the intensity and spread of wildfires, have increased since the 1950s²⁵, resulting in large economic losses. For example, climate change was responsible for approximately US\$8.1 billion of the total damages of US\$60 billion from Hurricane Sandy in 2012⁴⁴, whilst

approximately US\$30-67 billion of the \$US90 billion damages from Hurricane Harvey in 2017 have been estimated to be attributable to anthropogenic climate change.⁴⁵ Monetary losses from property damage caused by wildfires in California have been increasing, from an average annual loss of US\$0.19 billion in 1989-98, to US\$0.40 billion in 1999-2008 and almost US\$1 billion in 2009-18 (all prices in US 2018 dollars).⁴⁶ Taking a broader approach to calculate both direct and indirect costs, Wang et al (2021) estimated the 2018 Californian wildfire damages to be approximately US\$148.5 billion, or 1.5% of California's gross domestic product.⁴⁷ Similar impacts from wildfires are seen across different continents. The 2007 wildfires in Greece were estimated to have caused €2-5 billion in costs⁴⁸, whilst in Australia, the economic impact of the 2019/20 wildfires was estimated to be approximately A\$20 billion.⁴⁹

2.3.2 Health impacts due to climate change

These extreme events have impacts on human health. Apart from hurricanes causing direct deaths due to flooding, they have also been shown to increase in the incidence of myocardial infarction and deaths post landfall⁵⁰⁻⁵², in addition to an increase in emergency department presentations for poisoning, respiratory and renal disease, and skin and soft tissue infections.⁵³ Fine particulate matter (PM_{2.5}) from wildfire smoke adversely affects both respiratory⁵⁴⁻⁵⁶ and cardiovascular morbidity⁵⁷⁻⁵⁹, and there are positive associations between short-term exposure to PM_{2.5} emissions and the incidence of septicaemia, fluid and electrolyte disorders, and renal failure.⁶⁰ Whilst the impacts of chronic exposure to wildfire smoke is unknown, chronic exposure to anthropogenic PM_{2.5} has been associated with all-cause mortality^{61,62}, lung cancer^{63,64}, and cardiopulmonary mortality.^{65,66} Heatwaves are another form of extreme event, and are associated with increased visits to emergency

departments^{67,68}, and increases in cardiorespiratory^{69,70} and stroke^{71,72} mortality, especially amongst the elderly.^{73,74} Heat stress caused by an extreme wet-bulb temperature of 35°C, above which the human skin is unable to be cooled through sweat evaporation, has been estimated to have caused 783 deaths between 1980 and 2014, with deaths expected to rise over the course of the current century due to ongoing warming resulting in more days where this wet-bulb temperature is achieved or exceeded.^{75,76}

Climate change has a range of other impacts on human health apart from individual extreme events. For example, in addition to reduced agricultural yields, which contribute to undernutrition^{77,78}, climate change is reducing yields from marine fisheries due to an increasing ocean temperature and acidification, with global fisheries currently providing 2.9 billion people more than 20 percent of their animal-based protein requirements.^{79–82} Additionally, climate change is affecting biodiversity, which in turn further threatens food security.⁸³ A meta-analysis of 97 studies investigating the increase in global temperatures compared to 1880 levels showed the fraction of remaining species (FRS) decreased by 14% and the fraction of remaining area with a suitable climate for each species (FRA) decreased 35%.⁸⁴ Markedly, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) estimates that 12.5%, or approximately 1 million species, are threatened with extinction within decades due to climate change.⁸³

Higher temperatures and changes in precipitation patterns from climate change increase the risk of gastrointestinal and diarrhoeal disease.⁸⁵ Extreme water-related weather events are associated with increases in waterborne pathogens and contamination of drinking water supplies.⁸⁶ Climate change affects geographical expansions of vector-borne diseases, as well

as the vector life cycles and the reproduction rate of parasites and viruses in both vectors and infected humans.^{87–89}

Utilising the World Health Organization's (WHO) assessment on the effects of climate change on mortality due to undernutrition, diarrhea, malaria, dengue fever, heat stress and coastal floods⁹⁰, Tang et al calculated health damage factors for three Shared Socio-Economic pathways (SSPs) that were developed by the IPCC, and that reflected high, medium, and low economic growth scenarios (SSP 1-3 respectively).⁹¹ The calculated damage factors, defined as the additional health damage in disability-adjusted life years (DALY) per 1 kg of additional carbon dioxide equivalents (CO₂e) emissions, were 1.3×10^{-6} , 1.5×10^{-6} and 2.0×10^{-6} for SSP1, SSP2 and SSP3 respectively, with the majority of the health impacts occurring due to undernutrition, and to a lesser extent malaria, coastal flooding and diarrhoea.⁹¹

Paradoxically, healthcare is itself a major carbon emitter. If international healthcare was a country it would be the world's fifth largest emitter producing 4.4% (2.4 Gt CO₂e) of global emissions annually⁹², with these emissions in turn resulting in approximately 3,000,000 disability life years (DALYs) reduction in human health.⁹¹ Focussing on Australia, healthcare is currently the largest sector of the Australian economy, being responsible for 10% of national GDP⁹³, with the provision of healthcare resulting in 7% of Australia's carbon emissions.⁹⁴ The Australian Medical Association and Doctors for the Environment have called for carbon emissions to be reduced by 80% by 2030, and for healthcare to be carbon neutral by 2040.⁹⁵ Although individual states have given a commitment to be carbon neutral by 2050, only a few states have acknowledged that healthcare will need to reduce its emissions, with none of those yet providing details on how this will occur.^{96–98}

2.3.3 Positive impacts of climate change

Not all impacts of climate change have negative consequences. For example, while increased temperatures overall globally result in negative impact on crop yields, there can be greater agriculture yields in certain locales, and for certain crops. This is especially true in cold locales such as the Nordic countries, where climate change is extending the growing season and allowing for a more northerly expansion of growing areas.^{99–101} This lengthened growing season does come with some challenges, however, due to increased precipitation leading to leaching of fertiliser from soils, increased pests and disease, and “drowned crops”, with especially barley being particularly sensitive to precipitation both before and after sowing.¹⁰²

In terms of human health, currently global excess deaths resulting from non-optimal temperatures is primarily due to cold weather rather than hot weather (67 vs. 7 per 100,000).¹⁰³ Since 2000, however, cold-related excess deaths have fallen 0.51% and heat related excess-deaths have increased 0.2%. This indicates that whilst in the short-term climate change is reducing temperature-related deaths due to cold weather, in the longer term it is expected to increase mortality.¹⁰³

2.4 Quantification of carbon impacts

The internationally recognised way to undertake carbon footprinting is life cycle assessment (LCA), with the first LCAs being performed in 1969 by Coca-Cola comparing glass and plastic bottles.¹⁰⁴ In the 1980s, industrial companies joined with research companies and institutes under the leadership of the Society of Environmental Toxicology and Chemistry (SETAC).¹⁰⁵

SETAC working groups standardised LCA methodology, after which the International Organization for Standardization (ISO) assumed leadership, resulting in the publishing of standards for LCA between 1997 and 2006, with the current standards being ISO 14040:2006 (Life cycle assessment – Principles and framework) and ISO 14044:2006 (Environmental management — Life cycle assessment — Requirements and guidelines).^{106,107} Whilst LCA quantifies a range of environmental impacts, such carbon emissions, eutrophication, ozone depletion or toxicity, when focused purely on carbon it underpins all major international carbon footprint standards.¹⁰⁸⁻¹¹¹

What distinguishes LCA from other methods of environmental assessment is its comprehensive scope, including raw material acquisition, manufacture, use, and disposal / recycling.¹⁰⁶ This whole-of-system approach means materials, energy and processes that are not in the immediate area of study are included in quantifications. For example, there have been calls by a number of authors to preference regional or total intravenous (TIVA) anaesthesia over gaseous anaesthesia, given the high carbon footprint of gaseous anaesthetics such as desflurane, nitrous oxide and sevoflurane.^{112,113} A recent study by McGain et al (2021), however, showed that the carbon emissions resulting from gaseous, spinal, or a combination of gaseous and spinal anaesthesia for a knee reconstruction were similar.¹¹⁴ The study showed that although spinal anaesthesia did not have the high carbon emissions arising from gaseous anaesthetics, there was instead large carbon emissions associated with the delivery of oxygen and the washing and sterilisation of reusable equipment that was not required for gaseous anaesthetics.¹¹⁴ When used for mitigation, this whole-of system approach allows LCA to avoid unintended consequences whereby an

environmental burden is shifted to a different part of the life-cycle, or from one environmental impact to another.¹¹⁵

2.4.1 Life cycle assessment structure

Under ISO 14040 (2006) LCAs are structured to have four phases LCA: goal and scope definition; life-cycle inventory analysis (LCI); life-cycle impact assessment (LCIA); and interpretation.¹⁰⁶ Goal and scope definition includes the reasons the LCA is being undertaken; the definition of the functional unit, which defines the function of a product as opposed to just its physical characteristics; and the determination of the reference flow which defines the material requirements to achieve the functional unit. Examples of functional units in healthcare are the treatment in ICU of a patient with septic shock (Sepsis-3), or a 100 ml intravenous bag containing 100 mg of morphine at the manufacturers warehouse ready for transport.^{116,117} Apart from defining which inputs and outputs of the system should be included in an analysis, a functional unit allows for the strict comparisons of two alternatives, such as the treatment of sepsis patients in different countries in the above example, or standard vs. robotic surgery.

During the life cycle inventory phase, all the natural resources and material inputs related to the functional unit over the life cycle, as well as all the corresponding emissions to the environment, are collated. Emissions to the environment are aggregated and “characterised”, whereby the physio-chemical qualities of an emission are used to convert it to a reference unit so that they can be added together to form a total footprint. For carbon, all greenhouse gases are converted to the reference unit of carbon dioxide equivalents (CO₂e), based on the global warming potential of carbon dioxide. As an example, 1 kg of the

gaseous anaesthetic desflurane has a global warming potential over a 100-year period equivalent to 1,790 kg CO₂eq, whilst 1kg of the gaseous anaesthetic sevoflurane has a global warming potential equivalent to 216 kg of CO₂.¹¹⁸ This level of impact assessment is known as “midpoint” assessment.

Multiple midpoints may be further characterised to calculate “endpoint” assessments, for example as in the ReCiPe LCA impact assessment model (Figure 2-1). Under this model, the endpoint of damage to human health, expressed in DALYs, is estimated by the integration of epidemiological studies (which quantify the effect of midpoints on health outcomes) with the distribution, transport and ultimate fate of emissions.¹¹⁹ Endpoints have the advantage of providing information about the expected impacts of emissions, but they also have disadvantages due to the high degree of uncertainty in the characterisation factors required to reach an endpoint due to the complexity of impact pathways.^{120–122}

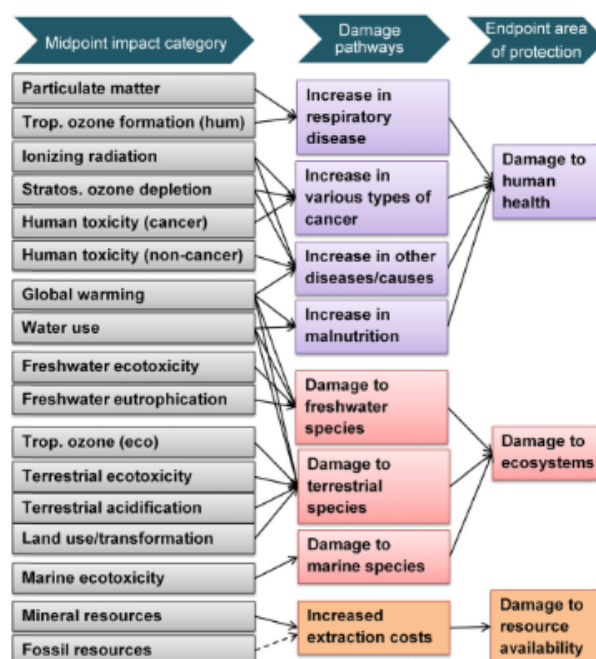


Figure 2-1: ReCiPe 2016 midpoint impact categories damage pathways and endpoints¹¹⁹

2.4.2 Life cycle assessment methods

There are two broad categories of LCA; environmental input-output (EIO), and process based (P-LCA).

2.4.2.1 *Environmental input-output*

EIO is based on the work of the economist Leontif, who in 1936 constructed a linear model of the U.S economy that tracked both the monetary inputs any given sector receives from other sectors, and similarly the monetary outputs from any given sector to other sectors.¹²³ Major world economies now regularly produce these input-output tables for economic research and structural analysis.¹²⁴

In the 1970s, Leontif theoretically extended the IO model to include the generation and abatement of pollutants.^{125,126} This initial work developed into national EIO models, which calculate environmental impacts based on the monetary amount spent on a product or service from a given sector by combining both the direct emissions from the sector with the indirect emissions that result from purchases from other sectors.^{127–131} Given the global nature of trade, environmental multi-regional models (MRIO) have been further developed to include the international trading of goods and services.^{132–134}

Due to EIO having a top-down approach that covers the whole economy, proponents claim its greatest benefit is the lack of truncation errors that are inherent in the bottom-up process-based LCA, where a subjective decision must be made about what to include in the analysis (the system boundary).¹²³ A substantial part of this truncation can be the indirect impacts associated with a product, such as marketing or legal services, and which are not

typically covered in P-LCAs, with multiple studies showing that this truncation error can result in an under-estimation of emissions from a process-based LCA by over 50 %.^{135–138}

EIO, however, has a number of drawbacks. The main one is that IO tables contain at most a few hundred sectors. This results in a high level of aggregation, with all products in each sector deemed homologous.^{139–141} This is further exacerbated by products with high economic activity, such as steel, being placed in single-product sectors, while those of low activity, such as medical equipment, being aggregated into a single sector with multiple products.¹⁴² Furthermore, there is also the inherent assumption that monetary flows have a linear correlation with environmental impacts, and that any dollar spent in a given sector results in a set quantum of emissions.¹⁴³ This is clearly not the case.

For example, the price paid for a medical device or pharmaceutical can be dependent on the negotiations of an individual payer. Using EIO, differences in negotiated prices would result in differing calculated emissions, even though the emissions resulting from manufacturing would be the same. This would similarly occur when the price of a pharmaceutical dropped when it moved to be off patent. Analysis on a single product or services within an aggregated sector using EIO is not indicative of its environmental impact, and therefore EIO cannot be used to compare products or procedures such as robotic vs. conventional surgery, nor improvements within a sector.¹⁴⁴ Rather, EIO works best at the level of analysing entire economies or sectors.^{142,145}

Furthermore, EIO is simply a linear extrapolation of the original IO tables. This means, for example, that in modelling the doubling of the supply of a product from a sector it is

assumed that all the inputs are similarly doubled, with no economies or diseconomies of scale; that there is an infinite elasticity of supply of all those inputs with no constraints; and lastly that there is adequate market capacity to absorb the production of any co-products.¹⁴⁶ In addition to these drawbacks, EIO does not include either the use phase of an LCA, nor the impacts arising from end-of-life such as the emissions resulting from landfill or recycling; and they are typically several years out of date due to the time it takes to compile them.^{138,147}

2.4.2.2 Process based LCA

Process based LCA (P-LCAs) use a series of interlinked processes to model the entire life cycle. An individual process quantifies all material and energy inputs, all products from the process that may be single products such as kg of polyvinylchloride plastic or multiple products such as wool and meat arising from a sheep, all wastes, and all emissions to the environment.¹⁴⁸ Resultant process trees are typically very large. As an example, in the Ecoinvent LCA database, recycled aluminium is directly and indirectly linked to 1,958 individual processes (Figure 2-2).¹⁴⁹

Compared to EIO, P-LCA's greatest advantage is being able to investigate individual products or services at a great level of detail so as to be able to make comparisons, although they may miss emissions due to a P-LCA being required to draw a boundary around the system under investigation, typically by excluding existing infrastructure and the "the machine that makes the machine".¹³⁵

There are two types of P-LCA; attributional and consequential. Plevin et al (2014) defines attributional LCA as "... an accounting system that attributes a share of total pollution to a

specific product¹⁵⁰, and that it “... represents the average operation of a static system irrespective of economic or policy context”.¹⁵¹ By comparison, consequential LCA describes the resultant environmental impacts due to decision making and the subsequent changes in demand.¹⁵²

Attributional LCA works as a linear steady-state model that has fixed input and output coefficients, with no economies of scale or capacity effects. It is assumed to have an infinite elastic supply of inputs irrespective of production outputs, and that there is enough demand to utilise any co-products from production.¹⁴⁶

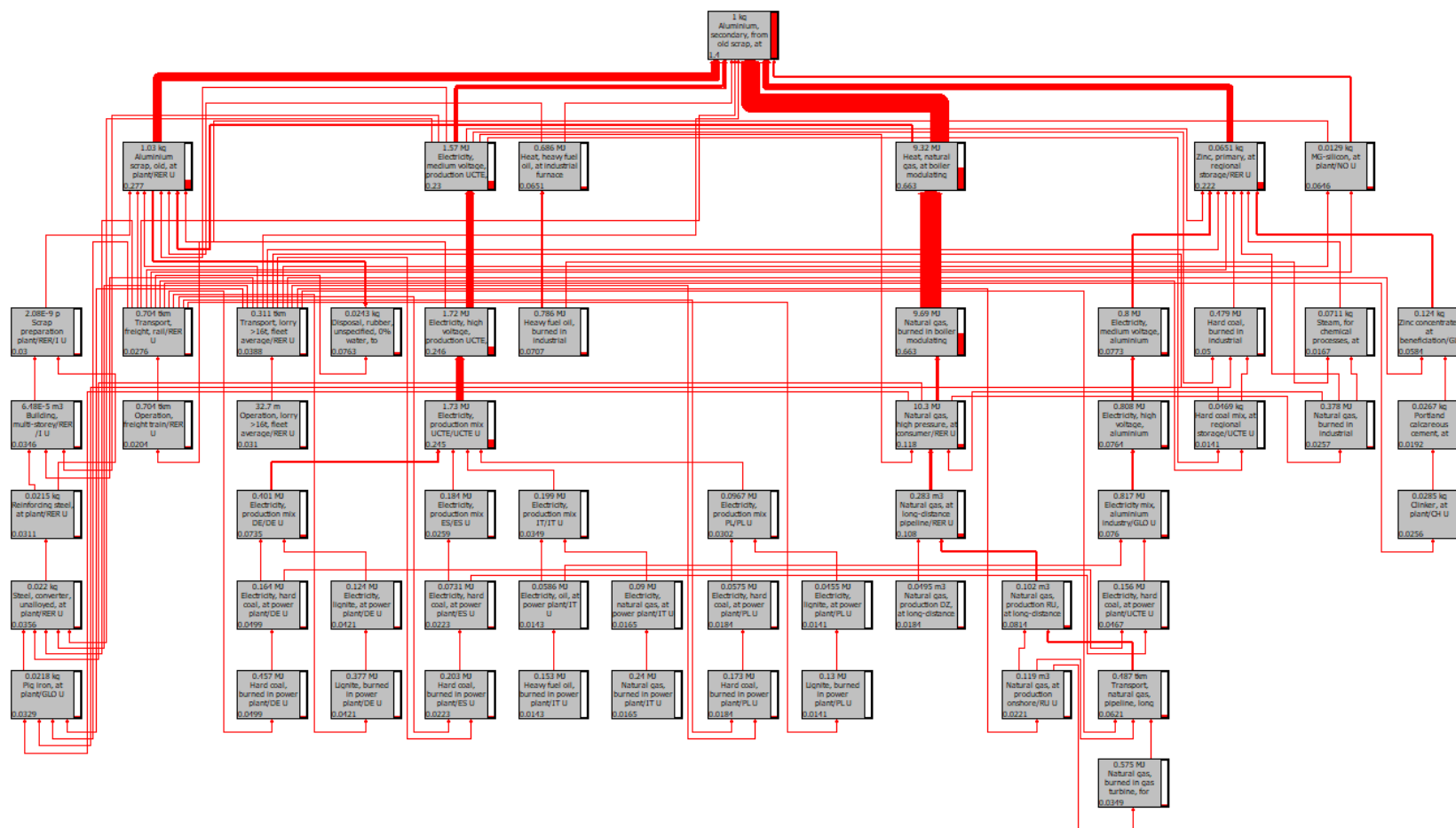


Figure 2-2: Example of a process tree for recycled aluminum for carbon emissions (kg CO₂ eq) showing 57 of 1,958 processes^{149,153}

To address these concerns, consequential LCA only uses marginal suppliers or technologies that are affected by changes in demand as a result of decision making, including those that are remote from the area under study.^{154,155} As an example, the consequence of soybean oil being used for biodiesel results in less oil being available in the international market, with this shortfall being met by the marginal global supplier of oil, which is palm oil from Malaysia.¹⁵⁶ A consequential LCA on using soybeans to make biodiesel therefore includes this production of Malaysian palm oil. The consequences of an increased demand for a product, however, might not result in more of that product being produced, but rather may result in an increase in recycling rates, less demand, or a product substitution.¹⁵⁷ Similarly for the impacts of electricity, consequential analysis uses the marginal supplier that is able to respond to the increased demand and that will provide the next kWh of energy, which is predominately renewable energy, compared to attributional analysis that would use the relative contributions of a range of fuels, typically including a mixture of fossil fuels and renewables.

Consequential LCA has been criticised for its inherent uncertainty, both in modelling the consequences of a change in demand outside of the immediate system under investigation, as well as estimating the future in terms of expected demand and supply.^{158,159} To these criticisms Plevin et al (2014) replied that an uncertain estimate is better than no estimate.¹⁵⁰

2.4.2.3 Hybrid LCA

A number of researchers have proposed combining EIO and process LCA into so-called “hybrid LCA”, to try and benefit from their respective strengths. There are three types of hybrid LCA; tiered analysis, hybrid-analysis, and integrated hybrid analysis, of which tiered analysis is the most common. Tiered analysis uses process data for the direct area under

study, and EIO for remaining data.^{123,160} By comparison, hybrid-analysis further disaggregates EIO sectors based on detailed environmental and monetary sectorial data¹⁶¹, whilst an integrated hybrid analysis combines process-based physical data in a technology matrix with monetary IEO data.^{148,160}

There are criticisms of hybrid EIO. Crawford et al (2018) note that EIO data is often added to process analysis, and vice versa, in an ad-hoc manner¹⁴³, whilst Suh and Huppes (2005) states that without a clear boundary between EIO and process data, there is a risk of double-counting which can only be avoided by subtracting the process data from the EIO matrix.¹⁴⁸ Given the level of aggregation within an IO table, this is difficult to achieve in practice.¹⁴³ This issue of potential double-counting can also occur in tiered-hybrid studies that use EIO data in place of process data for a product when process data is unavailable, especially when a product system with process data is being compared to another system that has a mix of process and EIO data.^{162,163}

Yang (2016) has a broader criticism of hybrid analysis, giving the example that under the input-output portion of a hybrid model the manufacture of a device made for the large hadron collider in Geneva would affect durian growth in Thailand.¹⁶⁴ In addition, Yang criticises the EIO model's assumption of a linear interaction between sectors due to increasing demand, instead of economies of scale and market elasticities causing a diversity of changes.¹⁶⁴

2.4.3 LCA and healthcare

Compared to other industries or sectors of the economy, very few healthcare LCAs have been performed. Using EIO, the percentage contribution to national carbon emissions from healthcare been determined for the USA (10%)¹⁶⁵, Australia (7%)⁹⁴ with the source of these emissions shown in Figure 2-3, Canada (5%)¹⁶⁶, Japan (5%)¹⁶⁷, and China (3%)¹⁶⁸, whilst a hybrid analysis has calculated that healthcare was responsible for 5% of the UK's emissions.¹⁶⁹ In Australia, using EIO the health system has been estimated to be responsible for 7% of the state of New South Wales's carbon emissions.¹⁷⁰ Furthermore, multi-regional IO (MRIO) has estimated healthcare's global footprint to be 4.4% of total emissions.^{92,171} In addition to these studies that use EIO to determine the sectorial emissions of healthcare, EIO has been used to calculate the carbon emissions of an Australian ambulance service¹⁷², and of unused pharmaceuticals from cataract surgery.¹⁷³

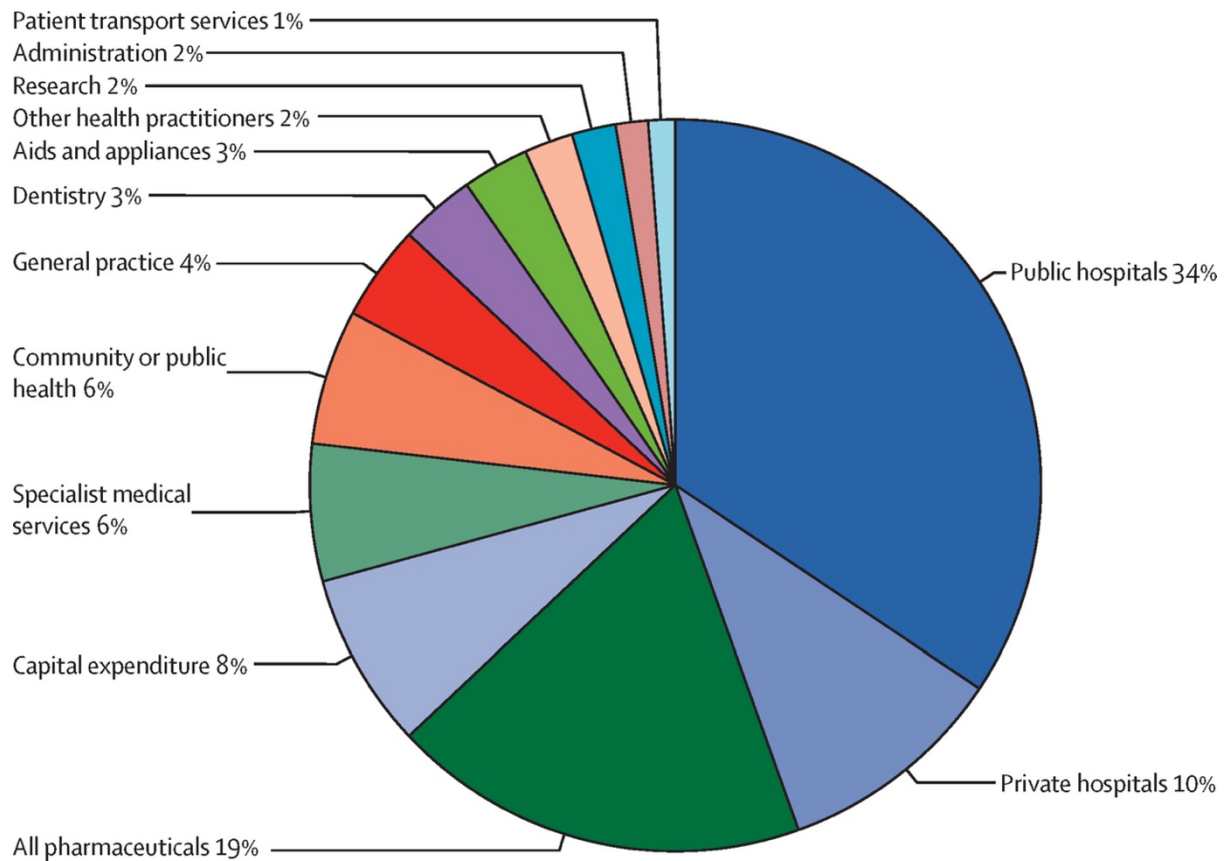


Figure 2-3: Source of Australian healthcare CO₂e emissions, from Malik et al (2018)⁹⁴

Compared to EIO, a greater number of healthcare P-LCAs have been performed, with most originating from the fields of surgery, anaesthesia, and intensive care, and of these, the majority have investigated the differences between single use and reusable items such as breathing circuits, laryngoscopes, venous catheter insertion kits and laryngeal masks^{174–183}. Moving away from specific items, MacNeill et al (2017) investigated the carbon emissions of an operating theatre¹⁸⁴, whilst McGain et al (2018) investigated the carbon emissions of caring for a patient with septic shock in an intensive care ward.¹¹⁶ Lastly there have also been a limited number of studies investigating anaesthetic pharmaceuticals and morphine.^{117,185,186}

Other P-LCA papers have had limitations. Of three papers by Campion and Thiel investigating the impacts of birth, two did not include a definition of the functional unit, whilst third did

include the functional unit but did not use it to compare materials used.^{187–189}. Similarly, Unger and Landis’s (2016) study of reprocessed medical devices contained an incomplete functional unit of “seven medical devices”.¹⁹⁰ Lastly, a small number of studies used either generic or estimated data rather than doing a detailed investigation of the system under study or omitted data from large parts of the life cycle.^{191–195}

Six papers used tiered-hybrid analysis, with EIO data being utilised to substitute when no process data is available, have been performed. In all these papers EIO data was used in the ad-hoc manner as described by Crawford’s et al’s (2018) criticism of hybrid EIO.¹⁴³ Of these papers, Thiel wrote three. Thiel used EIO data for pharmaceuticals when investigating cataract surgery¹⁹⁶; for robotic instruments when comparing types of hysterectomy¹⁹⁷; and for single use equipment used for laparoscopic surgery.¹⁹⁸ Similarly, Morris et al (2013) used EIO for pharmaceuticals and medical equipment when calculating the carbon footprint of cataract surgery.¹⁹⁹ Lastly, two papers investigating the emissions associated with the provision of hemodialysis used EIO for pharmaceuticals.^{200,201} In all these studies the data modelled with EIO had the largest emissions due to the expanded system boundary, with this resulting in either an inaccurate total footprint, or in the cases comparing types of surgical instrument types, inaccurate comparisons.

2.4.4 Summary

Life cycle assessment (LCA) forms the basis of all major carbon footprinting methods. It is unique in that its comprehensive scope includes aspects of the life cycle, including the mining and production of raw materials through to disposal or recycling. Environmental input-output (EIO) LCA uses nationally produced IO tables that model the flow of money between business

sectors to calculate environmental impacts. Whilst appropriate when investigating sectors at a national level, the degree of aggregation and the lack of sectorial resolution means it is not suitable to investigate individual products in highly aggregated sectors. Process LCA (P-LCA) links individual processes, each process having material and energy inputs, a product or products as outputs, and emissions to the environment. The disadvantage of P-LCA is that because it has to include a system boundary of inclusions and exclusions it inherently has truncation errors.

Attributional P-LCA attributes a share of the overall emissions to a product, whilst a consequential P-LCA models the marginal producers of materials due to a change in demand. Whilst consequential LCA has increased uncertainty compared to attributional P-LCA, it is arguably more useful for decision making. Hybrid LCA attempts to combine EIO and P-LCA, although in practice it is difficult to avoid double counting, or to have a model with differing system boundaries.

There have been a limited number of LCAs performed in health care. A small number have been performed using EIO to determine the environmental impacts of healthcare at a national level, and using multiregional modelling (MRIO), at an international level. Whilst some high-quality P-LCAs have been performed, primarily in the fields of surgery, anaesthesia and intensive care, there are also a similar number of low-quality studies due to using estimated rather than collected data, data omissions from parts of the life cycle, or the incorrect application of tiered-hybrid LCA, resulting in inaccurate comparisons.

2.5 Health technology assessment

Health technology assessment (HTA), which determines whether the cost of a new medical device, pharmaceutical, or intervention is justified compared to the health benefit conferred to patients, forms a vital component of both policy and clinical practice guidance. HTA can be performed at the level of an individual payer such as an insurance provider; as guidance such as from the US Preventative Services Taskforce; or to determine whether a device or intervention will be funded by a national health service, such as the UK's National Institute of Health and Care Excellence (NICE).

This section will review the main methods available to perform health technology assessments: cost-effectiveness analysis, cost-benefit analysis, and cost-consequence analysis

2.5.1 Cost-effectiveness and cost-utility analysis

Cost-effectiveness analysis (CEA) is the primary way new healthcare interventions are evaluated worldwide.^{203–205} CEA estimates the opportunity costs and health outcomes of an intervention and compares this to an alternative such as no treatment, another treatment option, or a differing intensity of the intervention.²⁰⁶ The perspective of the CEA will determine which costs and outcomes are included. A health system payer perspective includes only the monetary costs of treatment and other health resources borne by a third-party such as a national health service or insurance.²⁰⁷ By contrast, a patient's perspective could additionally include out-of-pocket medical expenses, direct non-medical costs such as patient transport, or indirect costs or productivity losses, such as the loss of work income due

to illness or premature death.²⁰⁸ Lastly, a societal perspective is inclusive of all relevant sectors for the intervention in question, such as social welfare, education or the criminal justice system, and can include items such as unpaid caregiver time, teaching or police costs.²⁰⁷

The basis of CEA is the calculation of the incremental cost-effectiveness ratio (ICER), which determines the incremental cost of an additional unit of effectiveness (health) of an intervention compared with an alternative, given as:

$$\text{ICER} = \frac{C_1 - C_0}{E_1 - E_0}$$

where:

- C_1 and E_1 are the cost and effect (health) in the intervention group
- C_0 and E_0 are the cost and effect in the control care group

Cost-utility analysis (CUA) is a subset of CEA. Rather than using a single measurement of effectiveness as in a CEA, a CUA uses morbidity and mortality as a multi-dimensional measure of utility due to an intervention. In health care, the most well-known are the 'quality-adjusted life year' (QALY)²⁰⁹, and the 'disability-adjusted life year' (DALY).²¹⁰ QALYs combines duration of life with quality of life (Year of Life x Quality of Life weighting), such that a value of 1 is a year in full health whilst a value of 0 is being deceased.²¹¹ By comparison, DALYs have a disability-based perspective, and are calculated as the sum of Years of Life Lost (YLL) and Years Lost due to Disability (YLD) for individuals living with a disability due to a health condition.²¹² For DALYs, a value of 0 indicates no disability whilst a value of 1 is equivalent to death.

Whilst some interventions clearly show an additional health benefit for a lower cost compared with its alternative, for most others an incremental health benefit is accompanied by an additional cost. In a constrained health budget, spending on one intervention means monetary resources aren't available for other patient's treatments (the opportunity cost). This opportunity cost is represented as the cost-effectiveness threshold (k), or the cost to displace one quality-adjusted life year (QALY) somewhere in the health system ($\$/\text{QALY}$ gained).

As an example, Figure 2-4 shows the comparison of a new intervention B compared to an existing intervention A . Assuming a willingness to pay threshold of $\$20,000/\text{QALY}$ gained, at a price of P_1 the new intervention creates 2 additional QALYs of benefit at an additional cost of $\$20,000$. This cost of $\$20,000$ displaces a health benefit of one QALY elsewhere in the health system. Therefore, at price P_1 there is a net benefit of one QALY (2 QALYS benefit minus 1 QALY displaced), and the intervention is cost effective. The higher price of P_2 results in no net benefit (2 QALYS gained displace 2 QALYS lost elsewhere), whilst at P_3 there is a negative net benefit (2 QALYS displace 3 QALYS lost elsewhere).

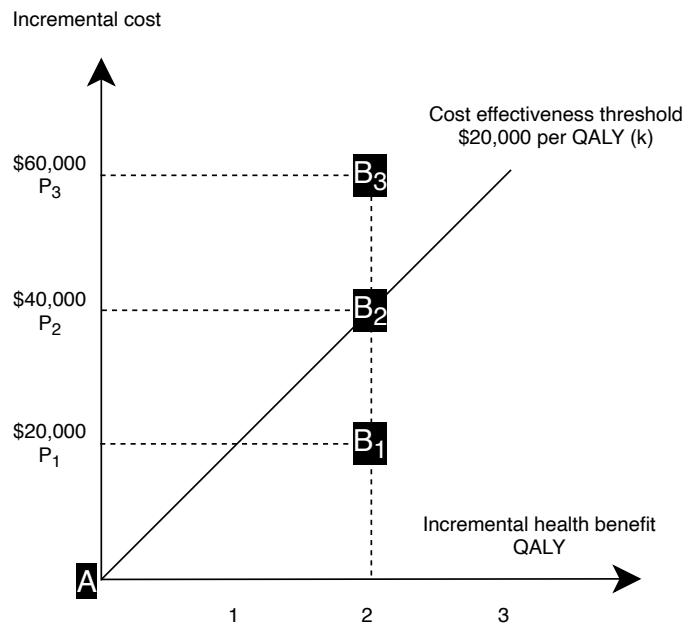


Figure 2-4: Value, price and cost effectiveness (based on Claxton et al 2008)²¹³

The UK, and more recently Japan, are the only countries with an explicit threshold for cost-effectiveness (£20,000 – 30,000 and ¥5 million per QALY respectively), although unofficial thresholds have been shown in other countries including Australia, Canada, the Netherlands, and Spain.^{205,214–218} Whilst there have been numerous studies using CEA in the United States, the Affordable Care Act of 2010 specifically forbids the use of cost effectiveness thresholds, thereby suggesting a de facto ban on their use for policy making and limiting their ongoing adoption.^{219,220}

From a decision maker's perspective, the outcomes of a CEA can be implemented in two ways. Within a fixed budget a 'league table' can be developed, with interventions being adopted in a descending order as the budget is expended.²²¹ Alternatively, decision makers can use the cost effectiveness threshold, and create a decision rule that if it is below the threshold the intervention will be adopted. A criticism of this approach is that because the

threshold value is public, manufacturers have awareness of the maximum willingness to pay for an intervention by decision makers and will therefore seek a price as close to the threshold value as possible.²²² This results in inefficiency, as any difference between the sum of a manufacturer's fixed cost plus a normal profit and the threshold value is an additional health gain forgone by other patients.²²²

2.5.2 Cost effective analysis modelling techniques

CEAs can be performed empirically using data such as those collected by an individual clinical trial, or if benefits and costs of an intervention are expected to accrue at a longer time scale, by modelling.^{223,224} As well as extending the results of short-term analysis, modelling additionally allows for the inclusion of data from disparate data sources to model consequences, and allows for the head-to-head comparisons of numerous alternate interventions to be made.^{224,225}

The most commonly used modelling techniques in CEA are decision trees and Markov models.²²⁶ Decision trees are the simplest model, with each branch of the tree representing possible health outcomes and their probability. At the end of the tree is a final outcome, such as a specific health state or death, along with their respective costs and health impacts such as QALYs (Figure 2-5). Decision trees are only useful for modelling interventions that have a short time horizon. For example, in Figure 2-5 a repetition of the tree for one additional time period would result in 17 terminal branches, whilst 5 additional time periods would result in hundreds of branches.

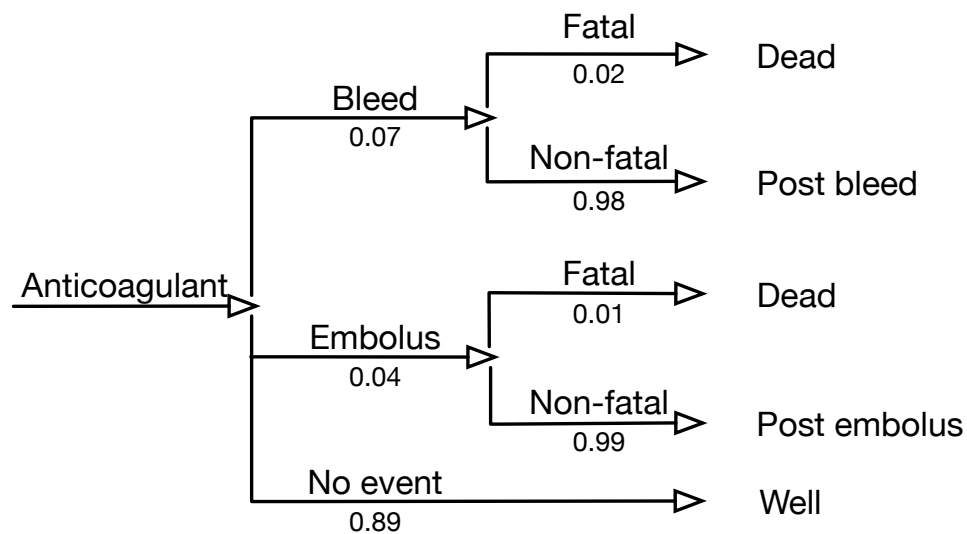


Figure 2-5: Example of a decision tree for modelling complications of anticoagulant therapy, showing the probability of an event occurring (based on Sonnenberg & Beck 1993)²²⁷

State-transition models, such as Markov models, allow for the modelling of interventions that have longer time horizons. Markov models describe the transitions of a cohort of patients between discrete health states based on transition probabilities, until reaching the “absorbing” or death state, from which there are no further transitions (Figure 2-6). Time is represented by discrete repeating cycles of a fixed length, such as a month or a year, with individuals at the end of each cycle either remaining in their current health state or moving to a different health state. Each health state and transition have a cost associated with it, enabling cost effectiveness to be calculated from the simulation of the patient cohort as they move through their illness.

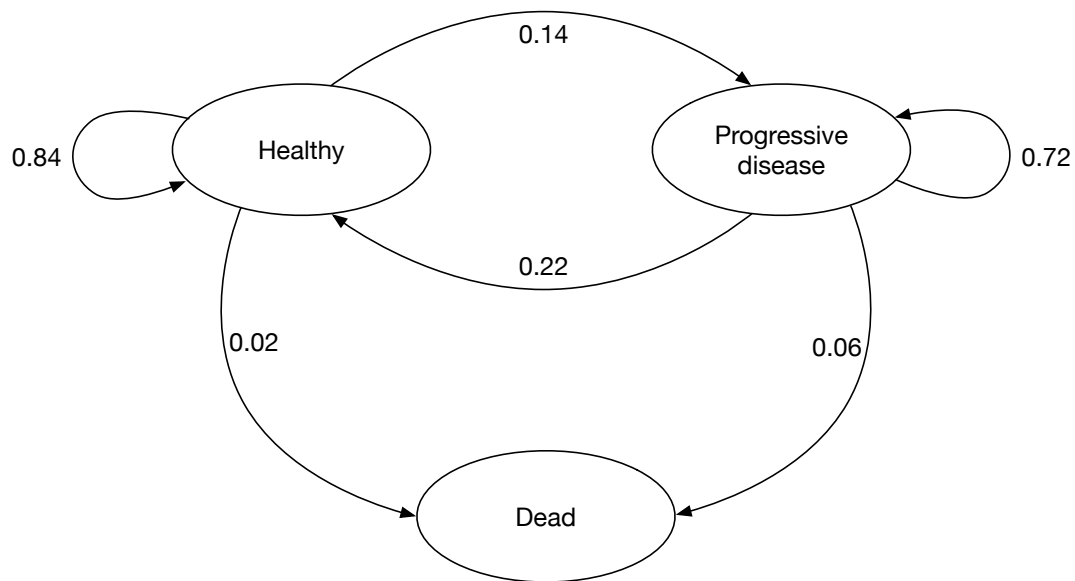


Figure 2-6: Example of a Markov model, showing the probability of an event occurring at the end of each time cycle

Markov models are limited due to an underlying assumption that the probability of moving to a different state is not dependent on the past history of the patient, such as the number of years that they spent in a diseased health state.²²⁸ Whilst this limitation can be addressed through modelling techniques such as time dependent states or probabilities, an alternative is to use microsimulation, or individual-level models. These simulate one individual at a time rather than a whole cohort of patients, allowing both the patient's history to be tracked and multiple comorbidities to be modelled, without requiring the multiple unique health states needed in a Markov model.²²⁸ A criticism of Markov modelling is the level of uncertainty associated with modelling the future, especially in models encompassing the lifetime of an individual. Due to this, Diaz et al (2018) suggests "results should be considered an approximation"²²⁹, with many models utilising Monte Carlo analysis to attempt to quantify this uncertainty.^{230,231}

2.5.3 Cost benefit analysis

In contrast to CEA, cost-benefit analysis (CBA) monetises all costs and benefits of an intervention, including those of non-market goods such as good health, with an intervention being deemed worthwhile if the monetary benefits outweigh the costs.²³² Whilst CBA is firmly established as the preferred methodology for environmental economic analysis, more limited numbers have been performed in healthcare, with examples including, pharmacy services, chronic disease, ventilator-associated pneumonia prevention, bariatric surgery, and diagnostic testing.^{233–237}

In healthcare, CBAs are typically undertaken in the absence of a budgetary constraint²³⁸, and therefore implicitly take a societal view as an additional cost from an unconstrained budget will require resources from outside of a particular budget. In the case of healthcare, this would include other government sectors such as employment or housing.²³⁹ For this reason, Culyer and Chalkidou (2019) note the difficulty in using CBA to value healthcare interventions, as they need the inclusion of interventions from other sectors to allow for comparison.²⁴⁰ Healthcare decision makers, however, typically only manage their own constrained budgets, with everything else falling outside their sphere of control.²⁴¹

2.5.4 Valuing non-market goods

The monetary value of non-market goods is determined through the willingness to pay (WTP) to either gain a benefit, or to avoid a negative outcome. There are two main methods to calculate WTP; revealed preference and stated preference. Revealed preference models infer a WTP indirectly by utilising market data, with proponents of this methodology expressing the benefit of using actual market data rather than hypothetical scenarios.²⁴² The most

commonly used revealed preference model is the value of a statistical life (VSL), estimated through studies of the labour market, and in particular the marginal wages required due to an increased risk of death on the job.²⁴³

Whilst VSL has the benefit of being easy to use, many authors have criticised VSL as being inaccurate due to the wide disparity between studies undertaken on the same population; that the required assumption that workers have both accurate knowledge on wages and risk exposure, and that labour markets operate efficiently, are not met in reality; and that VSL is age dependent.^{243–245} For example, a paper by Park et al (2018) that compared eight methods to value productivity losses associated with the benefits of vaccination showed a twenty-fold difference between the methods, leaving the paper to conclude that “... (CBA) will require greater convergence around the appropriate methodology to use in order to achieve consistency and comparability across different studies”.²⁴⁶

Stated preference models, by comparison, rely on surveys of individuals to elicit the valuation of non-market goods, with the predominant methods being stated / discrete choice (SC), used extensively in marketing and transportation; and contingent valuation (CV), used extensively in environmental literature.²⁴⁷ In SC experiments individuals must choose between two alternatives, such as two formulations of the same drug (e.g. pill and liquid) that have differing speeds of onset, and that have different prices. By varying the price upwards and downwards, it is possible to establish the WTP for a given outcome.^{248,249}

By comparison, CV elicits non-market values from individuals by creating hypothetical markets for non-market goods, with participants being directly asked their WTP for that

good.²⁵⁰ A systematic review by Carson in 2011 found over 7,500 papers utilising contingent valuation, the largest area of study being environmental evaluation.²⁵¹ The preponderance of environmental studies using CV has its historical basis from the *Exxon Valdez* spill in 1989, and the subsequent use of CV to estimate the willingness of the public to avoid a similar spill, and therefore the compensation to be paid as a result by Exxon.²⁵² Following this case, the U.S Department of Commerce instigated an expert review on CV, the outcome being the National Oceanic and Atmospheric Administration (NOAA) Panel Report. The findings of the report were supportive, albeit cautiously, of CV.²⁵³

2.5.5 Criticisms of contingent valuation

Since the 1993 NOAA report, there have been numerous papers critiquing CV, especially around bias associated with surveys.^{254–256} For example, criticisms from Hausman (2012) include hypothetical response bias; that there is a difference between willingness to pay and a willingness to accept for the same good when they should be equal; and that good has a different value dependent on whether it is assessed separately or is embedded in another good.²⁵⁷ Dickson and Whitehead showed that the WTP for a renewable energy project was dependent on the time of day, with participants willing to pay more at night.²⁵⁶ Proponents of CV acknowledge these biases. As an example, some authors note that the difference between WTP and WTA is to be expected, due to prospect theory where the loss of a commodity has a greater weight than gaining the same commodity.^{258,259}

Other critics of CV state that the general public are ill-equipped in valuation outside of their experience and therefore valuation is best performed by experts.²⁵⁷ In response, Haab et al (2013) notes that we if we are unable to survey the general public, then we have no way of

determining whether an expert's opinion is reflective of the populations.²⁶⁰ Additionally, both Haab and Rakotonarivo et al (2016) note the difficulty in determining what is a 'true' value, especially given that a WTP is performed within a particular temporal and spatial context, with the economic situation or the public's awareness changing with time.^{260,261}

2.5.6 Cost consequence analysis

CCA aims to combine CBA and CEA into a single evaluation. Rather than producing a single metric such as cost per QALY gained (CEA) or the net benefit in dollars (CBA), CCA tabulates costs and benefits in their natural units from a range of different methods to allow the decision maker to examine outcomes explicitly and in a disaggregated form. As an example, a CCA of a healthcare intervention may include cost per QALY gained, reduced anxiety for patients, overall patient satisfaction or effects on inequality.²⁶² Multi-criteria decision analysis (MCDA) may then be used to provide a structured process to allow for the disparate outcomes to be compared, based on their relative importance for the decision makers.²⁶³ Whilst there are multiple methods of MCDA, most are based on weighted-sum models.²⁶⁴ Criteria are weighted based on their relative importance to the decision maker, with the sum of all the weightings equalling 100%. Each intervention or technology is then given a performance score for each criterion, which is then multiplied by the criteria's weighting to give a weighted score. Finally, all the weighted scores are added to create a final score, which can then be used to identify a single preferred option or to rank a range of alternatives.²⁶⁵

Along with CEA, CCA is one of the methods of evaluation of the UK's National Institute for Health and Care Excellence (NICE) when undertaking health technology assessments, and in particular for medical devices when the item is considered to be cost saving or cost neutral.

^{266,267} CCAs and CBAs have more extensive data requirements compared to CEAs, and therefore by comparison require more resources and time to complete.²⁶⁶

2.5.7 Economic cost of environmental emissions

The two main methods used to monetise emissions are damage costs and marginal abatement costs (MAC).²⁶⁸ Starting with damage costs, there are two main ways used to monetise emissions. The first requires that emissions are converted to endpoint impacts, with the monetary value of the endpoint being determined through contingent valuation and a willingness to pay (WTP) or willingness to accept (WTA). For health impacts, contingent valuation studies have produced a wide range of monetary values per DALY, which are dependent on the country the valuation took place in, as well as the question being asked.^{268,269} Focussing on European studies quantifying a DALY due to air pollution, values have ranged between €₂₀₁₁50,000 – 156,000 per DALY^{269–271}, although Chanel and Luchini (2014) found a higher value of €₂₀₁₁172,000 in France when the WTP for avoiding premature death included family members.²⁷² Some CV studies additionally include damage costs based on the costs of health treatment, such as treating the asthma caused by air pollution.^{273,274}

The second method of monetisation, unique to carbon emissions, is the social cost of carbon (SCC), which rose to prominence due to the UK's Stern Review in 2006.²⁷⁵ SCC calculates the marginal damage cost of emitting an additional tonne of carbon using integrated assessment models (IAM).²⁷⁶ IAMs model the interrelationships between economic growth, the resultant rise in CO₂e emissions, the impacts of an these increasing CO₂ concentration such as changes in precipitation patterns and a rising sea-level, and the damages due to a varying climate such as reduced crop yields and flooding, hence feeding back to economic growth.²⁷⁶

A wide range of SSC values have been reported. In a meta-analysis of 58 studies by Wang et al (2018), estimates of SSC ranged from \$-13 – 2,386 / t CO₂e, with a mean value of \$55 / t CO₂e.²⁷⁷ Van den Bergh and Botzen (2015) determined that differences between SCC models are due to costs associated with political instability or armed conflicts due to climate change being ignored or only partially included, uncertainties around extreme weather events and climate systems, uncertainty around discount rates and thus intergenerational equity, and the risk individuals and thus society are willing to accept.²⁷⁸

Due to this uncertainty around the SSC, Isacs et al (2016) suggest the use of MAC instead of SSC to monetise GHGs in short-term assessments.²⁷⁹ MAC values are calculated by estimating the engineering costs required by either the whole economy, or within a specific sector, to reduce emissions to reach a given target (Figure 2-7).²⁶⁸ As low-cost abatement measures are undertaken before more expensive ones, the marginal cost of abatement rises over time. The accuracy of MAC values, however, diminishes the further into the future that an assessment is occurring, due to the increasing uncertainty surrounding future mitigation technologies and costs.

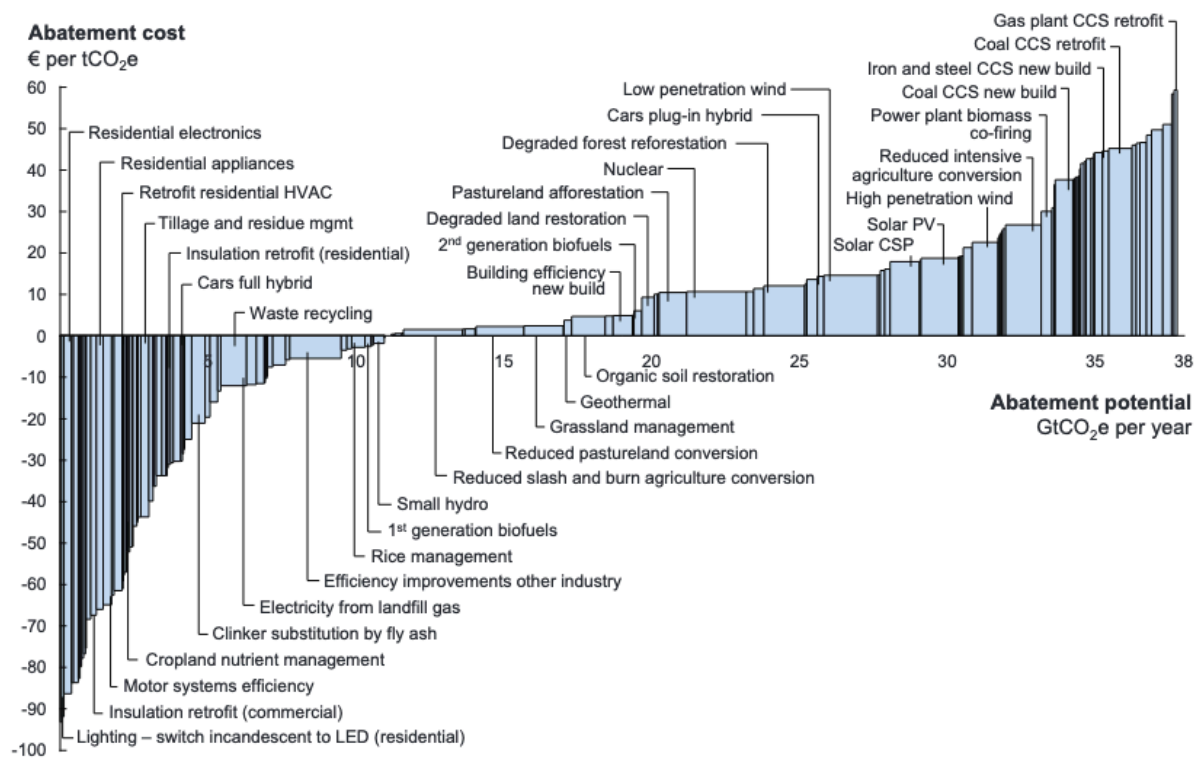


Figure 2-7: Global Marginal GHG abatement cost curve for 2030, from McKinsey & Company (2009)²⁸⁰

MAC has been used extensively in the UK (AEA Energy and Environment), and in CEAs of agriculture and the transport sector.^{281–283} A meta-analysis of MAC to keep temperatures below 2° showed a considerably smaller range of values compared to SSC (€ 69-241 / t CO₂e).²⁸⁴

Additionally, the carbon price from regional emission trading schemes (ETS) or carbon offsets available on the voluntary market could be used as a proxy price for emissions. These prices, however, are associated with a high degree of volatility, in part due to the high integration among global financial markets and the trading activities of financial speculators.^{285,286}

2.5.8 Summary

There are three main methods to perform health technology assessments: cost effectiveness analysis (CEA), cost benefit analysis (CBA), and cost-consequence analysis (CCA). CEA is the most used method worldwide for assessing healthcare, including being used to determine whether an intervention will be funded by the UK's National Health Service. The difference between the methods is broadly one of perspective. CEAs are most commonly used to compare interventions from a healthcare payer perspective that has a constrained health budget, so as to maximise health for a given budget, whilst healthcare CBAs are undertaken in the absence of a strict budgetary constraint, taking a broader societal view including resources outside of healthcare. In addition, CBAs can include the valuation of non-market goods through surveys of individuals using contingent valuation, as well as through revealed preference models utilising market data. CEAs, however, can broaden their perspective to a patient's perspective that includes items such as out-of-pocket medical expenses and productivity losses, or a societal perspective that includes sectors that will be impacted by an intervention, such as social welfare or the criminal justice system. By comparison, CCAs tabulate all investigated costs and benefits in their natural units, and then use techniques such as multi-criteria decision analysis (MCDA) to allow decision makers to be able to compare disparate outcomes based on their relative importance.

The two main ways to monetise carbon emissions is by damage costs, and by marginal abatement costs (MAC). For damage costs whilst contingent valuation can be used, the most common method is through the social cost of carbon (SCC), which uses integrated assessment models (IAM) to model the interactions between the atmospheric CO₂ levels, damages from these CO₂ levels and economic growth. There are criticisms, however, about

the use of SSC due to the wide range of values calculated from different studies. By contrast, MAC calculates the engineering costs required to reduce emissions to a given target, with MAC studies resulting in a considerably smaller range of costs per tonne of CO₂e compared to SSC. Additionally, prices from carbon markets could be used, although they are associated with a high degree of volatility.

2.6 Overdiagnosis

The OECD has estimated that approximately one fifth of global health expenditure has no or little positive impact on health outcomes, consistent with an earlier 2010 World Health Organisation study that found between 20 – 40% of health spending is wasted.^{287,288} Focussing on the United States, a study by Berwick and Hackbarth (2012) on US healthcare spending found between \$558 and \$910 billion of healthcare expenditure was wasted, or 21 – 34% of total funding.²⁸⁹ Whilst this waste included administrative complexity, failures of care co-ordination, and fraud, Berwick and Hackbarth also identified between \$158 and \$226 billion as originating from overdiagnosis.

Overdiagnosis can be narrowly defined as when patients without symptoms are diagnosed with a disease or medical condition that does not ultimately result in them having either symptoms or an early death.²⁹⁰ More broadly, overdiagnosis is used as an umbrella term to include overdetection by increasingly sensitive tests and equipment, false positives from tests, overtreatment that provides no clinical benefit, overutilisation of tests, expansion of definitions of diseases, and overmedicalisation of human conditions such as childbirth.²⁹¹ Unnecessary testing and overdiagnosis can lead to a cascade of treatments, resulting in physical, psychological and financial consequences for patients^{292–294}, and lead to adverse health outcomes.^{295–298}

Whilst reductions in all aspects of unnecessary care that come under the overdiagnosis umbrella would be expected to see commensurate reductions in economic and

environmental impacts with no adverse, and potentially positive, outcomes on human health, this review will focus on overutilisation of pathology and diagnostic imaging tests.

2.6.1 Test ordering in Australia

Pathology testing in Australia for 2020/21 cost the federal government \$3.9 billion per year, accounting for 14% of all Medicare (MBS) spending, with the per capita cost of testing rising by 25% over the last decade.²⁹⁹ By comparison, for 2020/21 diagnostic imaging has both a greater overall cost, accounting for \$4.5 billion, or 16% of MBS spending, and has seen a greater cost per capita increase of 52% over the last decade, driven predominately by an increase in the number of ultrasounds and Computed Tomography (CT) scans performed.²⁹⁹ It is forecasted that demand for imaging services will continue to increase into the future due to the Australian Federal Government indexing MBS rebates from 1 July 2020, making imaging cheaper for patients.³⁰⁰ It is also predicted that there will be a shift away from the radiation-based imaging modalities of CT and X-rays and an increased demand for ultrasound and Magnetic Resonance Imagery (MRI) due to safety concerns.³⁰⁰

Eishaug et al (2012) identified over 150 potentially low-value practices funded by the MBS, including vitamin D & folate testing for patients with Chronic Fatigue Syndrome; chest X-rays (CXR) for the diagnosis of acute coronary syndrome or acute respiratory syndrome; routine daily CXRs in intensive care units; the use of CT or ultrasound to diagnose appendicitis; routine spinal MRI for men with hormone-refractory prostate cancer and bone metastases; and routine imaging of the spine in patients with a previous diagnosis of malignancy.³⁰¹

2.6.2 The clinical utility of testing

It is useful to view the predicative value, and hence clinical utility, of diagnostic testing and imaging through the lens of Bayesian probability, and the interaction between pre- and post-test probability. Bayes' rule is a method of calculating conditional probability, which in the case of diagnostic testing is given as:

$$\text{Post-test odds} = \text{pre-test odds} \times \text{likelihood ratio}$$

where odds are:

$$\text{odds} = \frac{\text{probability}}{1 - \text{probability}}$$

and the likelihood ratio (LR) for positive and negative tests is given as:

$$\text{LR}^+ = \frac{\text{Test sensitivity}}{1 - \text{test selectivity}}$$

$$\text{LR}^- = \frac{1 - \text{test selectivity}}{\text{Test sensitivity}}$$

The sensitivity of a test (the true positive rate) is the probability of a positive test from people who are positive, while the selectivity of a test (the true negative rate) is the probability of a negative test from people who are negative. Whilst the sensitivity and selectivity of a test can be calculated by comparing results against a gold standard for diagnosis, estimating the pre-test probability of a condition requires clinical knowledge and experience.³⁰²

To avoid having to do bedside calculations, Fagan (1975) created a nomogram to rapidly determine the post-test odds of a patient having a condition.³⁰³ In the following example by

Caraguel and Vanderstichel (2013), a MRI screening test with a sensitivity of 75% and a selectivity of 96% was used in a high-risk population (2% prevalence) for breast cancer (Figure 2-8).³⁰⁴ Using the above formulas, LR^+ was calculated as being 18.75, whilst LR^- was calculated as 0.26. For a patient in this high-risk population, a positive test would indicate a 28% post-test probability that the patient truly had cancer, whilst a negative test would indicate the patient had a 0.6% chance.

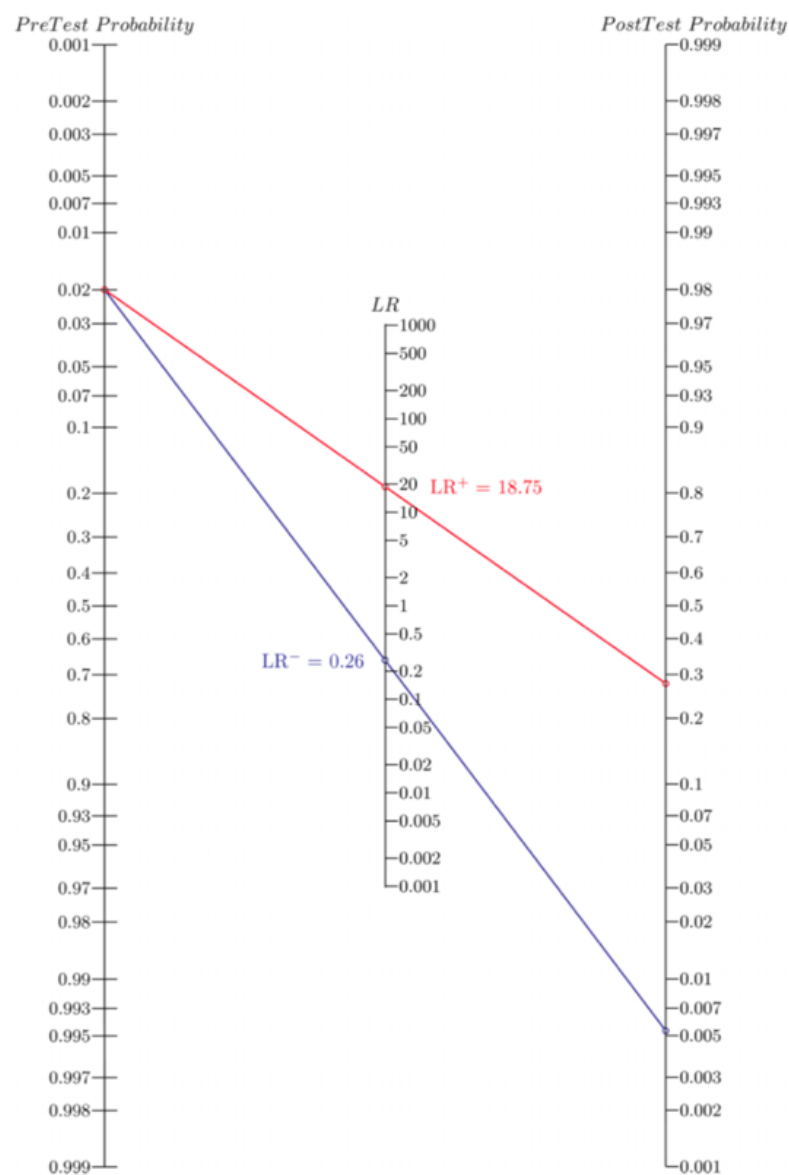


Figure 2-8: From Caraguel (2013,) showing the post-test probability of a patient having breast cancer after an MRI screening test³⁰⁴

This interaction between pre- and post-test probability led Pauker and Kassirer (2008) to develop the “Threshold Model” of decision-making.³⁰⁵ Under the model, there is a treatment threshold probability below which a treatment is withheld, and above which a treatment is given. A test is therefore only useful when it shifts the probability of a disease from one side of the threshold to the other; if the pre-test probability of having a disease is sufficiently low or high, a positive test won’t change the post-test probability relative to the threshold, and therefore there will be no change in patient management (Figure 2-9).

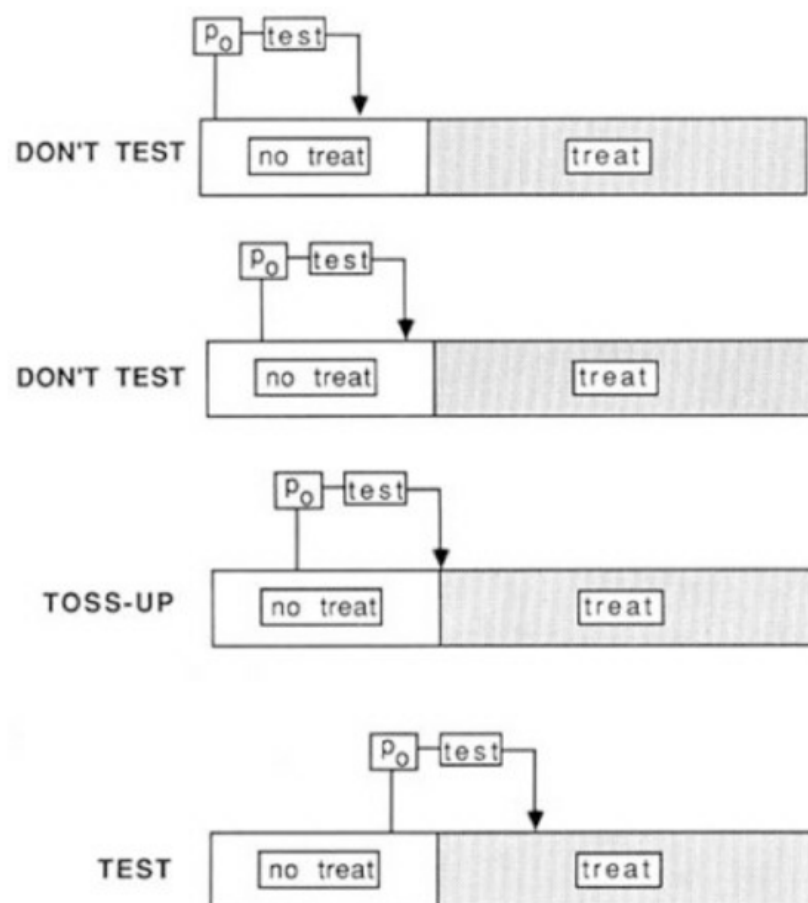


Figure 2-9: From Sox (1989). p_0 is the pre-test probability. Testing should only be done when a positive test will shift the probability of a condition over the treatment threshold³⁰⁶

Greer and Irwin (2002) therefore state that testing is best suited to a population with a moderate (30-70%) chance of having a disease.³⁰⁷ In healthy asymptomatic patients, the usefulness of routine testing for screening is therefore limited. Furthermore, Berte and Nevalaninen (1998) suggest the ordering of tests should only be performed after a clinician determines the answers to the following questions:

- “Does the laboratory test change the way the clinician thinks about the patient?
- Does that change in thinking alter the way the clinician manages the patient?
- Does that change in treatment affect outcome, as measured by death, sickness, or reduced cost of care?”³⁰⁸

2.6.3 Unnecessary testing

A 2014 survey of physicians from the American Medical Association reported 20.6% of medical care was unnecessary, including 24.9% of tests.³⁰⁹ Reasons given in the study for this unnecessary testing were similar to those found in other studies, and included fear of malpractice, clinician experience, risk aversion, cognitive biases, patient pressure, financial incentives.^{309,310} There is a plethora of studies showing unnecessary testing over a range of tests and disciplines.

For pathology testing, a 15-year meta-analysis by Zhi et al (2013) determined that the mean rate of overutilisation of tests was 21%, with this rising to 44% if measured according to more restrictive criteria.³¹¹ Focusing on examples of specific tests, Cadamuro et al (2018) reports that 60-70% of ordered coagulation profiles, potassium, lactate dehydrogenase and aspartate-aminotransferase tests in a high throughput hospital were unnecessary³¹², whilst in

Australia a study showed that 64% of coagulation testing in an ICU was not necessary.³¹³

Worldwide, there are concerns about high levels of unindicated vitamin D testing.^{314–318}

Utilising the UK's National Institute for Health and Care excellence (NICE) guidelines on routine preoperative testing as a basis for determining rates of unnecessary³¹⁹, Clair et al (2010) found that that none of the coagulation profiles or liver function tests ordered for gynaecological patients were indicated, nor were 83% of the metabolic profiles and 71% of the full blood counts.³²⁰ Several other smaller studies also found unindicated ordering of coagulation profiles^{321,322}, whilst Leung et al (2017) found 69% of preoperative tests for ear, nose and throat surgery were unnecessary, and in particular clotting profile (99.2%), U+E (63.5%) and FBE (63.5%).³²³ This study additionally found that only 0.5% of the unnecessary tests were abnormal, that they were all clotting profiles, and that they were all clinically insignificant.³²³

High rates of unnecessary diagnostic imaging have also been reported. In Australia, between 35 – 50% of CT scans for suspected pulmonary thromboembolism^{324–326}, 77% of X-rays for ankle injury and 54% imaging for patients with non-traumatic abdominal pain³²⁶, and between 36 – 40% of imaging for patient with lower back pain (LBP)^{327,328} are unnecessary. A review by Brownlee et al (2017) showed that overuse, or the proportion of patients who received service inappropriately, included repeated CT scans (46%), the use of MRI for LBP (39.5%), repeated spine CTs (29%), and the use of X-rays for LBP (22.5%).³²⁹ A subsequent systematic review and meta-analysis by O'Sullivan et al (2018) included high rates of overuse for spine X-rays (13-68%), hip X-rays (57%), brain CT and MRIs (14%).³³⁰ A Canadian study showed that 31% of Albertan patients with LBP had unnecessary imaging within six months of

their initial consultation ³³¹, even though studies such as a meta-analysis of randomised controlled trials comparing immediate lumbar imaging (X-ray, CT or MRI) vs clinical care without imaging has shown that there is no differences in pain and function between the two groups over 12 months.³³² There may also be opportunities to use less costly imaging. For example, Sheehan et al (2016) showed that 45% of shoulder MRIs were inappropriately ordered, with traditional US and X-ray being able to characterise most shoulder pathologies instead.³³³

2.6.4 Summary

Overdiagnosis describes a range of low-value or unnecessary interventions and testing that at most results in little benefit to patients, and at worst, results in harm. As this care is unnecessary, it is an ideal starting place to reduce both carbon emissions associated with healthcare, as well as reducing economic costs.

Overutilisation of testing is one aspect of overdiagnosis. On average, one-fifth of pathology tests are unnecessary, although this could be closer to half dependent on the criteria used to determine whether the test is indicated or not. Specific pathology tests, and in particular vitamin D and coagulation tests, appear to be more overutilised compared to other tests. Overutilisation of imaging tests is reportedly higher. Rates of unnecessary imaging range include between 20 – 50% for patients with lower back pain, up to 68% of spinal imaging, up to half of CT scans for suspected pulmonary thromboembolism, and 77% of ankle X-rays. There are therefore extensive opportunities to reduce the rates of unnecessary testing.

Testing and imaging should ideally only be ordered when the results of a test will change clinical management of a patient, and more specifically, that the result of the test changes the probability of a patient having a condition from one or the other side of a treatment threshold probability, above which a treatment is given.

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Chapter 3 Carbon and health technology assessments

Incorporating carbon into healthcare's future: adding carbon emissions to health technology assessments

In progress at The Lancet Planetary Health, December 2021

3.1 Abstract

3.1.1 Background

At Glasgow COP26 fifty countries committed to develop low-carbon health services, with fourteen of these countries further committing to a net-zero carbon health service by 2050. There is currently, however, little data on the health impacts of healthcare, nor any methods to include carbon emissions in clinical decision making.

3.1.2 Methods

We investigated how to integrate carbon emissions calculated by life cycle assessment (LCA) into health technology assessments. Health technology assessments are extensively used in developing clinical and policy guidelines by individual public or private payers, and by government organisations.

3.1.3 Finding

We suggest that the quantification of carbon emissions in healthcare activities should be undertaken using process-based life cycle assessment (P-LCA). Further, we propose that carbon emissions could be incorporated using one of these four approaches: as a decision modifier when two or more technology alternatives are clinically and economically similar; as

a criterion in a multi criteria decision analysis (MCDA); monetized and included in a cost-benefit (CBA) analysis; or as an additional cost in a cost-effectiveness analysis (CEA).

3.1.4 Interpretation

As healthcare moves into a carbon constrained world, decision makers will increasingly have to include carbon emissions when evaluating both new and existing treatments. There are no technical impediments to incorporating carbon emissions calculated by LCA into health technology assessments. Rather, the main challenge is a practical one, as to date few LCAs have been undertaken in healthcare. It is therefore important to establish a healthcare specific LCA database, so as to speed up the decarbonisation of healthcare.

3.1.5 Funding

National Health and Medical Research Council, Australia (NHMRC) PhD scholarship

3.2 Research in context

3.2.1 Evidence before this study

We searched the Scopus from its inception up to Feb 22, 2021, using the terms (("life cycle assessment") OR ("LCA") OR ("Environmental impacts") OR ("carbon footprint") OR ("carbon emission*")) AND (("health technology assessment*") OR "economic evaluation*"). Only three studies were found. The first and second study identified methods of health technology and environmental evaluations and considered the benefits of incorporating environmental impacts into health technology assessments along with some of the challenges for this occurring. The second paper additionally discussed methods to monetise environmental emissions. The third paper provided a very simple example of incorporating environmental impacts calculated by environmental input-output life cycle analysis into a health technology assessment.

3.2.2 Added value of this study

Healthcare must begin to decarbonise, but there is no method to include carbon emissions in clinical decision making. This study goes much further than the previous studies by describing a detailed method to integrate carbon emissions into health technology assessments. This approach provides the required level of specificity and rigour to enable health service providers to fully operationalise at a practical level the inclusion of carbon emissions alongside economic costs when undertaking these assessments.

3.2.3 Implications of all the available evidence

In healthcare, unlike other major sectors of the economy, there have been very few studies quantifying the carbon emissions of medical devices and treatments. In concert with previous studies, this paper provides adds to theoretical framework for decarbonisation of healthcare. The combined evidence will now enable healthcare providers to integrate carbon emissions into health technology assessments, and so speed the decarbonisation of global healthcare that fifty countries have committed to.

3.3 Introduction

Climate change is causing an increase in the frequency and intensity of flooding and wildfires in North and South America, Europe and the Asia-Pacific, resulting in record temperatures, deaths and extensive property damage.¹ These and other extreme weather events have focused attention on the effects of climate change on health.

Globally, healthcare is responsible for 2.0 gigatons (2×10^9 tons) of carbon dioxide equivalent emissions (CO_2e) annually, or 4.4% of global emissions.² Converted to disability adjusted life years (DALYs), these emissions may cause up to 3,060,000 DALYs reduction in human health annually, due to increases in undernutrition, malaria, water and vector borne diseases, and heat stress.³ Further, converted into dollar terms using the global average GDP per capita, these DALYs result in an economic cost of between US\$ 32.7 and 98.2 billion.⁴

At the United Nations Climate Change Conference COP26 in Glasgow in November 2021, thirty-six countries made commitments to develop low-carbon health systems, with a further fourteen countries setting a target for a net-zero health service by 2050.⁵ The methods and evidence base for measuring the carbon emissions of healthcare and including them in clinical decision making to achieve this is, however, lacking.

Healthcare relies heavily on health technology assessments (HTA) to determine whether the economic cost of a new pharmaceutical, medical device, or model of care is justified given the health benefits the technology will provide to patients.⁶ Methods of HTA include health economic evaluations and comparative effectiveness studies, and while these economic

assessments are now routine and sophisticated, presently HTA does not include environmental impacts such as carbon emissions. HTAs can be undertaken as part of an internal process by individual public or private payers, and they form a vital component of clinical and policy guidance used by leading agencies such as the US Preventive Services Taskforce and the National Institute of Health and Care Excellence in the UK (NICE). The outcomes of these HTAs, including reports to regulatory bodies like the FDA, determine the scope and nature of clinical practice, guiding the day-to-day clinical decisions of physicians in hospitals and in primary care settings. In addition to determining the costs to healthcare payers, they also lock in healthcare's future carbon footprint. Critically, these carbon emissions influence not only current global health outcomes, but they also irreversibly influence those of future generations for centuries to millennia.⁷ In order to be environmentally as well as economically sustainable, healthcare decision makers and clinicians must now take account of carbon emissions.

Earlier work considered the case for incorporating environmental impacts into HTAs and listed some of the challenges for this to occur.^{8,9} Marsh et al (2016) gave a broad overview of HTA methods and ways to monetise carbon emissions, and listed challenges as being a lack of environmental information of different technologies, and that cost-benefit analysis (CBA) and multi-criteria decision analysis (MCDA) are not familiar to healthcare decision makers.⁸ Hensher (2019) provided a more detailed analysis of how to monetise carbon emissions, and especially the use of integrated assessment models to calculate the social cost of carbon; and undertook some simple illustrative examples by applying a carbon price to the carbon footprints of different health services and interventions obtained from previous studies.⁹

This case for incorporating environmental impacts into HTAs is even stronger now in view of recent events. We therefore seek to build on this previous research by resolving two main challenges. The first is that little quantification of the carbon emissions of medical devices, procedures, or pharmaceuticals associated with healthcare has been performed, meaning studies will be required to fill these gaps in knowledge. Second, there have been no published studies on how carbon costs should best be incorporated in HTAs.

Our aim in this paper is to outline (1) how carbon emissions from healthcare can be best quantified, and (2) ways in which carbon emissions can then be integrated into HTA as a decision criteria or in economic evaluation.

3.4 Measuring carbon emissions

Carbon emissions are best quantified by life cycle assessment, an internationally standardised method to calculate environmental emissions (ISO 14040-44)¹⁰, and which forms the foundation for all major carbon footprint standards.^{11,12} The basis of analysis within LCA is the functional unit, which clearly defines the functions of a product or service rather than its physical characteristics. An example of a functional unit is all anaesthesia for a total knee replacement in a hospital in St. Louis, Missouri. A number of LCAs have been performed in healthcare, including calculating national carbon emissions from healthcare, comparisons of single-use and reusable items, pharmaceuticals, and the impacts of intensive patient care.¹³⁻¹⁶

Similar to health economic evaluations when deciding which costs to include for a particular activity, LCA utilises a system boundary of inclusions and exclusions based on the defined functional unit. For example, a LCA of a surgery may exclude the impacts of postoperative monitoring. In contrast to health economic evaluation, the LCA system boundary extends out temporally to incorporate life cycle impacts of all items included in an analysis, including raw material acquisition such as mining, the manufacture of items, and their use and disposal / recycling (Figure 3-1).

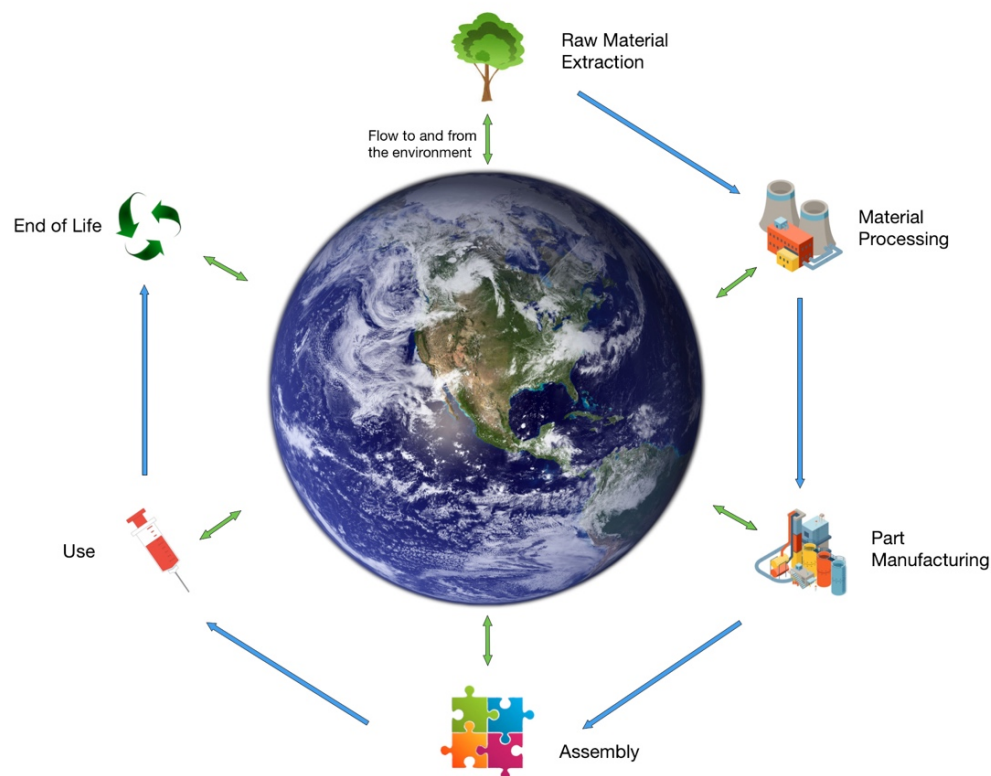


Figure 3-1: Stages of Life Cycle Assessment

3.4.1 Life cycle assessment methods

There are two methods of undertaking LCA; economic input-output (EIO) and process-based (P-LCA). EIO is based on the economic input/output tables produced by all major economies that track the flow of money between sectors of the economy. Carbon emissions are

calculated on a per dollar basis of a purchase from a given sector, with there being a linear relationship between price and impact. Whilst this method has been used to calculate the footprint of healthcare as a whole sector, it has limitations when used for individual items or activities within a sector due to the high level of aggregation.¹⁷ For example, the price paid for the same medical device can vary widely depending on what has been negotiated by an individual payer. Using EIO, the carbon emissions would also vary due to these differences in price, even though the emissions from manufacturing would be the same. Healthcare is replete with similar examples, and therefore EIO is not recommended to quantify emissions of specific items or services within healthcare LCAs.

By contrast, P-LCA quantifies the carbon emissions of the functional unit using a series of interlinked processes. A process describes all the material and energy inputs, and associated environmental emissions, for an individual activity at a high level of detail, such as forming stainless steel into a hypodermic needle (Figure 3-2). Processes are then linked together to form a process tree consisting of raw material extraction at the bottom and the functional unit at the top, with a typical process tree having upwards of 1,000 individual processes.¹⁸

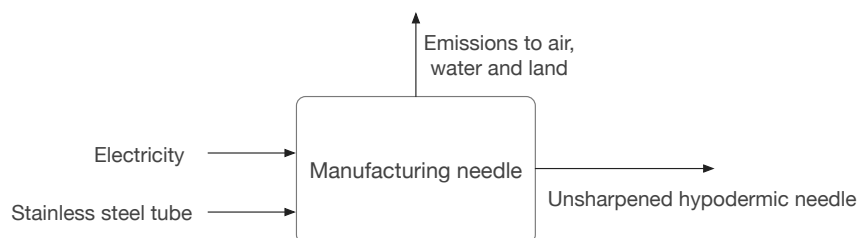


Figure 3-2: Process for turning stainless steel tube into unsharpened hypodermic needle

There are two types of P-LCA; attributional and consequential. Attributional P-LCA estimates the what proportion of a healthcare service's total carbon footprint can be attributed to a

specific clinical activity, while consequential P-LCA only estimates the change in emissions that occur by performing an additional clinical activity (the marginal impact). As an example, hospital X-ray machines run 24/7 so they can be used in emergencies. An attributional analysis would include this standby power when the machine is on but is not being used for imaging. By comparison, the consequence of ordering an X-ray is not that the X-ray machine is turned on – it is operating regardless of whether an X-ray is ordered or not. The consequence of ordering an image, therefore, is the small change in power when an image is taken. These two approaches complement each other by providing information on the overall impact of a clinical activity in addition to the impact of a change in clinical behaviour. We therefore recommend both attributional and consequential LCAs be performed and reported.

P-LCA enables individual interventions to be modelled at a fine level of detail, thereby identifying carbon hotspots that can be targeted for mitigation. Importantly, and similarly to health economic evaluation, P-LCA makes comparison possible between a healthcare technology or intervention and an alternative (e.g. standard surgery versus robotic surgery). This is essential to enable informed choices to be made between two clinical options on the basis of individual health outcomes, economic costs and environmental impact.

3.4.2 Converting LCA results to carbon reference units

The worldwide reference unit for carbon emissions is carbon dioxide equivalents (CO_2e), which may be expressed as kg CO_2e , KT CO_2e or MT CO_2e . A reference unit is used as there are a range of greenhouse gases, all with different global warming potentials, which contribute to climate change. To allow for their respective impacts to be added together to

calculate a total carbon footprint, each greenhouse gas must be multiplied with an emission factor based on their global warming potential, with these factors being published by the International Panel on Climate Change (IPCC).¹⁹ Using gaseous anaesthetics as an example, 1 kg of desflurane is equivalent to 1,790 kg CO₂e, whilst 1kg of sevoflurane is equivalent to 216 kg CO₂e.¹⁹ An LCA performs these calculations for greenhouse gas emissions from all stages of a life cycle.

3.5 Health technology assessments and carbon emissions

Next we explore how carbon emissions could be included in HTA.

Carbon emissions are examples of externalities. An externality is a cost or benefit from a person's or organisation's activity that is borne by an unrelated third party, and, as such, the cost or benefit of the externality is excluded from the market transaction. For example, unless being in a one of small number of jurisdictions covering 22% of carbon emissions that have a carbon price²⁰, the market price of fossil fuels does not include the cost of morbidity and mortality resulting from forest fires caused by climate change, even though combustion of fossil fuels is the chief cause of rising atmospheric carbon dioxide levels driving climate change.

Environmental externalities due to healthcare production and consumption are not currently included in HTAs due to their focus on optimising the allocation of healthcare resources relative to health outcomes. Environmental externalities must be internalized, that is, included and considered in HTAs alongside the costs and benefits to the healthcare sector and to individuals. This will require a broader societal perspective to be adopted rather than

the narrowly focused health system or payer perspective that is typically applied.

Furthermore, this societal perspective will need to extend beyond the traditional framework to include environmental impacts.²¹

Broadly, carbon emissions could be internalised in HTA using four different approaches, enabling a comprehensive assessment of the health, economic and environmental impacts of a specific healthcare technology or intervention (in comparison with alternatives). These approaches include (1) to modify a decision; (2) to be one criterion of a MCDA; (3) to be monetized and included in a CBA; or (4) as an additional cost in a cost-effectiveness analysis (CEA). We build on the limited research to date.⁹

3.6 Linking LCA to health technology assessments

The first stage of linking carbon emissions to a HTA is to quantify all the emissions resulting from all the health interventions contained within the assessment. All four approaches noted above will require that an individual P-LCA for each specific healthcare activity (e.g. a prostate cancer biopsy administered under general anaesthetic in a public hospital) is undertaken. The functional unit of each P-LCA should match the system boundary of the healthcare activity as closely as possible. Initially, the work required to conduct the necessary P-LCAs will be considerable, but each one could contribute to a library or inventory of the environmental footprint of specific healthcare interventions. Inventories could be housed nationally or shared internationally, similar to current international LCA databases of materials and products such as Ecoinvent.¹⁸

For single year economic evaluations, such as calculating the expenditure per year associated with false-positive mammograms²², we recommend the environmental impacts from the whole life cycle (“cradle-to-grave”) of each LCA should be calculated as a single value (e.g kg CO₂e). This temporal aggregation of emissions is the way LCAs are typically performed.^{15,16}

For multi-year economic evaluation models, such as determining the lifetime cost-effectiveness of breast cancer screening²³, an individual LCA will need to be performed for each year of the economic analysis, so that monetised emissions can be discounted alongside other economic costs and benefits. This will require that anticipated changes in technology, such as an expected increased use of renewable energy, be temporally integrated into each year’s LCA. Additionally, the LCA will need to be dynamic, with environmental emissions assigned to specific years.²⁴ Fortunately in healthcare, the life cycle of many items (from manufacture, through use to disposal) is only several years, and there are few long-term emissions due to disposal as most medical equipment is inert (metal and plastic), with biodegradable items such as cotton gauzes making up only a very small proportion by mass of items used clinically.¹⁶ Together, this makes dynamic modelling easier to achieve compared to other sectors such as buildings.

Impacts in kg of CO₂e calculated from each LCA can be then included as an additional ‘cost’ in decision-analytic or Markov models, to be incorporated alongside other economic costs and health outcomes.

3.6.1 Carbon emissions as a decision modifier

At this point, the modelled greenhouse gas emissions from each intervention can be used as a simple modifier. This can occur when costs and health outcomes of any two or more technologies are similar, so that the choice of which one to adopt is dependent on the greenhouse gas emissions. An example of this is demonstrated in anaesthesiology departments moving from the gaseous anaesthetic desflurane to sevoflurane to reduce carbon emissions.²⁵

3.6.2 Carbon emissions as part of MCDA

In cases where there are differences in costs and health outcomes between technologies, or where there are additional criteria that the decision maker wants to include such as health equity; a MCDA could be undertaken. While there are multiple ways MCDA can be operationalized, most are based on weighted-sum models.²⁶ Criteria are weighted based on their relative importance to the decision maker, with the sum of all the weightings equalling 100%. Each intervention or technology is then given a performance score for each criterion, (including a criterion on carbon emissions) that is then multiplied by the criteria's weighting to give a weighted score. All weighted scores are added to create a final score, which can then be used to identify a single preferred option or to rank the alternatives.²⁶

3.6.3 Monetizing carbon emissions

Alternatively, carbon emissions can be monetized alongside health benefits and included in a CBA study design; or as an additional cost in a CEA where the outcomes remain in their natural units. There are multiple ways to monetize carbon emissions, including:

- The Social Cost of Carbon, which uses integrated assessment models of ecosystems, economics and political responses to estimate the damage cost of an additional ton of carbon emitted²⁷;
- The price of carbon offsetting credits from schemes such as forestry or soil sequestration, or methane capture, and
- Marginal Abatement Costs which are calculated based on the engineering costs to reduce emissions to reach a given target²⁸

Some countries and individual states such as California, have a price on carbon that uses the above methods of monetization. For example, California's cap-and-trade emissions trading scheme, which sets an emissions target that declines over time, follows prices predicated by Marginal Abatement Costs.²⁹ By comparison, in Australia there is no official carbon market, with the unofficial carbon price being the cost of carbon offsets.³⁰ Different jurisdictions, therefore, have different carbon prices.

Table 3-1 provides an illustration of the three approaches to incorporating carbon emissions into HTA, using an example of the home monitoring of cardiac implantable electric devices compared to conventional periodic in-office monitoring. It should be noted that if monetized emissions are used in a multi-year economic model, we recommend that they be treated like any other cost and are discounted at the same rate as healthcare costs. We recommend, however, that greenhouse gas emissions in kg CO₂e should not be discounted, but rather be considered constant over time, hence maintaining intergenerational equity.²⁴

Table 3-1: Illustration of approaches to incorporating environmental impacts into HTA using CEA, CBA and CCA, comparing home (daily electronic) vs. conventional periodical in-office monitoring of cardiac implantable electric devices

CCA (outcomes and units)		CEA (outcome and units)		CBA (outcomes and units)	
Financial cost to health service	\$	GHG emissions for health service monetised with MAC	\$	Financial cost to health service	\$
Financial cost to health service to offset carbon emissions	\$	Monetised emissions included in costs	\$	Financial cost to patient (pharmaceuticals and travel)	\$
Financial cost to patient (pharmaceuticals and travel)	\$	Benefit to health	QALY	Monetised health service and patient carbon emissions using SSC	\$
Scheduled and unscheduled follow up visits	Time	Cost-effectiveness of remote vs. in-office monitoring	ICER	Productivity cost to patient	\$
Battery replacements	\$	Environmental impacts in DALYs	DALY	Productivity cost to carer	\$
Lead malfunctions resulting in lead repair	\$			Willingness to pay for improved quality of life due to reduced unnecessary electric shocks	\$
Unnecessary electric shocks	Patient anxiety				
GHG for health service	kgCO ₂ e				
GHG for patient	kg CO ₂ e				

Benefits of home monitoring include reduced travel burden for patients, and reduced unnecessary electric shocks, length of hospital stays and battery replacements. Based on: *Cost–consequence analysis of daily continuous remote monitoring of implantable cardiac defibrillator and resynchronization devices in the UK*, Europace (2013) 15, 1601–1608

3.7 Discussion

Health services globally are starting to commit to net-zero targets for carbon emissions, although with little detail on how this will be achieved. We propose that an important method to achieve carbon neutrality will be the inclusion of carbon emissions in health technology assessments. The main challenge is that, unlike other major sectors of the economy where extensive LCA studies have quantified emissions, to date there have been very few undertaken in healthcare.

LCA practitioners currently use ‘background’ databases such as Ecoinvent to obtain high quality, country specific process-based life cycle data, on basic materials such as plastic and steel, manufactured goods such as computers, and processes such as recycling plastic, in order to accurately model whole supply chains without needing vast multi-disciplinary expertise.¹⁸ Further, specific sectors that are arguably more complex than healthcare, such as agriculture that has a very high degree of variability due to local conditions and farming practices, have developed sector-specific databases.³¹ There is therefore no technical obstacle to the development of healthcare-specific database containing country specific common items such as syringes, procedures such as MRI, or processes such as sterilisation, to enable expeditious and accurate modelling, but rather the main barrier is that it will be initially be time consuming and costly as a knowledge base is built up. Once this initial start-up work has been done however, it will be relatively quick and inexpensive to quantify carbon emissions as is now routinely done in other sectors. The process should, with time, become as routine as quantifying costs is currently.

It is paramount that any data underpinning healthcare LCAs is made readily accessible (not subject to charges or intellectual property constraints), so that those with limited resources are not perversely incentivised to avoid inclusion of carbon quantification or repeat what others have already done, potentially at lower levels of accuracy or quality.

Once quantified, the second challenge is how to best include carbon emissions in health technology assessments, as decision makers have not yet had to consider environmental externalities when choosing between technologies. As we move into a carbon constrained world, environmental impacts will become a major consideration for decision makers.

Including carbon emissions in HTA will ensure their decisions will result in genuinely sustainable healthcare for present and future generations. This work is also vital for health equity as, without it, the greatest health impacts of climate change will disproportionately fall on vulnerable populations and low-income countries.

The choice of whether to use carbon emissions as a decision modifier, in a MCDA, or as a monetized cost in a CEA or CBA will likely be dependent on the funding organisation, jurisdiction or decision makers and may be guided by purely technical considerations. The benefit of having several options is that they can be incorporated into standard health technology assessment agency processes, even where countries differ markedly in their need for comparative effectiveness evidence.

The challenge of incorporating carbon emissions into health technology assessments is considerable but not unsurmountable. We hope this work will lay the foundation to meet this important challenge.

3.8 References

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Chapter 4 The carbon footprint of pathology testing

This chapter consists of two papers: The carbon footprint of pathology testing, and a letter in response to the paper.

4.1 The carbon footprint of pathology testing

The Medical Journal of Australia (2020), 212:377 – 382

4.2 Abstract

4.2.1 Background

To use consequential life cycle assessment to calculate the carbon footprint of five commonly used pathology tests: Full blood examination, coagulation profile, urea plus electrolytes, C-reactive protein and arterial blood gas.

4.2.2 Design, setting

Prospective observational life cycle assessment of five common pathology tests examining the use of all associated consumables and their waste for venepuncture and laboratory analysis; and electricity and water use during laboratory analysis, at Austin Hospital, Heidelberg Melbourne, and Sunshine Hospital, Sunshine, Melbourne.

4.2.3 Main outcome measures

Greenhouse gas footprint, in kg CO₂e.

4.2.4 Results

Carbon dioxide equivalents (CO₂e) emissions for haematology tests is similar; coagulation profile was 81.9g CO₂e (range 72.7–91.4 CO₂e) and full blood examination was 116.3 g CO₂e (range 101.2–135.3 CO₂e). By comparison, biochemistry tests were highly variable, and dependent on whether the ordering of a test required additional venepuncture and collection. C-reactive protein was 0.5g CO₂e (0.4–0.6g CO₂e), arterial blood gas was 48.5g CO₂e (44.6–52.6g CO₂e) and urea plus electrolytes was 99g CO₂e (84.7–113.2g CO₂e). The main source of emissions (60-95%) originated during the collection of samples, including phlebotomy and all collection tubes.

4.2.5 Conclusion

The carbon footprint of pathology tests is dominated by sample collection. As there are only limited opportunities to reduce the impacts of collection through reuse or recycling, reducing pathology's carbon footprint will require a change in how clinicians order tests by eliminating unnecessary tests. By combining environmental impacts with the health and economic outcomes associated with unnecessary testing, clinicians and policy makers are provided with a key point of intervention in care practices which will have positive impacts on all three domains.

4.3 Research in context

4.3.1 The known

Health care ultimately generates 7% of national carbon emissions in Australia. A considerable proportion of the cost of health care in Australia is associated with pathology services (12% of Medicare spending).

4.3.2 The new

The overall carbon footprints of five common hospital pathology tests, measured as carbon dioxide equivalent (CO₂e) emissions, ranged between 0.5 and 116 g CO₂e, equivalent to driving a car between 3 m and 0.8 km.

4.3.3 The implications

Opportunities to reduce the carbon footprint of pathology testing are limited. The greatest environmental benefit can be achieved by reducing unnecessary testing. Environmental impact, together with cost-effectiveness and health outcomes, should be considered when ordering tests.

4.4 Introduction

Climate change is one of the most important threats to human health of the 21st century.¹

Yet, healthcare itself contributes to climate change and is 'carbon intensive'.² Australian healthcare contributes 7% of the carbon dioxide equivalent (CO₂e) emissions from Australia's total CO₂e emissions.³ If global healthcare were a 'country' it would be the fifth-largest greenhouse gas emitter (4.4% of global annual CO₂e emissions), with hospitals being the dominant source of these emissions.⁴ Within the UK's National Health Service (NHS), two thirds of CO₂e emissions are caused indirectly, i.e. from the purchasing of consumables (e.g. pharmaceuticals and medical devices).⁵

Pathology services are significant contributors to costs of healthcare in Australia (12.4% of Medicare spending in 2018/19).⁶ However, studies have shown that between 12% and 44% of pathology tests ordered were not indicated.⁷ There are therefore increasing calls to encourage evidence-based testing, and for physicians to 'choose wisely' when ordering pathology tests.⁸ Such efforts could be further strengthened with evidence regarding the environmental effects of unnecessary testing.⁹

Life cycle assessment (LCA) is a method used to estimate the environmental footprint (CO₂e emissions, water, pollutants, etc.) of a product or service throughout an entire life cycle (Figure 4-1). The international standard ¹⁰ for LCA methodology prescribes: (i) raw material acquisition, (ii) processing and manufacturing, (iii) distribution and transportation, (iv) use, reuse, and maintenance, and (v) waste management/recycling. While the impact of other clinical services, e.g. use of anaesthetic agents, pharmaceutical products and surgical

techniques, have been previously estimated¹¹⁻¹⁴, the carbon footprint of pathology testing is unclear.

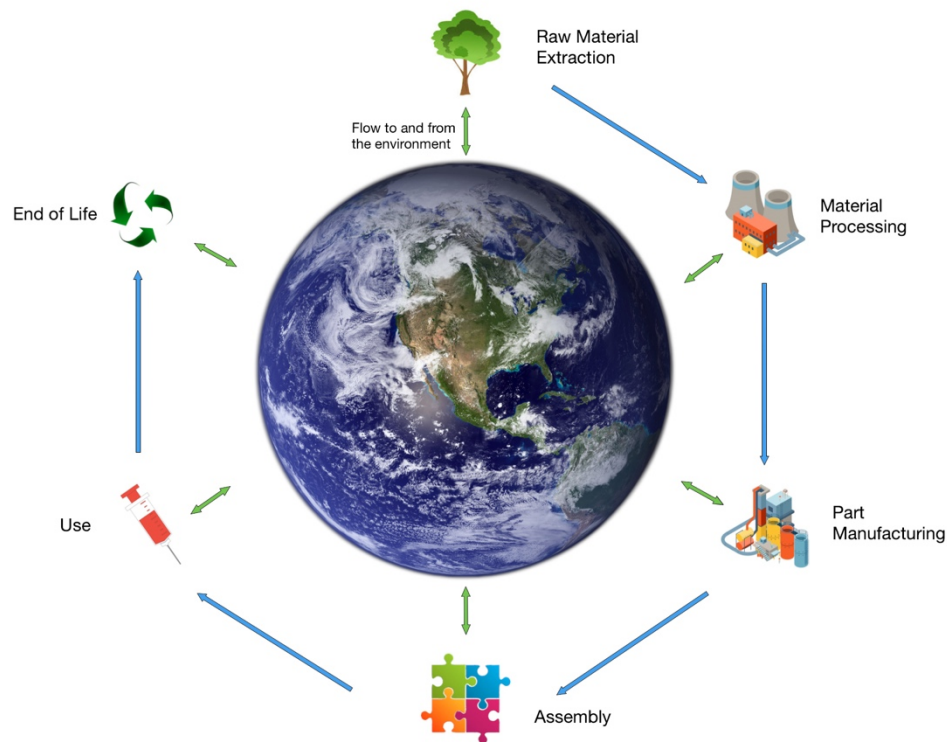


Figure 4-1: Stages of a life cycle assessment

We calculated the carbon footprint (CO₂e emissions) of five common pathology tests ordered as routine monitoring in hospital patients: (i) full blood examination (FBE), (ii) creatinine, urea, and electrolytes (U+E), (iii) clotting profile (APTT and INR), (iv) C reactive protein (CRP), and (v) arterial blood gas (ABG). We focussed on the carbon footprint (rather than other environmental effects), due to the increasing role of climate change in health.¹⁵

4.5 Methods

4.5.1 Study setting

We examined the carbon footprint of five pathology tests undertaken within a hospital setting. We performed the study at two health services: Austin Health (Austin Hospital) and Western Health (comprising Sunshine, Footscray, and smaller hospitals), both university affiliated health services located in Melbourne, Australia. Ethical consent for this observational study was waived by both health services (Q 32631). Both health services process >2,000 pathology tests per day, with Austin Hospital performing four times the number of biochemistry tests as Sunshine Hospital. Results were given as a weighted average (based on the number of tests performed at each site).

4.5.2 Study design

We performed a consequential process based life cycle assessment (LCA), in accordance with the International Organization for Standardization (ISO) 14040 series.¹¹ Consequential LCA analyses the impact of an additional test (marginal or incremental impact), rather than average impact across the total number of tests conducted calculated with an attributional analysis (Appendix 1).

The functional unit of our studied system was the collection of a sample using a plastic vacutainer tube holder and collection tube, and the analysis, of a single blood test in a hospital for FBE, clotting profile, U+E, CRP, and ABG. As CRP tests are typically ordered in concert with a U+E test, for the CRP analysis impact was limited to the additional electricity

and reagents required for analysis (and not impacts of sample collection or test consumables).

The system boundary defined what was included/excluded in analyses (Figure 4-2). We excluded capital infrastructure as is standard LCA practice as their environmental impacts are amortised over decades and tens of millions of tests, with the resultant impact per test being minimal.

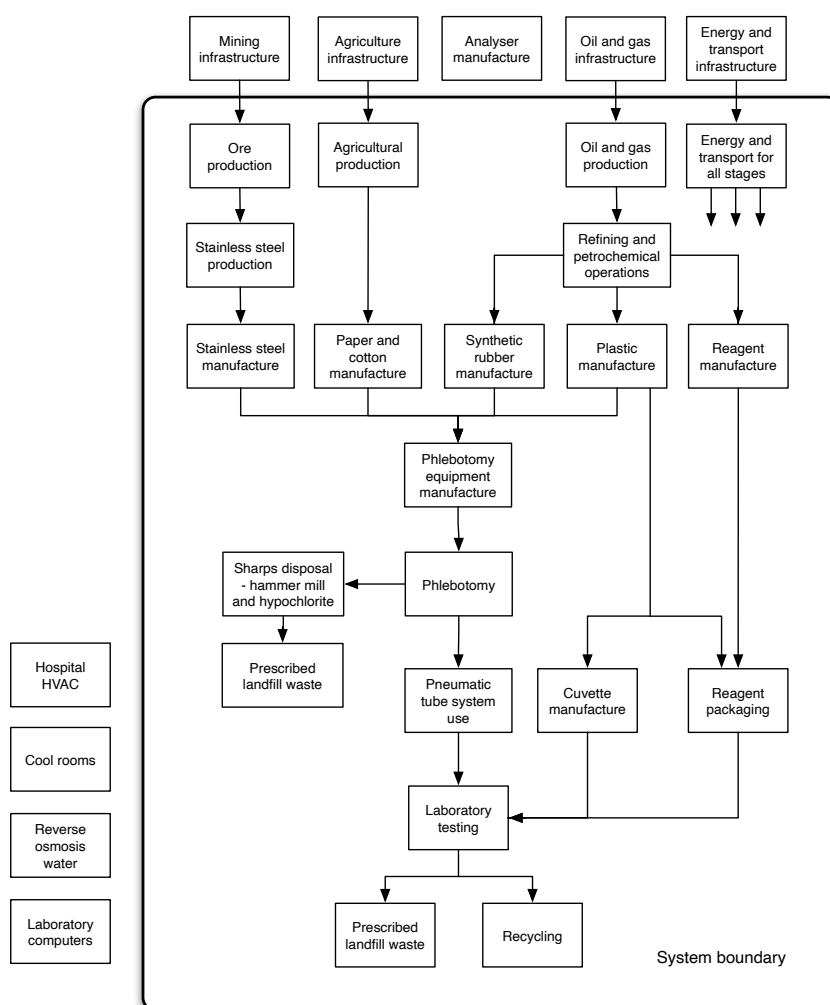


Figure 4-2: System boundary of our life cycle assessment of the carbon footprint of pathology tests, showing processes and systems included in or excluded from our study

4.5.3 Study outcomes

Our primary outcome was the climate change impact, reported in g CO₂e, and in kilometres driven in a passenger car.

4.5.4 Data collection

All data were collected between November 2018 and August 2019. In brief, weights and composition of all materials used in each test were measured, together with energy usage required to undertake each test.

All materials were weighed using a Digitech QM7259 scale (± 0.01 g), or if >200 g with a Heller KSH66 scale (± 1 g). For phlebotomy we sampled equipment used by the major Australian pathology providers ^{16,17}, including nitrile gloves, cotton swabs, alcohol swabs, BD-vacutainers (plastic tubes and needles), syringes and adjuncts (serum separators, syringes, and sealable plastic specimen bags); whilst for pathology testing this included aliquots, pipettes, and reagents and their packaging that included glass and plastic bottles, plastic “cartridges”, paper instructions, and cardboard boxes. The measured weights of all consumables required for sample collection, energy consumption, weights and volumes of consumables and reagents used are given in the Supplementary materials. Transport from the place of manufacture was searched for and included for all these items.

Three-phase electrical power of all pathology machines was sampled and logged every 15 seconds using a Hioki® PW3365-20 power meter for four days. Single phase power was sampled and logged every 30 seconds using a Watts Up Pro® power meter and Logger Pro® for 4 days. Marginal electricity use from an individual test was estimated to be an additional

minute of operation from the machine being active to returning to standby power usage. This minute of additional operation was estimated from observation of the time the machine analysers took to pipette multiple sequential samples, the time it took for a single test to be completed, and the time between multiple sequential tests being completed. The exception to this was the ABG analyser, where single tests were performed. As this was a consequential analysis, we calculated electricity usage per test from the difference in the active electricity used and the average standby electricity.

4.5.5 Data analysis

All life cycle impacts were modelled using SimaPro® software, version 9.0.0.27 (PRé Consultants, Amersfoort, The Netherlands). Background data, containing the environmental impacts of materials and energy, was sourced from the consequential version of Ecoinvent 3.5®, an international ISO 14044 compliant database.¹⁸ Impact assessment was modelled using the European Commission's ILCD V1.10 impact assessment method.¹⁹

All inputs into the model had an uncertainty value expressed as a lognormal probability distribution. This is calculated by a "pedigree matrix"²⁰, based on the data's reliability, completeness, and temporal and geographical proximity. A 95% confidence interval (CI) was calculated using Monte Carlo analysis, whereby 1,000 'runs' were performed, with each run having a random value generated within the range of every input's distribution.

50% of the number of the chemicals contained in pathology reagents were not available in the Ecoinvent database (e.g. adenosine triphosphate). Furthermore, the high purities and small production volumes associated with fine chemical production may result in impacts up

to 25 times higher than the comparable basic (low purity) chemical production.²¹ We therefore estimated a single conservative fine chemical as a proxy for all chemicals. We searched the Ecoinvent database for all the chemicals contained within reagents, and for those that were available, averaged their impacts, and multiplied the resultant average by 25 to account for fine chemical production.²¹ Additionally, the composition for nine of the twenty-three reagents was unavailable due to commercial confidentiality. We therefore calculated the average percentage concentration of fine chemicals based on mol/L from known reagents (3.7%) and used this as proxy for unknown reagents. The remaining volume of all reagents was assumed to be ultra-pure water.

4.5.6 Sensitivity analysis

Because of uncertainty around the impacts of the chemicals in the pathology reagents, we performed a sensitivity analysis by modifying the multiplication factor used to account for the difference between basic and fine chemical production from the initial 25 down to 10; and by modifying the average percentage concentration for unknown reagents from 3.7% to 1%.

4.6 Results

Table 4-1 lists the CO₂ impacts in g CO₂e, with 95% CI, for each test. CO₂e ranged between 48.5g (95% CI 44.8-53.2) for ABG to 116.3g (101.3-135.4) for FBE. In contrast the footprint of CRP was extremely small at 0.5g CO₂e. Expressed as kilometres driven by car, the carbon impact of the tests ranged from a few metres (for CRP) to most of a whole kilometre (for FBE).

Table 4-1: Carbon dioxide equivalent (CO₂e) emissions for five common hospital pathology tests, with distance driven in a standard car producing equivalent emissions

	Mean g CO ₂ e (g) (95% CI)	km driven in car	Equivalent distance in car (km/ 1000 tests)
Full blood examination	116 (101 – 135)	0.77	770
Coagulation profile	82 (73 – 91)	0.54	540
Urea and electrolytes	99 (84 – 113)	0.65	650
C-reactive protein*	0.5 (0.4 – 0.6)	0.003	3
Arterial blood gases	49 (45 – 53)	0.32	320

CI = confidence interval. *Ordered in conjunction with urea and electrolyte assessment

For all tests except CRP, the main source of CO₂ gas emissions were consumables used in sample collections (swabs, gloves, vacutainer holder, collection tubes and specimen bags). However again there was variation. The proportions of CO₂e emission of each test that was due to sample collection were 63% (74 of 116g CO₂e) for FBE, 90% (89/99g CO₂e) for U+E, 94% (46/49g CO₂e for ABG) and 95% (78/82g CO₂e) for coagulation profile. As CRP was assumed to be always ordered in conjunction with U+E, it had no emissions impact during the collection phase (Figure 4-3).

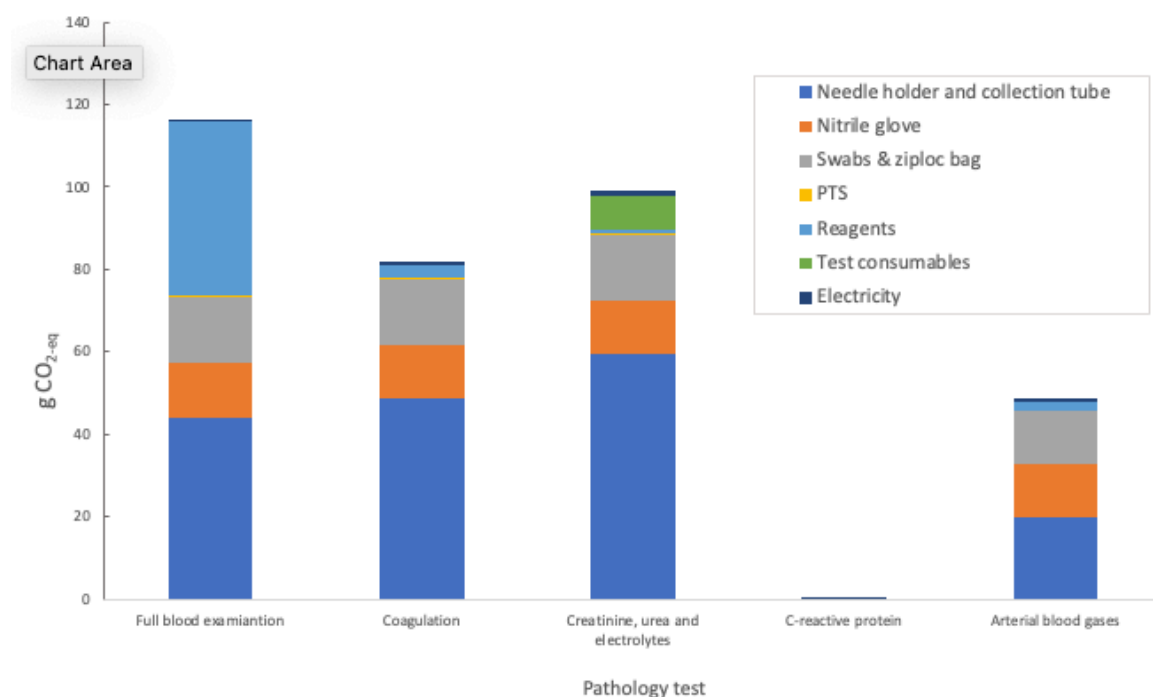


Figure 4-3: Carbon dioxide equivalent (CO₂e) emissions associated with single pathology tests, by test component

These differences in the contributions of sample collection to the total CO₂e are due to the respective volumes of each tube, and hence the mass of polyethylene terephthalate (PET) required to manufacture them. Additionally, adjuncts in the collection tubes such as anticoagulants and serum separators contributed to overall emissions. The lower carbon impact from collection of ABG tests reflects the fact that only a single syringe and needle is used, whereas the other tests use a vacutainer holder and collection tube.

During the laboratory analysis stage for FBE, coagulation, U+E and CRP, the g CO₂e emissions from the electricity used to perform each test were very similar, ranging from 0.2– 1.4g CO₂e. By contrast, the impacts of the reagents and their packaging resulted in CO₂e emissions ranging from 0.3g and 0.9g CO₂e for CRP and U+E respectively through to 42.1g CO₂e for FBE.

Whilst U+E had a low impact from its reagents, it had considerably higher impacts (8g CO₂e) from the use of consumables, and in particular aliquots and pipettes, and the polypropylene caps needed for recapping before storage. Coagulation studies by comparison do not require the use of aliquots, with samples being taken directly from collection tubes so the laboratory impact is dominated by reagents and their packaging (2.9g CO₂e).

The higher laboratory CO₂ emissions associated with FBE were due to both the number and volume of reagents needed (38.8ml compared to 160μL for CRP). This high volume of reagents meant that CO₂ emissions due to transport from Singapore were 5.0g CO₂e, twice that of the ABG reagents transported from Poland (2.6g CO₂e), and 4 to 5 times that higher than the remaining tests (range 1.1 – 1.3g CO₂e).

When, in sensitivity analyses, we reduced the multiplication factor (used to account for the difference between basic and fine chemical production for the pathology reagent) from 25 to 10, there was less than a 1% difference for all tests except FBE (Table 4-2). For an FBE, the overall impact was reduced 16%, from 116g to 97g CO₂e. Similar percentages were calculated when undertaking a sensitivity analysis for the reagents only found in FBEs and coagulation profiles with unknown fine chemical concentrations. Changing the fine chemical concentration from the 3.7% study average to 1% for FBE resulted in an 18% decrease, from 116g to 96g CO₂e, and a less than 1% difference for the coagulation profile.

Table 4-2: Carbon emissions (CO₂e; in grams) for five common hospital pathology tests: sensitivity analyses

Fine chemical multiplication factor	10	15	20	25*	30
Full blood examination	98	104	110	116	122
Coagulation profile	81	82	82	82	82
Urea and electrolytes	99	99	99	99	99
C-reactive protein [†]	0.5	0.5	0.5	0.5	0.5
Arterial blood gases	49	49	49	49	49
Unknown reagent concentration	1%	2%	3%	3.7*	4%
Full blood examination	96	103	111	116	118
Coagulation profile	81	82	82	82	82

* Factor applied in major analysis. [†] Ordered in conjunction with urea and electrolyte assessment

4.7 Discussion

We provide the first ‘cradle-to-grave’ carbon footprint of five common pathology tests.

While the CO₂e emissions associated with different haematology tests are similar (82g CO₂e for coagulation profile and 116g CO₂e for FBE), those associated with biochemistry tests are highly variable (0.5g CO₂e for CRP to 99g CO₂e for ABG), with this variation due to whether additional venepuncture and collection are needed. The majority (60-95%) of the carbon footprint was from blood sample collection (including test tube plastics), rather than reagents or machine electricity use in performing the test. The estimated CO₂e emissions for each test are equivalent to driving a standard Australian car ²² from <1 metre for an ABG to 0.8 km for an FBE test. Whilst the greenhouse gas impacts of each individual test are relatively small, there are 17.8 and 56.2 million haematology and biochemistry tests respectively funded by Medicare annually. ²³

Our study was performed at two hospitals in Melbourne, Australia. These results are likely to reflect the carbon footprint of pathology tests at other metropolitan hospitals in Australia. Pathology tests in the community will have a differing footprint, due to the impacts of road transport and the different analysers used. Whilst variability in pathology testing between different laboratories occurs, the limited number of reagents used, and the similarities in impacts from analysers in this study, suggest our results are likely reflective of the CO₂e emissions associated with the same pathology tests elsewhere. Importantly, given collection is the dominant CO₂ impact, there is unlikely to be major variability in phlebotomy items used. Lastly, as some pathology tests can be collected in the same test tube, e.g. CRP with U+E, we attributed all venepuncture consumables to U+E as this test is routinely performed, whilst CRP is routinely ordered as an “add on”. Point of care testing, however, is likely to have a differing impact, and will be an important area for further analysis.

Environmental sustainability is often considered in terms of a hierarchy of waste reduction: “Avoid, Reduce, Reuse, and Recycle”. Prior LCA studies have focused on reusing and recycling rather than reducing.^{15,16} For pathology testing, however, there are limited opportunities to reuse items, and recycling is problematic because of infection control. Changing materials for blood collection and storage will have minimal impact on emissions if the substitute has a similar carbon intensity. Further, since only a small proportion of the CO₂e emissions for pathology tests arose from machine electricity use, improving machine energy efficiency and increasing renewable electricity will have limited effect on pathology’s carbon footprint. The main opportunities for waste and CO₂ emission reduction in pathology are from measures to change clinician behaviour and to “Avoid and Reduce” unnecessary pathology testing.

Studies have shown that pathology testing is often unindicated and unnecessary, resulting in over-testing ⁷. This over-testing in turn can lead to false positives, which result in unnecessary further testing, and to over diagnosis, with overtreatment and a downstream cascade of unnecessary and potentially harmful healthcare.^{24,25} Each element in this cascade also has an associated detrimental environmental impact. Overtesting may be driven by a number of non-clinician factors, and targeting these may provide further opportunities to reduce carbon costs attributable to tests. For an in-depth discussion on these factors, see (Pathirana (2017), Rao (2003), Spelman (2015) and Brown (2011)).²⁶⁻²⁹

While we acknowledge that under-testing may occur in some circumstances with a risk of adverse outcomes, this study underscores the importance of appropriate testing, and in particular, ordering of tests only when the outcome will inform clinical decision making and patient care.

Sherman et al recently (2019) noted: "... eliminating unnecessary care reduces unnecessary resource use and emissions. Such partnerships could be encouraged to bring environmental stewardship into the health care quality discourse".¹¹ Considered together with the health outcomes of pathology testing, and with cost-effectiveness data, our environmental data provide a more robust evidence base for clinicians and policy makers to use when choosing pathology tests. Together, this approach will support a more sustainable and healthy future for our patients.

4.8 Acknowledgements

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4.10 Supplementary materials

Table 4-3: Life cycle assessment inventory: pathology testing

	Material	Mass
Phlebotomy		
Nitrile gloves	Synthetic rubber	3.3 g
Cotton swab	Cotton	0.54 g
Tube holder including needle		
(FBE, coagulation, U+E, C-rp)	Polypropylene	2.9 g
	Polyethylene terephthalate	1.5 g
	Stainless steel	0.05 g
Gold top collection tube	Polyethylene terephthalate	5.9 g
(For U+E and CRP)	Polypropylene	1.0 g
	Synthetic rubber	1.3 g
	Polydimethylsiloxane	0.5 g
Light Blue top collection tube	Polypropylene	1.0 g
(Coagulation)	Polyethylene terephthalate	5.0 g
	Synthetic rubber	1.3
	Citric acid	0.2 g
Purple top collection tube	Polypropylene	0.9 g
(FBE)	Polyethylene terephthalate	3.7 g
	Synthetic rubber	1.3 g
safePICO syringe	Polyethylene terephthalate	2.1 g
(ABG)	Polypropylene	2.4 g
	Stainless steel	0.2 g

10 ml syringe, for ABG	Polypropylene	6.16 g
	Polyethylene terephthalate	1.28 g
	Synthetic rubber	0.49 g
Pneumatic tube system	Electricity	1.2 Wh

Testing

Full blood examination

Electricity	Electricity	1.2 Wh
Packaging	Low density polyethylene	0.4 g
	High density polyethylene	0.1 g
	Cardboard	1.7 g
Reagent	Fine chemical	649 µg
	Ultrapure water	38.6 ml

Coagulation profile

Electricity	Electricity	2.45 Wh
Packaging	Glass	0.4 g
	High density polyethylene	0.01 g
	Polystyrene	0.02 g
	Low density polyethylene	0.02 g
	Paper	0.03 g
	Cardboard	0.3 g
Reagent	Fine chemical	19 µg
	Ultrapure water	0.4 ml

Urea/electrolytes

Electricity	Electricity	2.88 Wh
Packaging	High density polyethylene	2.0 g
	Polypropylene	2.0 g
	Glass	0.05 g

Reagent	Cardboard	0.06 g
	Fine chemical	10.7 µg
	Ultrapure water	0.2 ml
<i>C-reactive protein</i>		
Electricity	Electricity	0.5 Wh
Packaging	High density polyethylene	1.7 g
	Polypropylene	1.1 g
	Glass	0.02 g
Reagent	Cardboard	0.01 g
	Fine chemical	5.4 µg
	Ultrapure water	0.151 ml
<i>Arterial blood gases</i>		
Electricity	Electricity	19.56 Wh
Packaging	Polypropylene	0.605 g
Reagent	Fine chemical	4.4 µg
	Ultrapure water	4.3 ml

Table 4-4: Number of tests performed per day in each health service

Test	Austin Health	Sunshine Hospital
Full blood examination	423	392
Coagulation profile	111	81
All biochemistry tests	6331	1719
Arterial blood gases	49	80

4.11 The carbon footprint of pathology testing - letter

The Medical Journal of Australia (2020), 213:477 – 477:e1

Thank you for the comments on our research. There are a number of points that we would like to elaborate on. We apologise if we gave the impression that pathology organisations are environmentally unaware. Inherent in our statement that there are limited opportunities for reuse and recycling was recognition that pathology organisations are already implementing procedures to reduce environmental waste ¹.

Pathology tests should not be avoided on the basis of their carbon footprint; rather, all medical interventions should be evaluated by considering their impact on three factors – health outcomes, cost-effectiveness and environmental impact including carbon footprint. The first two are uncontroversial. We are only at the beginning of our knowledge base of the carbon footprint of healthcare and how to most effectively reduce it whilst maintaining/improving human and planetary health. Our paper is an exquisite example of this: it is the first published, peer reviewed paper about the carbon footprint of pathology tests and it is published in 2020, 5 years after the Paris Climate Agreement.

We agree that other healthcare activities have large footprints, some of which have been measured and reported ². The study by Tennison ³, however, cannot be directly compared to our results as their analysis to calculate impacts per bed-day was an attributional analysis based on economic and building energy data of the whole NHS, unlike our study which was the consequential analysis of an additional test. An attributional approach would see our results, expressed as impact per test, increasing approximately three to four-fold. Whilst this

is still a relatively small number, our previous work has shown that many items in healthcare individually have a small impact, but, as they are used in large volumes, the total impact is substantial.

We agree that much pathology testing is vital for ensuring and protecting health, and also that undertesting can be a problem too. There is, however, significant evidence of overutilization of some pathology tests ⁴. The net number of tests done could be reduced without adverse effects on health outcomes, while still increasing testing where there is evidence of undertesting ⁵.

4.11.1 References

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4.12 An LCA of hospital pathology

The International Journal of Life Cycle Assessment (2021), 26:1753 – 1763

4.13 Abstract

4.13.1 Purpose

There is increasing interest within the healthcare sector about the environmental impacts associated with the provision of health services, with the sector being responsible for approximately 4.4% of global greenhouse gas emissions. The aim of this study is to develop an LCA of six commonly used pathology tests in hospitals in Australia, as testing is ubiquitous within healthcare.

4.13.2 Methods

The study is a cradle to grave assessment of pathology testing, from raw material acquisition for collection equipment and reagents, the collection of the sample from the patient, sample transport to the pathology lab and its subsequent analysis, and the disposal of clinical waste. The study has been performed in accordance with ISO 14040 and ISO 14044. The data were modelled using SimaPro® software, version 9.0.0.27, using the Australian National Life Cycle Inventory Database (AusLCI) for Australian specific data, and from Ecoinvent 3.5® for all other data. Impact assessment was performed using the ReCiPe 2016 V1.02 (H). We focused on midpoint indicators that damage human health, as well as reporting in disability adjusted life years (DALYs).

4.13.3 Results and discussions

Focussing on climate change, the impact of a single blood test given in a hospital ranges from 74g CO₂e through to 274g CO₂e, whilst for a urinalysis in a hospital the impact is greater at 538g CO₂e. Expressed in DALYs, blood tests ranged from impacts range from 0.146 µDALYs through to 0.383µDALYs, whilst urinalysis was 0.701 µDALYs. For the majority of the tests, the major source of impacts was the collection tubes and jars, and the electricity use of the analysers. Test reagents had only a minimal impact. Urinalysis had additional impacts due to test consumables (agar plate), and compressed air required for the automated analyser and incubator.

4.13.4 Conclusion

Globally, tens of billions of pathology tests are performed annually, with each individual test having a low environmental impact. Not all testing, however, is necessary, and reducing this unnecessary testing will reduce environmental and economic impacts and potential adverse health outcomes. Increasing laboratory utilisation (efficiency) will additionally reduce environmental impacts per test.

4.14 Introduction

In 2009 *The Lancet*, concluded that “... climate change is the biggest global health threat of the 21st century”.¹ Ten years later, *The Lancet* noted that climate change induced impacts on human health continued to worsen, and that “The life of every child born today will be profoundly affected by climate change. Without accelerated intervention, this new era will come to define the health of people at every stage of their lives”.²

Healthcare, paradoxically, is a major contributor to greenhouse gas emissions (GHG).

Individual studies using EIO (economic input output) have calculated healthcare’s percentage contribution to national emissions in the USA to be 10%, 7% in Australia, 5% in Canada, 4.6% in Japan, 3% in the UK, and 2.7% in China.^{3–8} A 2019 report using the EORA multi-regional environmental input output model determined that if global healthcare, including purchased pharmaceuticals, were a country it would be the fifth-largest greenhouse gas emitter, equivalent to 1.6 Gt CO₂e, or 4.4% of global emissions.⁹ Using Tang et al’s (2019) damage factors, these CO₂e emissions result in 400,000 to 1,240,000 disability adjusted life years (DALYs).¹⁰

To date, there have been a limited number of process-based life cycle assessments (LCAs) investigating the impacts of healthcare. The majority of these studies have focussed on the impacts of medical equipment, such as nanosilver-enabled bandages¹¹, with an emphasis on single-use vs reusable items such as laryngeal masks and laryngoscopes^{12,13}, anaesthetic equipment¹⁴, and central venous catheter insertion kits.¹⁵ A smaller number of LCAs have sought to investigate the impacts treating specific health conditions rather than individual

items of medical equipment. These studies have included hysterectomy and cataract surgery^{16,17}, birth¹⁸, and the treatment of intensive care patients with septicaemia.¹⁹

One major limitation in these LCA studies is the lack of life cycle inventories (LCI) of pharmaceuticals and pathology testing (ubiquitous within healthcare). Global revenue for pharmaceuticals was US\$1.2 trillion dollars in 2018. Further, approximately 13 billion (USA), 1 billion (UK) and 500 million (Australia) pathology tests respectively are performed annually.^{20–}
²² Whilst the pharmaceutical sector has performed LCAs and is undertaking efforts towards more sustainable production through “green chemistry”²³, LCAs of named pharmaceuticals are rarely made public, such as for vancomycin²⁴, morphine²⁵, and estimations of 20 common anaesthetic drugs.²⁶ There have been fewer published LCA studies of the impacts of pathology testing, with only McAlister et al reporting the consequential impacts of five common blood tests.²⁷ The paper was written within the constraints of a medical journal for a non-LCA audience of doctors, with the underlying intent of influencing clinician behaviour. This paper by contrast measures the attributional impact of those five blood tests, with the addition of urinalysis, and provides the LCI of these tests for a readership of LCA professionals.

4.15 Methods

This study was done in accordance with the International Organization for Standardization (ISO) 14040 (Environmental management, LCA Principles and framework) and 14044 (LCA Requirements and Guidelines).^{28,29}

4.15.1 Goal and scope

The goal of the study was to develop an LCA model of six commonly used pathology tests within a hospital setting. These tests are:

- Full blood examination (FBE)
- Coagulation profile (APPT or INR)
- Urea plus electrolytes (U+E)
- C-reactive protein (C-Rp)
- Arterial blood gas (ABG)
- Urinalysis

We examined data from the collection of test samples from patients through to disposal of clinical waste.

The study was performed at two 400-bed public hospitals located in Melbourne, Australia: Austin Hospital (Austin Healthcare) and Sunshine Hospital (Western Health). Ethics approval was waived by both health services. The two pathology laboratories process differing numbers of tests daily, especially for biochemistry tests (Table 4-5), and this is reflected in the analysers that the two laboratories use. Whilst the two laboratories use the same analyser for FBE and ABG tests, and a similar analyser for coagulation profiles, where they differ is with the biochemistry analysers used, with the Austin Health analysers able to process a higher volume of tests. This LCA is not meant to be comparative between the laboratories, so a weighted average based on the number of tests performed daily at each

laboratory was used to determine impacts. For urinalysis, samples at Sunshine Hospital are taken offsite, and thus only Austin Health’s analyser was modelled.

Table 4-5: Mean number of tests performed daily at each health service for study (averaged over a month)

Test	Austin Health	Sunshine Hospital
Full blood examination (FBE)	423	392
Coagulation profile	111	81
All biochemistry tests	6331	1719
Arterial blood gases (ABG)	49	80
Urinalysis	82	

In addition to midpoint indicators we calculated impacts in DALYs so that results could be utilised by health economists. We therefore used impact pathways for damage to human health, based on the ReCiPe method (2016), which includes climate change, ozone layer depletion, photochemical oxidation, particulate matter, human toxicity and water scarcity. In addition, we are reporting the results of these indicators as an aggregate, based on the cumulative contribution of all indicators to disability adjusted life years (DALYs).

4.15.2 Functional unit

The functional unit of the study is the collection and analysis within a Victorian public hospital of a single urine sample (urinalysis), or a single blood test.

4.15.3 Process flow

The first process for blood tests is phlebotomy (blood collection). A reusable tourniquet is placed around the arm, and the skin of the needle insertion site is cleaned with a single use

alcohol swab. A vacutainer tube holder, consisting of a polypropylene sheath that is able to accept a blood collection tube, and contains both an internal rubber coated needle and an external hypodermic needle, is used to pierce a vein (venepuncture). A blood collection tube is then inserted into the tube holder, with the rubber top of the collection tube being pierced by the tube holder's internal needle. Each collection tube contains a vacuum, with the extent of the vacuum determining the volume of blood that will flow into the tube. The tubes have color-coded lids to distinguish between the tests, with the tubes for each test containing specific additives, such as an anti-coagulant to keep blood liquid for a coagulation profile, or silicone gel to promote plasma separation for a U+E.

The site of the venepuncture is covered with a cotton swab and taped, to stop any further bleeding. Collection tubes are placed in a Ziploc® plastic bag and transported to the pathology laboratory using a pneumatic tube system (PTS). The PTS transports cylindrical containers containing the samples via a system of air blowers and divertors

At the pathology laboratory, tubes for biochemistry testing are centrifuged at 10,000 rpm for 10 minutes, to separate the erythrocytes (red blood cells) from the blood's plasma. The resultant plasma is then tested in the biochemistry analyser, although depending on the analyser the sample may be first pipetted into a smaller aliquot tube. Collection tubes for FBEs and coagulation profiles are not aliquotted, but rather are placed directly into their respective analysers. After testing, collection tubes for all tests are stored for a minimum of seven days between 4-8°C, before being disposed of.

Patients undergoing arterial blood gas analysis have the same skin preparation as the other blood tests. Rather than the vacutainer system utilised with the other blood tests, however, an artery in the wrist, arm or groin is punctured with a safePICO® syringe, consisting of a hypodermic needle, and a syringe containing a small gold-coated mixing ball used to ensure a homologous sample. After the sample is taken, a cotton swab is similarly placed over the site of the skin puncture. The syringe full of blood is then transported by foot to the pathology lab rather than by the PTS, due to its more fragile nature compared to a collection tube. At the laboratory, the syringe is then placed directly in the blood gas analyser, and after testing is not stored but is immediately disposed.

Urine samples are collected in a screw top collection jar and transported to the laboratory via the PTS system, where it is tested on both a fully automated microbiology analyser, and an analyser checking for the presence of leucocytes (white blood cell). For microbiological analysis, a small sample is automatically pipetted from the collection jar onto an agar plate containing a growth medium, then streak plated by the automated movement of a small magnetic ball across the surface of the agar plate. Streak plating acts to dilute the number of cells, so that by the final streak single discrete colonies remain. The streaked plate is then automatically loaded into a CO₂-rich incubator, kept at 30° for 24 hours, and then digitally imaged. The leucocytes analyser by comparison uses samples that are manually poured into test-tubes from the collection jar, before being placed in the analyser.

All clinical waste (hypodermic needles, syringes, collection tubes, urine jars and agar plates) are disposed of by shredding in a hammermill, followed by disinfection in a mist of sodium hypochlorite at 2,000 ppm (parts per million). The waste is compacted, then disposed of in

landfill. For non-clinical waste, cardboard from packaging is recycled, whilst all other waste enters landfill.

4.15.4 System boundary

The system boundary included the collection of samples; sample transport to the laboratory; manufacture, transport and packaging of analyser reagents; electricity, CO₂ and compressed air, and reverse osmosis water used during analysis, plus consumables (e.g. pipette tips); and clinical and non-clinical waste disposal.

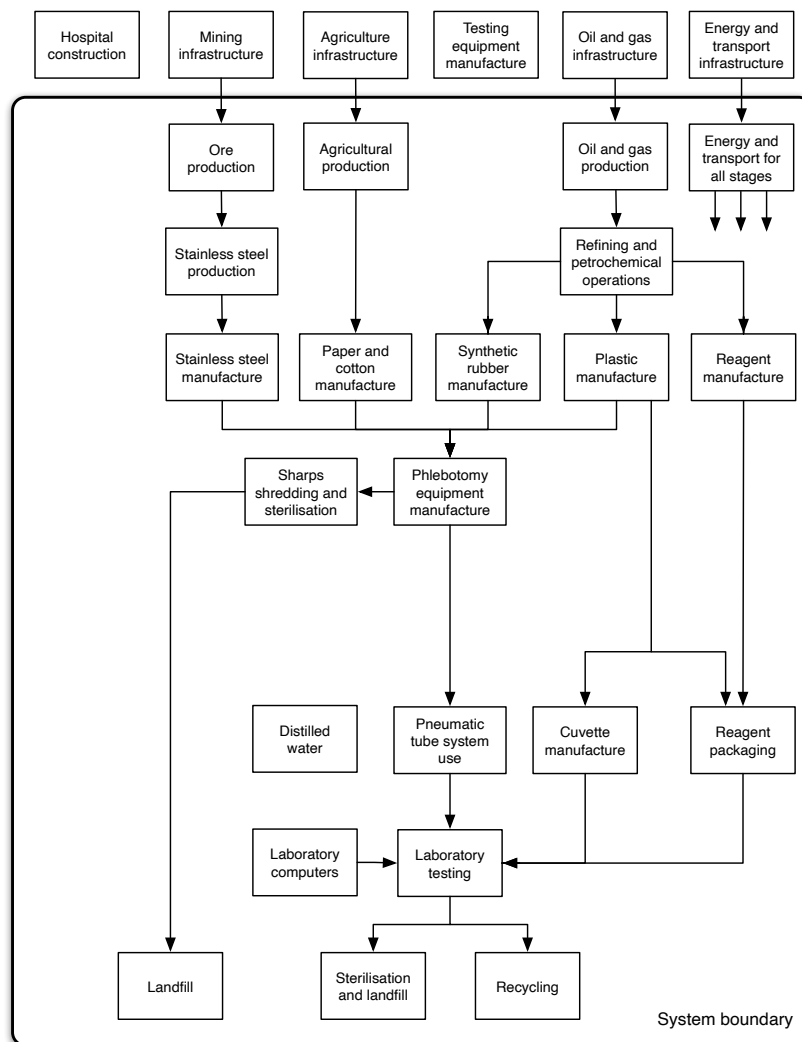


Figure 4-4: Study system boundary

Not included in the system boundary were items common between patients during sample collection such as plastic trays or tourniquets. Reagent refrigeration was not included, as the refrigeration contained reagents for hundreds of thousands of individual tests performed by the pathology laboratory, making the impact of an individual test negligible. Similarly, impacts for biochemistry calibrators were excluded as they consisted of very low volumes (< 5 ml) apportioned over thousands of tests.

Hospitals use large quantities of overhead energy for heating, ventilation and air conditioning (HVAC), as well as for general building services such as lighting and elevators. Hospitals in turn provide a large number of services to patients of varying types and complexities. Given that pathology labs do not require additional HVAC beyond what is supplied for wards and public areas of the hospital such as lobbies and corridors³⁰, we have chosen not to allocate the overhead energy in this study, given both the uncertainties around allocating a system with thousands of outputs, and the fact that thousands of pathology tests are performed daily meaning that the impact on an individual test would be negligible.

Upstream infrastructure in the economy was also excluded due to the small contribution and high variability surrounding these elements. The system boundary is shown in Figure 4-4.

4.15.5 Data sources

Foreground data was obtained from the Austin and Western hospitals. Materials less than 200g were measured using Digitech QM7259 scales ($\pm 0.01\text{g}$), whilst materials over 200g were measured with a Heller KSH66 scale ($\pm 1\text{g}$). The material composition of all items was determined using manufacturer's publicly available data. For reagents, packaging associated

with a single unit of reagent (e.g. 5 ml glass bottle) was included, as well as the cardboard boxes and instructions for each shelf unit (e.g. 12 bottles in a box). Manufacturer's data were used to determine the composition of reagents, as well as the volume used per test in analysers. Manufacturer's data were additionally used to determine reverse osmosis water use per hour for the biochemistry analysers, and compressed air and CO₂ use per hour for the urinalysis incubators.

Three-phase power was logged using a Hioki PW3365-20 power logger, for a minimum of 4 days, sampling every 15 seconds. Single phase power was logged using a Watts Up Pro, connected to a computer running Logger Pro, for a minimum of 4 days, with a sample taken every 30 seconds. All resultant data were checked to ensure that patterns of measured electricity use were consistent.

All data were modelled using SimaPro® software, version 9.0.0.27. Background data were sourced from the Australian National Life Cycle Inventory Database (AusLCI) for Australian specific data³¹, and from Ecoinvent 3.5® for all other data.³² Impact assessment was performed using the ReCiPe 2016 V1.02 (H).³³ All LCI data can be found in Supplemental tables 1-18.

4.15.6 Allocation

For data obtained from the Ecoinvent 3.5 database, the cut-off system model has been used.

4.15.7 Reagents

Nine of the twenty-three reagents in the study had an unknown composition due to manufacturer confidentiality. In addition, for those fourteen reagents where the composition was known, half of the chemicals they contained were not available in the background life cycle inventory databases (e.g. adenosine triphosphate). We therefore calculated a single reagent chemical as a proxy for all the chemicals used in the study.

Given the small quantities of reagents used per test (μL), meaning that an extremely small variation in concentration could lead to erroneous results, we assumed that reagents were highly purified and prepared in clean room conditions with high HVAC energy. We therefore did not use the fine chemicals in the Ecoinvent database, and instead took a conservative approach and used the multiplier of Wernet et al (2010) in the absence of any other published estimation to capture some of increased impacts of manufacturing highly purified compounds.³⁴ Wernet demonstrated that for pharmaceutical manufacture “fine chemicals”, or those chemicals with extremely high purity, were associated with impacts up to 25 times higher than their “basic chemical” analogues, due to their high purities and small production volumes.

We therefore first averaged the CO₂e emissions of the seven reagent chemicals that were available in Ecoinvent and AusLCI. We then multiplied this average by twenty-five to account for *fine chemical production*. We have therefore given the highest energy use/worst case scenario for fine chemical production.

For the nine reagents with unknown composition due to confidentiality, we used the average percentage concentration of reagent chemicals from those known reagent compositions (3.7% of total volume). We assumed that the remaining volume of all the reagents was ultra-pure water. The one exception to this was for a single reagent used for the FBE in very high volumes compared to other reagents (30.7 ml vs 50 μ L per test). This FBE reagent was 1% HCl, and we therefore modelled this, whilst using a 25 times factor to account for fine chemical production.

Due to the uncertainty surrounding the impacts of the reagent chemicals, we performed a sensitivity analysis on both the multiplication factor accounting for fine chemical production, and the calculated average percentage of reagent chemicals for those reagents with an unknown composition.

4.16 Results and discussion

The impacts per tests are shown in Table 4-6. Focussing on climate change, the impact of a single blood test given in a hospital ranges from 74g CO₂e through to 274g CO₂e, whilst for a urinalysis in a hospital the impact is greater at 538g CO₂e, with the source of these emissions being shown in Figure 4-5 and Supplemental Table 5-23. Focusing firstly on the collection stage (e.g. swabs, phlebotomy, collection tubes), the impacts for the tests ranged from 50 – 96g CO₂e, with all but one test being 73g CO₂e or greater. For FBE, coagulation profile, U+E and C-Rp, the dominant source of these emissions was the collection tubes (range 28 – 44 g CO₂e), with the differences in impact being due to the volume, and hence mass, of each tube, as well as the adjunct each tube contains. Other sources of emissions associated with

collection were the Vacutainer tube holders (18g CO₂e), gloves (14g CO₂e), the cotton and alcohol swabs (13g and 3g CO₂e respectively), and “ziploc” bags (4g CO₂e).

Table 4-6: Impacts per test

Impact category	Unit	ABG	C-Rp	Coagulation	FBE	U+E	Urinalysis
Climate change	g CO ₂ eq	74	148	233	117	274	538
Ozone depletion	g CFC11 eq	0.0000548	0.0008403	0.0000656	0.0000693	0.0008404	0.0000618
Ozone formation	g NO _x eq	0.1501	0.2514	0.2073	0.2789	0.253	0.3454
Fine particulate matter	g PM _{2.5} eq	0.1476	0.2652	0.4819	0.2383	0.5565	1
Carcinogenic toxicity	g 1,4-DCB	2.1	3.5	2.9	2.9	3.5	4.9
Non-carcinogenic toxicity	g 1,4-DCB	32.1	55.5	49.2	47.9	55.6	73.1
Water consumption	L	0.1	1.7	1.6	1.5	1.7	2.3
Disability adjusted life years	μDALY	0.146	0.265	0.325	0.232	0.383	0.701

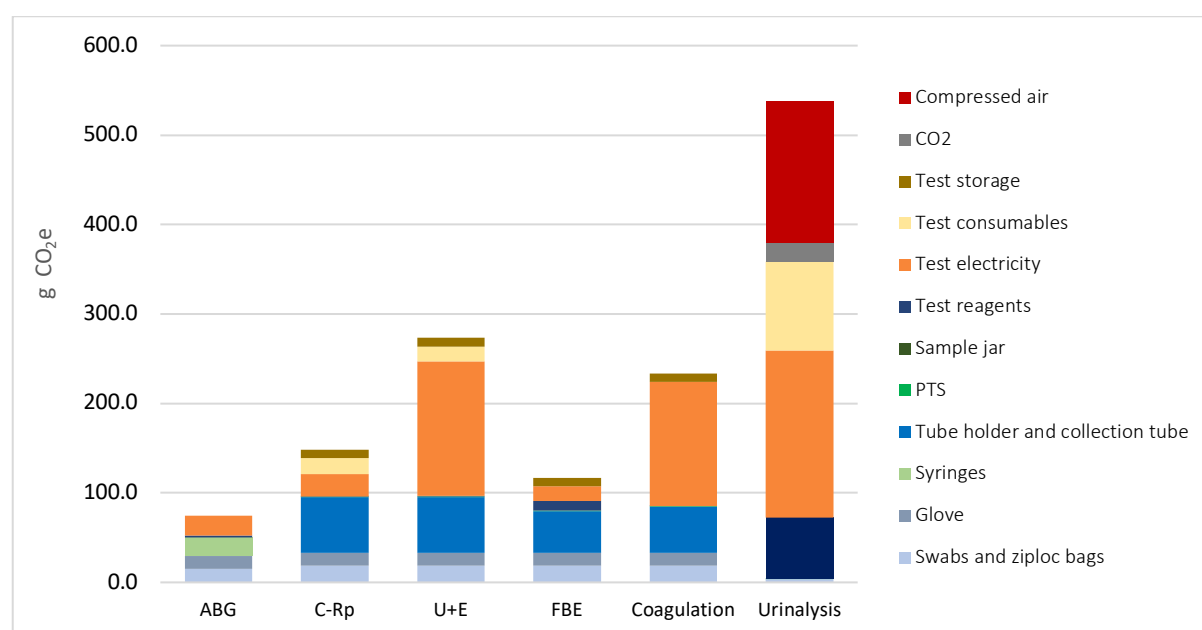


Figure 4-5: Source of greenhouse gas emissions per test

Whilst the relative impact of collection was high for ABG (67% of total impact), it also had the lowest absolute impact for collection, at 50g CO₂e. This was due to the safePico syringe having a lesser impact of 21g CO₂e compared to the tube holder and collection tube required

for the other tests. In addition, as the syringe is hand delivered rather than going through the PTS system, it did not require the “ziploc” bag nor the PTS system’s electricity use (0.8g CO₂e).

For urinalysis, the impacts for collection (73g CO₂e) were primarily due to the sample jar, with only an additional 5g CO₂e arising from the “ziploc” bag and PTS. Overall, collection for urinalysis had the smallest relative contribution, at 14%.

For the analysis stage, impacts ranged from 24.5g CO₂e for ABG through to 465g for urinalysis, with electricity usage of analysers being the major contributor for all tests. For urinalysis, the analyser’s electricity use resulted in 187g CO₂e, and compressed air resulted in an additional 158g CO₂e. Urinalysis additionally had the highest impact of all the tests due to consumable usage (120g CO₂e), arising from the agar growth plate (81g), the CO₂ used to create a CO₂-rich atmosphere for incubation (21g), the iQ200 test tube (15g) and pipette tips (4g).

Of the remaining tests, U+E had the next highest impact associated with analysis (177g CO₂e), predominately due to it being a combination of six individual tests (Na⁺, K⁺, Cl⁻, HCO₃⁻, creatinine, urea) that results in high analyser electricity use (150g CO₂e). For single tests, the coagulation profile analysers had high electricity usage (139g CO₂e) compared to FBE, ABG and C-RP, which all had similar analyser electricity usage (16, 22 and 25g CO₂e respectively). In addition to analyser electricity, C-Rp, U+E, FBE and coagulation studies each had an additional 9g CO₂e from electricity usage associated with sample storage for the week after the analysis had been undertaken.

In terms of consumables, three of the tests (ABG, FBE and coagulation) had no impacts associated with laboratory test consumables, whilst both C-Rp and U+E required the use of additional aliquots and pipette tips to procure a sample from the collection tube, resulting in 17g CO₂e of emissions. The majority of the reagents had a minimal impact on analysis (0.3 – 0.5%), although reagents associated with ABG and FBE contributed 2.4g and 11g CO₂e respectively, due to the higher volumes of reagents needed for these tests (ml compared to µl used in the other tests).

Our study was performed in Victoria, Australia, where approximately 70% of electricity is generated from brown coal, resulting in one of the highest emission factors worldwide of 1.12 kg CO₂e per kWh.^{35,36} If the same tests were performed in Europe, the UK or the USA, the impacts would be lower (Table 3). The Victorian Government has recently announced, however, that hospitals will be supplied with 100% renewable energy by 2025, and this will reduce the impact in particular for U+E, coagulation and urinalysis, as these tests have a high impact originating from electricity.

Given as an impact on human health, individual tests ranged from 0.146 µDALYs for ABG through to 0.701 µDALYs for urinalysis, with climate change and PM_{2.5} emissions contributing the greatest impact (Figure 4-6).

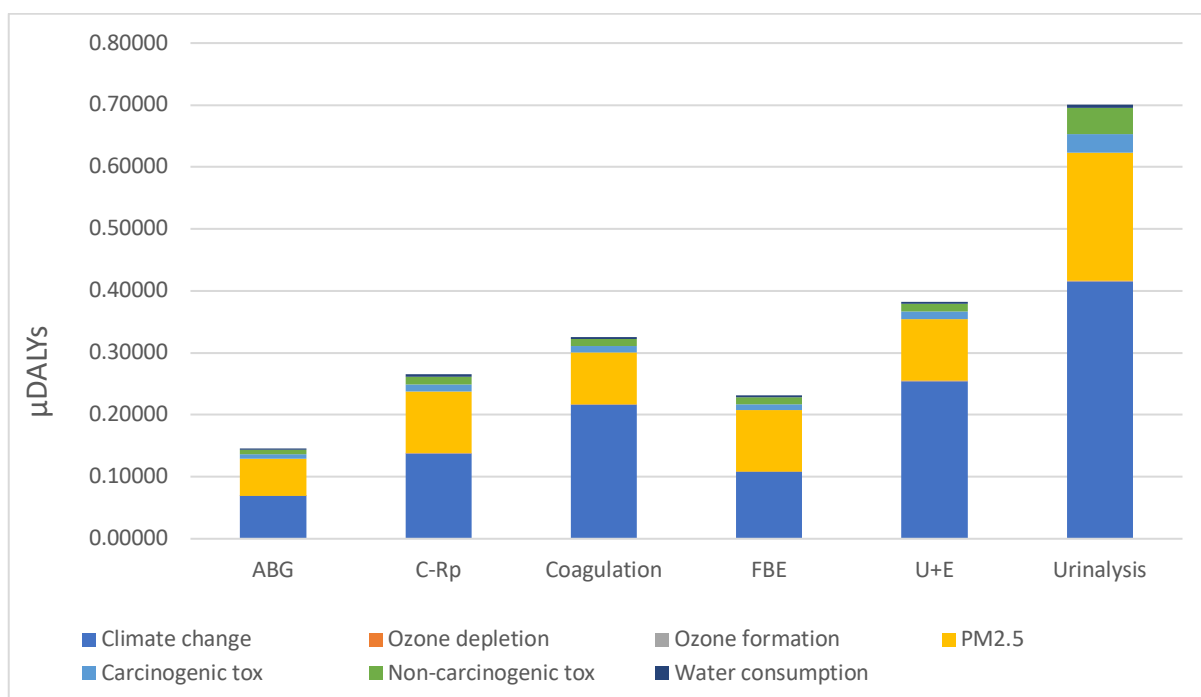


Figure 4-6: Impacts per test in Disability Adjusted Life Years (DALYs)

4.16.1 Sensitivity analysis

Due to the uncertainty surrounding the impacts of the reagent chemicals, we performed a sensitivity analysis on both the multiplication factor accounting for fine chemical production, and the calculated average percentage of reagent chemicals for those reagents with an unknown composition (Table 4-7, 5-4). The results are not very sensitive to the assumptions used to calculate the impacts of active ingredient used in reagents. All tests, with the exception of a FBEs, showed no change in impacts, due to only very small quantities of reagents being used in these tests. For FBEs, where larger quantities of reagents are used, the difference between a multiplication factor of 10 and 30 (25% being the study default) was 2.7g CO₂e, or 2.6% of total CO₂e emissions; whilst the difference between 1% and 4% for average reagent chemical concentration (3.7% being the study default) was 0.23g CO₂e, or 0.2% of total CO₂e emissions. Under the assumption that reagent chemicals were not further

purified beyond the commodity chemicals found within AusLCI's databases (a multiplication factor of 1), then the difference compared to the study's default is 8.6%.

Table 4-7: Sensitivity analysis for single FBE, for multiplication factor for fine chemical production

Impact category	Unit	Multiplication factor					
		1	10	15	20	25*	30
Global warming	kg CO ₂ eq	1.043	0.1056	0.1063	0.1070	0.1077	0.1084
Stratospheric ozone depletion	kg CFC11 eq	65.48E-9	66.87E-9	67.64E-9	68.41E-9	69.18E-9	69.95E-9
Ozone formation	kg NO _x eq	267.00E-6	271.46E-6	273.95E-6	276.43E-6	278.92E-6	281.40E-6
Fine particulate matter	kg PM _{2.5} eq	149.34E-6	152.22E-6	153.82E-6	155.43E-6	157.03E-6	158.63E-6
Carcinogenic toxicity	kg 1,4-DCB	598.72E-6	598.72E-6	598.72E-6	598.72E-6	598.72E-6	598.72E-6
Non-carcinogenic toxicity	kg 1,4-DCB	5.64E-3	5.64E-3	5.64E-3	5.64E-3	5.64E-3	5.64E-3
Water consumption	m ³	1.55E-3	1.55E-3	1.55E-3	1.55E-3	1.55E-3	1.55E-3

*Used in the study

Table 4-8: Sensitivity analysis for single FBE, for percentage active ingredient

Impact category	Unit	Percentage active ingredient				
		1	2	3	3.7*	4
Global warming	kg CO ₂ eq	0.10746	0.10754	0.10761	0.10767	0.10769
Stratospheric ozone depletion	kg CFC11 eq	69.04E-9	69.13E-9	69.22E-9	69.27E-9	69.30E-9
Ozone formation	kg NO _x eq	278.18E-6	278.46E-6	278.73E-6	278.92E-6	279.00E-6
Fine particulate matter	kg PM _{2.5} eq	156.71E-6	156.88E-6	157.06E-6	157.19E-6	157.24E-6
Carcinogenic toxicity	kg 1,4-DCB	2.91E-3	2.91E-3	2.91E-3	2.91E-3	2.91E-3
Non-carcinogenic toxicity	kg 1,4-DCB	47.88E-3	47.88E-3	47.88E-3	47.88E-3	47.88E-3
Water consumption	m ³	1.55E-3	1.55E-3	1.55E-3	1.55E-3	1.55E-3

* Used in study

4.16.2 Uncertainty analysis

We undertook a Monte Carlo analysis of 1,000 runs for each test. Values for uncertainty were obtained from the Ecoinvent and AusLCI's database for background data, and from the Pedigree Matrix for foreground data³⁷, except for the calculated active ingredient for which we used the calculated mean and standard deviation (Supplemental tables 20 – 26).

4.17 Conclusion and recommendations

The impacts of an individual pathology tests in a hospital setting range from 74 to 538g CO₂eq, or between 0.146 and 0.701 μ DALYs. Differences between hospital testing and the private providers that perform all non-hospital testing, and that transport samples from across the state to single centralised laboratories that have high utilisation rates; and the uncertainty about the actual number of pathology tests performed, both due to a lack of available information on state funded hospital-based testing, and that for all testing only the three most expensive tests per patient per day are paid for (coning) and hence recorded, means that it is not possible to extrapolate these results to calculate pathology's contribution to Australia's healthcare footprint.

Pathology testing importantly informs up to 70% of clinical decision making.³⁸ Given that clinical decision making has the potential to extend human life by multiple years, and that this is driven by pathology testing, it can therefore be assumed that the environmental impact on human health from a test is surpassed by the benefit to human health of performing that test. Not all testing, however, is necessary. A meta-analysis has shown that on average 20% of tests are unnecessary, with this rising to 44% if more restrictive criteria to determine unnecessary testing is used.³⁹ Unnecessary testing, apart from the associated environmental and financial costs, can result in adverse health outcomes.

Testing and diagnosis has uncertainty associated with it. Statistically, this uncertainty is sensitivity, or the percentage of those with a condition being correctly identified as positive by the test (i.e. true positive); and specificity, or the percentage of those without a condition

being correctly identified as negative by the test (i.e. true negative). Hammett et al (2002) discuss how sensitivity and selectivity can result in a 40% chance of at least one positive test if a healthy individual undergoes 10 unnecessary tests.⁴⁰ False positive tests lead to additional testing and unnecessary treatment, resulting in an environmental and economic impact and potentially patient harm.⁴¹ Similarly, overtesting can result in overdiagnosis, or the identification of abnormalities that were never going to cause harm, and that often leads to a clinical cascade of overtreatment and unnecessary medication.⁴²

Additionally, pathology testing can lead to iatrogenic anemia (a lowered hematocrit and haemoglobin count) from repeated blood collection, which leads to an increased risk of mortality.^{43,44} Testing, therefore, should only be undertaken where the outcomes of the test change clinical decisions, and that a change in clinical decision-making leads to better patient outcomes.⁴⁵

Apart from reducing unnecessary testing, increasing laboratory utilisation can also lead to better environmental (and financial) outcomes. Hospitals are characterised by the requirement that medical equipment is ready to be used without any delay 24 hours a day for cases of emergency. This results in equipment not being able to be switched off, but rather it sits idle using standby power for long periods of time. As an example, studies of diagnostic imaging (X-ray, CT scan and MRI scan) in hospitals have shown that energy use during standby greatly surpasses active use.^{46–48} Similarly for both laboratories examined in this study, the overnight period was characterised by analysers running on standby but with only the occasional test being performed, with the impacts from the standby electricity being

allocated to each test. Increasing the utilisation of the laboratories, especially overnight, would reduce therefore the impact per test.

For the laboratories investigated, increasing utilisation could be achieved in two ways. The first is centralising non-urgent hospital testing wherever geographically possible, so that a single laboratory is maximising the amount of time analysers are performing tests. Using Melbourne's hospitals, which are located approximately 7km away from each other as an example, and under the assumption that the daily number of pathology tests were transported equally each hour over an eight-hour period, car transport would add approximately 0.009 kg CO₂e to each test.

For urgent hospital tests, the use of smaller point-of-care analysers are increasingly able to substitute for larger analysers. Similarly, hospitals could increase utilisation by performing analysis for non-hospital pathology testing. In Australia, however, there are currently financial barriers to this occurring due to how Medicare, Australia's single-payer universal healthcare scheme, provides a higher fee to private pathology companies compared to hospitals, allowing private providers to have a competitive advantage.⁴⁹

In this study, there were limited opportunities to reduce impacts from changes in the actual testing process. For example, analysers currently require a minimum volume of blood for testing, driving the size of collection tubes, although future technological changes such as biosensors and microfluidics may only require pinpricks of blood. Similarly, there are no real opportunities to undertake reuse or recycling in pathology testing, and indeed for much of

healthcare, beyond what currently occurs with outer packaging materials such as boxes, due to infection control concerns.

4.18 Acknowledgements

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4.19 Declarations

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4.21 Supplementary materials

Table 4-9: Data assumptions for shipping and road transport

Component	Shipping assumption	Road transport assumptions
Singapore	7,143 km Singapore to Melbourne	100 km
Japan	9,153 km Kobe to Melbourne	100 km
USA	18,688 km Boston to Melbourne	100 km
Poland	21,892 km Szczecin to Melbourne	100 km
UK	23,161 km Dundee to Melbourne	100 km

Table 4-10: Data assumptions for 1 metric ton of clinical waste steam sterilised and landfilled

Component	Data Source	Data Assumptions	Manipulation
Electricity	AusLCI	46.6 kWh electricity	Victorian electricity used
Transport	AusLCI	52 km hospitals to disposal plant	Average 44 km Austin to disposal plant and 63 km Sunshine to disposal plant. 16 to 28t truck
Transport	AusLCI	64 km disposal plant to landfill	16 to 28t truck

Table 4-11: Data assumptions for 1,000 kg of material sterilised using ethylene oxide

Component	Data Source	Data Assumptions	Manipulation
Electricity	Ecoinvent	35.5 MJ	From ARTA and IAHTM LCA of surgical gowns
Heat, from steam	Ecoinvent	11.3 MJ	
Ethylene oxide	Ecoinvent	3.2 kg	

Table 4-12: Data assumptions for nitrile gloves

Component	Data Source	Data Assumptions	Manipulation
Nitrile glove	Ecoinvent	3.26 g synthetic rubber	

Table 4-13: Data assumptions for alcohol swab

Component	Data Source	Data Assumptions	Manipulation
Paper, silver coated	Ecoinvent	0.36 g paper	
Swab	Ecoinvent	0.19 g	
Alcohol 70% isopropyl, 2% chlorhexidine	Ecoinvent	0.4 g	
Ethylene oxide sterilisation	Project	0.83 g	Singapore electricity used
Transport	Project	0.83 g transport	Transport from Singapore

Table 4-14: Data assumptions for cotton swab

Component	Data Source	Data Assumptions	Manipulation
Textile cotton	Ecoinvent	0.54 g	

Table 4-15: Data assumptions for vacutainer

Component	Data Source	Data Assumptions	Manipulation
Clear packaging	Ecoinvent	1.45 g low density polyethylene	
Paper packaging	Ecoinvent	0.43 g paper	
Vacutainer body	Ecoinvent	2.85 g polypropylene	
Vacutainer top	Ecoinvent	0.51 g polyethylene terephthalate	
Injection moulding	Ecoinvent	3 g injection moulding	
Needle	Ecoinvent	0.05 g stainless steel	
Needle cover	Ecoinvent	0.08 g synthetic rubber	
Ethylene oxide sterilisation	Project	5.01 g sterilisation	Singapore electricity used
Transport	Project	5.01 g transport	Transport from Singapore

Table 4-16: Data assumptions for gold top collection tube

Component	Data Source	Data Assumptions	Manipulation
Top of tube	Ecoinvent	1.02 g polypropylene	
Tube	Ecoinvent	5.9 g polyethylene terephthalate	
Injection moulding	Ecoinvent	6.92 g injection moulding	
Rubber seal	Ecoinvent	1.3 g synthetic rubber	
SST	Project	0.46 g SST	Polydimethylsiloxane used for spray coated silica and polymer gel
Ethylene oxide sterilisation	Project	8.68 g sterilisation	Singapore electricity used
Transport	Project	8.68 g transport	Transport from Singapore

Table 4-17: Data assumptions for light blue top collection tube

Component	Data Source	Data Assumptions	Manipulation
Top of tube	Ecoinvent	0.97 g polypropylene	
Tube	Ecoinvent	5.01 g polyethylene terephthalate	
Injection moulding	Ecoinvent	5.98 g injection moulding	
Rubber seal	Ecoinvent	1.3 g synthetic rubber	
Sodium citrate	Project	0.21 g sodium citrate	Citric acid used for sodium citrate
Ethylene oxide sterilisation	Project	7.49 g sterilisation	Singapore electricity used
Transport	Project	7.49 g transport	Transport from Singapore

Table 4-18: Data assumptions for purple top collection tubes

Component	Data Source	Data Assumptions	Manipulation
Top of tube	Ecoinvent	0.93 g polypropylene	
Tube	Ecoinvent	3.68 g polyethylene terephthalate	
Injection moulding	Ecoinvent	4.61 g injection moulding	
Rubber seal	Ecoinvent	1.32 g synthetic rubber	
EDTA	Project	0.05 g EDTA	Al used for EDTA spray coated on interior surface
Ethylene oxide sterilisation	Project	5.98 g sterilisation	Singapore electricity used
Transport	Project	5.98 g transport	Transport from Singapore

Table 4-19: Data assumptions for safePICO arterial blood gas syringes

Component	Data Source	Data Assumptions	Manipulation
Plastic packaging	Ecoinvent	0.57 g low density polyethylene	
Paper packaging	Ecoinvent	0.33 g paper	
Syringe body	Ecoinvent	1.29 g polypropylene	
Syringe plunger		1.11 g polypropylene	
Rubber seal	Ecoinvent	0.08 g synthetic rubber	
Injection moulding	Ecoinvent	3.93 g	
safeTIPCAP	Ecoinvent	1.53 g polyethylene terephthalate	
Mixing ball	Ecoinvent	0.18 g stainless steel	Gold coating not included because of low mass
Ethylene oxide sterilisation	Project	5.09 g sterilisation	Polish electricity used
Transport	Project	5.09 g transport	Transport from Poland

Table 4-20: Data assumptions for urine specimen jar

Component	Data Source	Data Assumptions	Manipulation
Specimen jar	Ecoinvent	12.88 g polystyrene	
Injection moulding	Ecoinvent	12.88g	
Transport	Project	12.88 g transport	Transport from UK

Table 4-21: Data assumptions for “ziploc” specimen bag

Component	Data Source	Data Assumptions	Manipulation
Specimen bag	Ecoinvent	0.93 g low density polyethylene	

Table 4-22: Data assumptions for full blood examinations

Component	Data Source	Data Assumptions	Manipulation
Electricity			
Electricity usage analyser	AusLCI	8.65 Wh per test	Weighted average between Austin and Western hospitals. Victorian electricity used.
Electricity usage computers		4.4 Wh per test	Weighted average between Austin and Western hospitals. Victorian electricity used. Estimated 80W per hour
Electricity usage monitor		1.5 Wh per test	Estimated 25W per hour. Victorian electricity used.
Reagent 1			
	Ecoinvent	30.7 mL per test	32.2 mL per test, 1% HCl. 20L pack, 650 tests per pack
Inner container	Ecoinvent	0.32 g low density polyethylene	
Cardboard box	Ecoinvent	1.17 g cardboard per test	
Lid	Ecoinvent	0.05 g high density polyethylene per test	
Collar	Ecoinvent	0.03 g high density polyethylene per test	
Transport	Project	32.3 g transport per test	Transport from Singapore
Reagent 2			
	Project	2.3 mL per test	2.4 mL per test, assumed 3.7% Al. 20L pack, 8,600 tests per pack.
			0.115 g Al, 2.2 g ultrapure water
Inner container	Ecoinvent	0.024 g L low density polyethylene	
Cardboard box	Ecoinvent	0.09 g cardboard per test	
Lid	Ecoinvent	0.003 g high density polyethylene per test	
Collar	Ecoinvent	0.002 g high density polyethylene per test	
Transport	Project	2.4 g transport per test	Transport from Singapore

Reagent 3			
	Project	1.9 mL per test	1.9 mL per test, assumed 3.7% Al. 5L pack 2,700 tests per pack.
			0.095 g Al, 1.8 g ultrapure water
Inner container	Ecoinvent	0.032 g low density polyethylene	
Cardboard box	Ecoinvent	0.11 g per test	
Lid	Ecoinvent	0.011 g high density polyethylene per test	
Collar	Ecoinvent	0.007 g high density polyethylene per test	
Transport	Project	2.1 g transport per test	Transport from Singapore
Reagent 4			
	Project	1.9 mL per test	1.9 mL per test, assumed 3.7% Al. 5L pack 2,700 tests per pack.
			0.095 g Al, 1.8 g ultrapure water
Inner container	Ecoinvent	0.032 g low density polyethylene	
Cardboard box	Ecoinvent	0.11 g cardboard per test	
Lid	Ecoinvent	0.011 g high density polyethylene per test	
Collar	Ecoinvent	0.007 g high density polyethylene per test	
Transport	Project	2.1 g transport per test	Transport from Singapore
Reagent 5			
	Ecoinvent	0.02 mL per test	0.02 mL per test, from MSDS 80% ethylene glycol and 4% methanol. 42ml foil pack, 2,000 tests per pack
			0.017 g Al, 0.003 g ultrapure water
Foil bag	Ecoinvent	0.005 g per test	
Box	Ecoinvent	0.0087 g cardboard per test	
Transport	Project	0.034 g per test	Transport from Singapore
Reagent 6			
	Ecoinvent	2.1 mL per test	2.1 mL per test, from MSDS 1% maleic acid. 1L pack, 500 tests per pack
			0.021 g Al, 2.07 g ultrapure water
Bottle	Ecoinvent	0.226 g polypropylene per test	
Cardboard box	Ecoinvent	0.18 g linerboard per test	

Instructions	Ecoinvent	0.01 g paper per test	
Transport	Project	0.62 g transport per test	Transport from Japan
Reagent 7			
	Ecoinvent	5.6 mL per test	5.6 mL per test, from MSDS 4% polyethylene glycol and 1% sodium N-lauroylsarcosinate. 10L pack, 1,800 tests per pack
			0.224 g Al, 5.37 g ultrapure water
Inner container		0.250 g low density polyethylene	
Lid	Ecoinvent	0.002 g high density polyethylene per test	
Collar	Ecoinvent	0.001 g high density polyethylene per test	
Transport	Project	6.03 g transport	Transport from Japan
Reagent 8			
	Project	0.5 mL per test	0.5 mL per test, assumed 3.7% Al, 5L pack, 10,000 tests per pack
			0.025 g Al, 0.475 g ultrapure water
Inner container	Ecoinvent	0.008 g low density polyethylene	
Cardboard box	Ecoinvent	0.03 g cardboard per test	
Lid	Ecoinvent	0.003 g high density polyethylene per test	
Collar	Ecoinvent	0.002 g high density polyethylene per test	
Transport	Project	0.54 g transport per test	Transport from Singapore
Reagent 9			
	Project	2 mL per test	2 mL per test, assumed 1% Al, 1L pack, 500 tests per pack
			0.021 g Al, 2.08 g ultrapure water
Bottle	Ecoinvent	0.25 g polypropylene per test	
Cardboard box	Ecoinvent	0.17 g linerboard per test	
Instructions	Ecoinvent	0.005 g paper per test	
Dye	Ecoinvent	0.024 ml per test	sodium sulfate used
Dye foil package	Ecoinvent	0.014 g per test	
Transport	Project	2.4 g transport per test	Transport from Japan

Table 4-23: Data assumptions for coagulation studies

	Data Source	Data Assumptions	Manipulation
Electricity			
Electricity usage analyser	AusLCI	85.85 Wh per test	Weighted average between Austin and Western hospitals. Victorian electricity used.
Electricity usage computers		19.32 Wh per test	Weighted average, and Victorian electricity used. Estimated 80W per hour
Electricity usage monitor		6.05 Wh per test	Weighted average, and Victorian electricity used. Estimated 25W per hour. Victorian electricity used.
Reagent 1			
	Project	71.05µL per test	Weighted average, 5% wastage. Assumed 3.7% AI
Box	Ecoinvent	0.03 g white linerboard per test	Weighted average between Austin and Western hospitals
Glass bottle	Ecoinvent	0.19 g glass per test	Weighted average between Austin and Western hospitals
HDPE lid	Ecoinvent	0.003 g high density polyethylene per test	Weighted average between Austin and Western hospitals
Tray	Ecoinvent	0.01 g polystyrene per test	Weighted average between Austin and Western hospitals
Instructions	Ecoinvent	0.01 g paper per test	Weighted average between Austin and Western hospitals
Transport	Project	0.174 g transport	Transport from USA

Reagent 2			
Calcium chloride	Project	50µL per test	Weighted average, 5% wastage. Assumed 3.7% AI
Box	Ecoinvent	0.001 g white linerboard per test	Weighted average between Austin and Western hospitals
Glass bottle	Ecoinvent	0.06 g glass per test	Weighted average between Austin and Western hospitals
HDPE lid	Ecoinvent	0.01 g high density polyethylene per test	Weighted average between Austin and Western hospitals
Tray	Ecoinvent	0.0004 g polystyrene per test	Weighted average between Austin and Western hospitals
Instructions	Ecoinvent	0.0033 g paper per test	Weighted average between Austin and Western hospitals
Transport	Project	0.086 g transport	Transport from USA
Reagent 3			
CA Clean	Project	21.05 µL per test	Weighted average, 5% wastage. Assumed 3.7% AI
Box	Ecoinvent	0.004 g white linerboard per test	Weighted average between Austin and Western hospitals
PE bottle	Ecoinvent	0.008 g polyethylene terephthalate per test	Weighted average between Austin and Western hospitals
Instructions	Ecoinvent	0.004 g paper per test	Weighted average between Austin and Western hospitals
Transport	Project	0.016 g transport	Transport from USA

Table 4-24: Data assumptions for biochemistry

Component	Data Source	Data Assumptions	Manipulation
Electricity			
Electricity usage analysers	AusLCI	16.23 Wh per test	Weighted average between Austin and Western hospitals. Victorian electricity used. Includes all pre-analytics.
Electricity usage reverse osmosis	AusLCI	5.25 Wh per test	Weighted average between Austin and Western hospitals. Victorian electricity used
Electricity usage sample storage	AusLCA	8.3 Wh per tests	Weighted average between Austin and Western hospitals. Victorian electricity used
Electricity usage computers	AusLCI	0.5 Wh per test	Weighted average between Austin and Western hospitals. Victorian electricity used. Estimated 80W per hour
Electricity usage monitor	AusLCI	0.16 Wh per test	Estimated 25W per hour. Victorian electricity used.
Consumables per group of tests			
Aliquot	Ecoinvent	1.59 g high density polyethylene	Weighted average between Austin and Western hospitals
Pipette	Ecoinvent	1.09 g polypropylene	Weighted average between Austin and Western hospitals
Recap cap	Ecoinvent	0.87 g polypropylene	Weighted average between Austin and Western hospitals
Na ⁺ , K ⁺ , Cl ⁻			
Reagent	Project	7.98 µL per individual test, 23.95 µL in total	Weighted average between Austin and Western hospitals Assumed 5 % AI, 1.198 µg AI, 22.75 µg ultrapure water

HCO₃⁻			
Reagent	Project	58.85 µL per test	Weighted average between Austin and Western hospitals (PEP 63 mmol/L, NADH 3 mmol/L, NaOH 0.08%) 1.26 µg Al, 57.59 µg ultrapure water
Plastic packaging	Ecoinvent	0.02 g high density polyethylene per test	Weighted average between Austin and Western hospitals
Cardboard packaging	Ecoinvent	0.02 g linerboard per test	Weighted average between Austin and Western hospitals
Glass packaging	Ecoinvent	0.02 g glass per test	Weighted average between Austin and Western hospitals
Creatinine			
Reagent	Project	42.39 µL per test	Weighted average between Austin and Western hospitals (ADP K ⁺ salt 1.3 mg/ml, NADP 2.13 mg/ml, glucose 101.2 mmol/L, NAC 25.5 mmol/L, PO ₄ 135 mmol/L, KOH 900 mmol/L, picric acid 38 mmol/L) 7.79 µg Al, 34.67 µg ultrapure water
Plastic packaging	Ecoinvent	0.34 g high density polyethylene per test	Weighted average between Austin and Western hospitals
Cardboard packaging	Ecoinvent	0.03 g linerboard per test	Weighted average between Austin and Western hospitals
Glass packaging	Ecoinvent	0.02 g glass per test	Weighted average between Austin and Western hospitals

Urea			
Reagent	Project	57.2 μL per test	Weighted average between Austin and Western hospitals (NADH 0.23 mmol/L, NaN_3 0.09%, alpha-ketoglurate 8.3 mmol/L, NaN_3 0.09%, TRIS 220 mmol/L, NADH 2.5 mmol/L, ADP 6.5 mmol/L) 0.437 μg Al, 56.76 μg ultrapure water
Plastic packaging	Ecoinvent	0.07 g high density polyethylene per test	Weighted average between Austin and Western hospitals
Cardboard packaging	Ecoinvent	0.01 g linerboard per test	Weighted average between Austin and Western hospitals
Glass packaging	Ecoinvent	0.01 g glass per test	Weighted average between Austin and Western hospitals
C-reactive protein			
Reagent	Project	160.91 μL per test	Weighted average between Austin and Western hospitals (Glycine 170 mmol/L, NaCl 100 mmol/L, EDTA 50 mmol/L, NaN_3 0.09%,) 3.44 μg Al, 157.47 μg ultrapure water
Plastic packaging	Ecoinvent	0.13 g high density polyethylene per test	Weighted average between Austin and Western hospitals
Cardboard packaging	Ecoinvent	0.01 g linerboard per test	Weighted average between Austin and Western hospitals
Glass packaging	Ecoinvent	0.01 g glass per test	Weighted average between Austin and Western hospitals

Table 4-25: Data assumptions for arterial blood gas

Component	Data Source	Data Assumptions	Manipulation
Electricity			
Analyser electricity usage	AusLCI	19.56 Wh per test	Weighted average between Austin and Western hospitals. Victorian electricity used.
Reagent 1			
Calibration 1	Project	66 µL per test	3.3 µg Al, 62.7 µL ultrapure water
Bottle	Ecoinvent	21 µg polypropylene per test	
Reagent 2			
Calibration 2	Project	22 µL per test	1.1 µg Al, 20.9 µL ultrapure water
Bottle	Ecoinvent	6 µg polypropylene per test	
Reagent 3			
Rinse	Ecoinvent	4.126 ml per test	1.440 ml per Cal 1, 3.509 ml per Cal 2, 1.459 ml per rinse, 0.967 ml per flush, 1.459 per sample. Ultrapure water used 4.126 mL ultrapure water
Bottle		0.578 g polypropylene per test	
Transport		4.704 g transport per test	Transport Poland

Table 4-26: Data assumptions for urinalysis

Component	Data Source	Data Assumptions	Manipulation
Electricity			
Analyser electricity usage	AusLCI	141.94 Wh per test	Victorian electricity used
Analyser electricity usage	AusLCI	0.12 Wh per test	Victorian electricity used
Electricity usage computers	AusLCI	17.68 Wh per test	Estimated 80W per hour. Victorian electricity used.
Electricity usage monitor	AusLCI	5.52 Wh per test	Estimated 25W per hour. Victorian electricity used.
Gases			
Compressed air	Ecoinvent	0.99 m ³ per test	75 L/min, 8 bar, Victorian electricity used
CO ₂	Ecoinvent	0.011 m ³ per test	50 L/hour, Victorian electricity used
Consumables			
Sample jar	Ecoinvent	12.88 g polystyrene	
Pipette	Ecoinvent	1.04 g polypropylene	
Plate	Ecoinvent	14.39 g polystyrene	
	AusLCI	6.84 g agar	50% by weight sugar used as proxy
Test tube	Ecoinvent	4.01 g polypropylene	

Table 4-27: Source of impacts per test (g CO₂e)

	ABG	C-Rp	U+E	FBE	Coagulation	Urinalysis
Swabs and ziploc bags	15.1	18.9	18.9	18.9	18.9	3.5
Glove	14.2	14.2	14.2	14.2	14.2	
Syringes	20.6					
Tube holder and collection tube		61.9	61.9	46.5	51.2	
PTS		0.8	0.8	0.8	0.8	0.8
Sample jar						68.4
Test reagents	2.4	0.3	0.9	11.0	0.4	
Test electricity	22.1	25.0	150.0	16.4	138.7	186.7
Test consumables		17.6	17.1			99.0
Test storage		9.4	9.4	9.4	9.4	
CO ₂						20.9
Compressed air						158.0

Table 4-28: Uncertainty analysis (95% confidence interval) for arterial blood gas

		Mean	Range (95% CI)	
Global warming	kg CO ₂ eq	0.074	0.070	0.080
Stratospheric ozone depletion	kg CFC11 eq	54.98E-9	45.21E-9	66.06E-9
Ozone formation,	kg NO _x eq	149.89E-6	132.42E-6	175.92E-6
Particulate matter	kg PM _{2.5} eq	9.51E-05	8.53E-05	0.000107
Human carcinogenic toxicity	kg 1,4-DCB	0.0023	0.0011	0.0094
Human non-carcinogenic toxicity	kg 1,4-DCB	0.031	0.013	0.069
Water consumption	m ³	0.001	-0.030	0.026

Table 4-29: Uncertainty analysis (95% confidence interval) for C-Reactive protein

		Mean	Range (95% CI)	
Global warming	kg CO ₂ eq	0.147	0.133	0.164
Stratospheric ozone depletion	kg CFC11 eq	813.60E-9	405.02E-9	1.49E-6
Ozone formation,	kg NO _x eq	249.66E-6	221.99E-6	284.67E-6
Particulate matter	kg PM _{2.5} eq	0.000157	0.000139	0.00018
Human carcinogenic toxicity	kg 1,4-DCB	0.0035	0.0017	0.0103
Human non-carcinogenic toxicity	kg 1,4-DCB	0.052	0.021	0.123
Water consumption	m ³	0.002	-0.041	0.034

Table 4-30: Uncertainty analysis (95% confidence interval) for coagulation profile

		Mean	Range (95% CI)	
Global warming	kg CO ₂ eq	0.233	0.218	0.249
Stratospheric ozone depletion	kg CFC11 eq	65.57E-9	61.44E-9	70.00E-9
Ozone formation,	kg NO _x eq	207.27E-6	194.23E-6	221.26E-6
Particulate matter	kg PM _{2.5} eq	0.00013	0.00013	0.00014
Human carcinogenic toxicity	kg 1,4-DCB	0.0029	0.0028	0.0031
Human non-carcinogenic toxicity	kg 1,4-DCB	0.049	0.046	0.053
Water consumption	m ³	0.002	0.001	0.002

Table 4-31: Uncertainty analysis (95% confidence interval) for FBE

		Mean	Range (95% CI)	
Global warming	kg CO ₂ eq	0.117	0.108	0.126
Stratospheric ozone depletion	kg CFC11 eq	68.65E-9	58.66E-9	82.70E-9
Ozone formation,	kg NO _x eq	279.99E-6	248.67E-6	313.48E-6
Particulate matter	kg PM _{2.5} eq	0.000157	0.000143	0.000174
Human carcinogenic toxicity	kg 1,4-DCB	0.0029	0.0014	0.0065
Human non-carcinogenic toxicity	kg 1,4-DCB	0.050	0.020	0.128
Water consumption	m ³	0.001	-0.035	0.033

Table 4-32: Uncertainty analysis (95% confidence interval) for U+E

		Mean	Range (95% CI)	
Global warming	kg CO ₂ eq	0.274	0.256	0.295
Stratospheric ozone depletion	kg CFC11 eq	865.25E-9	389.59E-9	1.73E-6
Ozone formation,	kg NO _x eq	253.40E-6	223.25E-6	292.37E-6
Particulate matter	kg PM _{2.5} eq	0.000159	0.000139	0.000183
Human carcinogenic toxicity	kg 1,4-DCB	0.0036	0.0017	0.0096
Human non-carcinogenic toxicity	kg 1,4-DCB	0.055	0.021	0.147
Water consumption	m ³	0.003	-0.037	0.037

Table 4-33: Uncertainty analysis (95% confidence interval) for urinalysis

		Mean	Range (95% CI)	
Global warming	kg CO ₂ eq	0.537	0.493	0.583
Stratospheric ozone depletion	kg CFC11 eq	62.0E-9	34.9E-9	110.6E-9
Ozone formation,	kg NO _x eq	345.7E-6	285.4E-6	424.7E-6
Particulate matter	kg PM _{2.5} eq	0.0010	0.0010	0.0011
Human carcinogenic toxicity	kg 1,4-DCB	0.0048	0.0026	0.0123
Human non-carcinogenic toxicity	kg 1,4-DCB	0.075	0.031	0.189
Water consumption	m ³	0.0033	-0.0390	0.0345

Chapter 5 Consequential and attributional LCA of diagnostic imaging

The carbon footprint of diagnostic imaging

The Lancet Regional Health – Western Pacific (2022), 24:100459

5.1 Abstract

5.1.1 Background

Pathology testing and diagnostic imaging together contribute 9% of healthcare's carbon footprint. Whilst the carbon footprint of pathology testing has been undertaken, to date, the carbon footprint of the four most common imaging modalities is unclear.

5.1.2 Methods

We performed a prospective life cycle assessment at two Australian university-affiliated health services of five imaging modalities: chest X-ray (CXR), mobile chest X-ray (MCXR), computerised tomography (CT), magnetic resonance imaging (MRI) and ultrasound (US). We included scanner electricity use and all consumables and associated waste, including bedding, imaging contrast, and gloves. Analysis was performed using both attributional and consequential life cycle assessment methods. The primary outcome was the greenhouse gas footprint, measured in carbon dioxide equivalent (CO₂e) emissions.

5.1.3 Finding

Mean CO₂e emissions were 17.5 kg/scan for MRI; 9.2 kg/scan for CT; 0.8 kg/scan for CXR; 0.5 kg/scan for MCXR; and 0.5 kg/scan for US. When expressed as emissions per additional scan (results of consequential analysis) impacts were 1.1 kg/scan for MRI; 1.1 kg/scan for CT; 0.6

kg/scan for CXR; 0.1 kg/scan for MCXR; and 0.1 kg/scan for US, due to emissions from standby power being excluded.

5.1.4 Interpretation

Clinicians and administrators can reduce carbon emissions from diagnostic imaging, firstly by reducing the ordering of unnecessary imaging, or by ordering low-impact imaging (X-ray and US) in place of high-impact MRI and CT. Secondly, whenever possible, scanners should be turned off to reduce emissions from standby power. Thirdly, high utilisation rates of scanners will mitigate the impacts caused by standby power.

5.1.5 Funding

National Health and Medical Research Council, Australia (NHMRC) PhD scholarship

5.2 Research in context

5.2.1 Evidence before this study

We searched the Scopus from its inception up to August 15, 2021, using the terms (“life cycle assessment” OR LCA OR “greenhouse gas footprint” OR “GHG footprint” or “carbon footprint”) AND (“computerised tomography” OR “magnetic resonance imaging” OR ultrasound OR x-ray). Only two studies using life cycle assessment to determine the carbon footprint of diagnostic imaging were found. The first used both estimated examination times and power usage to calculate the carbon footprint of ultrasound, computerised tomography and magnetic resonance imaging rather than undertaking actual measurements, meaning the results are not accurate. The second was an attributional life cycle assessment that determined the carbon footprint of magnetic resonance imaging was 22.4 kg carbon dioxide equivalents.

5.2.2 Added value of this study

This is the first study to calculate the carbon footprint using life cycle assessment of the five most common imaging modalities. Additionally, it is the first study to perform both attributional and consequential life cycle assessment of diagnostic imaging.

5.2.3 Implications of all the available evidence

The study identifies three main ways that clinicians and administrators can reduce the carbon impacts of diagnostic imaging. 1) By reducing unnecessary imaging, or by changing imaging to a lower carbon modality; 2) By turning scanners off when they are not required rather than leaving them in standby; 3) By ensuring existing scanners have high utilisation rates.

5.3 Introduction

In 2020-21, many of the world's major economies made pledges to become carbon neutral between 2050 and 2060, including interim carbon emission reduction targets by 2030.¹ Furthermore, in August 2021 the Intergovernmental Panel on Climate Change (IPCC) released the first part of its Sixth Assessment, which states emphatically that globally we need to achieve net-zero carbon emissions as quickly as possible to stabilise global warming.² Decarbonising the economy to achieve net-zero emissions necessarily includes healthcare. Globally, healthcare is responsible for 4.4% of annual greenhouse gas emissions³, with emissions from individual countries such as UK, Australia and the US being higher than the global average (5%, 7% and 10% respectively).⁴⁻⁶ According to the UK's National Health Service (NHS), buildings currently only contribute approximately 12% to the NHS's total carbon footprint, with approximately 50% arising from pharmaceuticals and procurement.⁴ Assuming other health services are similar, rather than focusing on buildings, which will see mitigation occurring naturally from market-based mechanisms as energy systems move from fossil fuels to renewable energy, a larger reduction in healthcare's carbon footprint will be achieved by changes to clinical care.⁷

A recent Australian study by Malik et al investigating the carbon footprint caused by the whole health system of the state of New South Wales found that pathology and diagnostic imaging together accounted for approximately 9% of this healthcare footprint⁸, with the demand for imaging services per 100 people in Australia increasing by 9% over a five-year period.⁹ The carbon impacts of pathology testing have been reported^{10,11}, but to date there has not been a detailed analysis of the carbon impacts of the most commonly used diagnostic

imaging modalities using a standard methodology. Yet imaging is ubiquitous in healthcare globally. High rates of overuse and inappropriate use for screening and diagnosis have been demonstrated, including in low and middle-income countries¹², despite underuse and lack of access remaining problems in low-income settings.¹³

To support the more appropriate use of imaging, practitioners and policymakers need comparative data on different, commonly used imaging modalities, including data on the carbon emissions associated with their use. In this study, therefore, we aimed to estimate the carbon footprint of five common imaging modalities within an Australian public hospital setting: computerised tomography (CT); magnetic resonance imaging (MRI); ultrasound (US); chest X-ray (CXR); and mobile CXR (MCXR) in a “cradle to grave” life cycle assessment. Life cycle assessment (LCA) is a method for estimating the environmental impacts of products and services over their whole life cycle (raw material extraction, material processing, manufacture, use and end-of-life).¹⁴

5.4 Methods

5.4.1 Overview of methods

We used process-based LCA to undertake both attributional (ALCA) and consequential (CLCA) analyses, in accordance with the International Organization for Standardization (ISO) standard 14040:2000.¹⁴ Attributional and consequential LCA methods provide complementary perspectives of the carbon impacts of imaging.

In the case of imaging, ALCAs determine what share of the total impact from operating a given modality can be attributed to a single scan (mean impact), helping to identify the sources and magnitude of operating diagnostic imaging as a whole. By contrast, CLCAs only model the changes, such as a scanner moving from standby to active, that result from undertaking one additional (or fewer) scans within an already operational system (Box 5-1).¹⁵

Attributional impact is given by:

$$W_{ALCA} = W_O + (W_S \cdot T_S) / T_O$$

where W_{ALCA} is total attributional impact measured in Watts, W_O is Watts consumed when operating, W_S is Watts consumed in standby, T_S is total standby time and T_O is total operational time.

In an example where the operational power consumption of a scanner is 500W per hour, standby power is 100W per hour, and the scanner is only operational for 2 hours per day, with it being in standby the rest of the time, the attributional impact per hour of operation is:

$$1,600 \text{ W} = 500 + (100 \times 22) / 2$$

In a consequential analysis, the proportion of standby energy is not included, as the scanner is sitting in standby regardless of whether it is used or not. The consequence of using the scanner, therefore, is only the difference between standby and operational power, and hence the consequential impact per hour of operation is 400W (500W – 100W).

Box 5-1: Difference between attributional and consequential LCA

5.4.2 Study setting

We assessed the carbon footprint of four imaging modalities (CT, US, CXR, MCXR) at St George Hospital, a 653-bed tertiary referral hospital in metropolitan Sydney, Australia. Chest X-rays were chosen as they were the most commonly performed X-ray during the study period (338 CXRs compared to 261 combined for all other body imaging). The mobile X-ray scanner was located in the intensive care unit. Approval for this project was obtained from the South Eastern Sydney Local Health District (SESLHD) Human Research Ethics Committee: 2020/ETH03343. An error occurred from the power logger during the data collection of the MRI scanner at St George Hospital. A COVID-19 outbreak in Sydney prohibited further access to St George to repeat the data collection. The carbon footprint of MRI imaging, therefore, was undertaken at Footscray Hospital in Melbourne, Australia a 290-bed acute teaching hospital; ethics approval was waived by the Western Health Ethics Committee.

5.4.3 Study design

The functional unit of the ALCA is a CT, MRI, US, CXR or MCXR, in an Australian public hospital setting, while the functional unit of the CLCA is an additional CT, MRI, US, CXR or MCXR, in an Australian public hospital setting. The system boundary, defining what is included and excluded by the study, is shown in Figure 5-1. Capital infrastructure, including the manufacture of scanners, was excluded as environmental impacts are amortised over long periods of time and are typically small.

We additionally chose to exclude the energy used by both the hospital's HVAC (heating, ventilation, and air conditioning) system and the room-specific air conditioning energy required to maintain the CT and MRI scanner rooms at 18°C, so as to make the results

generalisable irrespective of geographic location and time of year. This was based on our previous study in which we calculated the HVAC energy requirements for a hospital ward in two different geographic and climatic locales, with the study showing that HVAC energy varied greatly due to both location and time of year.¹⁶ Furthermore, any additional cooling over and above what is provided by the hospital's HVAC system is similarly dependent on the set temperature of the hospital's HVAC system (a lower set temperature requires less additional cooling), making it difficult to properly attribute impacts for cooling between the hospital's HVAC and any additional cooling.

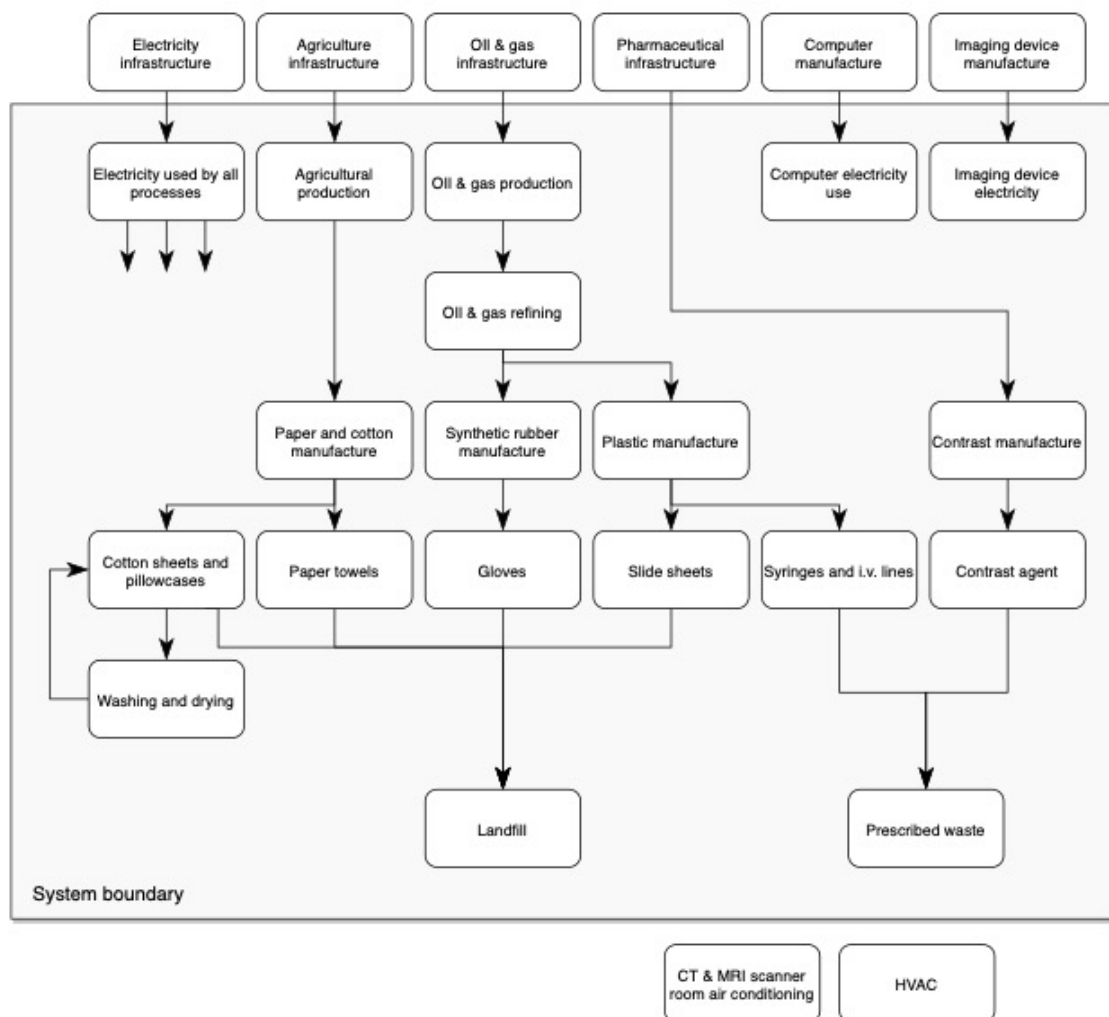


Figure 5-1: System boundary of study inclusions and exclusions

5.4.4 Study outcomes

The primary outcome was carbon emissions in kilogram carbon dioxide equivalents (kg CO₂e).

5.4.5 Data collection

All data were collected between 10 February 2021 and 30 August 2021. The electrical power consumed by each modality was collected, as was the weight and composition of materials used by patients and staff such as sheets, gloves, gowns, contrast, needles and syringes (consumables) (Supplementary materials Table 5-3). These materials were weighed with a Satrue KA-1000 scale (resolution 0.5g). Usage of consumables was estimated by the radiographers undertaking the scans and X-rays. Three-phase electrical power (400 volts) was measured sequentially during the collection period for each of the CXR, CT and MRI imagers (1.5 Tor) for a period of approximately two weeks by a Hioki PW3365-20 power meter (Hioki, Nagano Japan), using a sampling rate of one sample every 15 seconds. Single phase electrical power (230 volts) measured by a Watts Up Pro power meter (Vernier, Oregon USA) connected to Logger Pro 3.14.1.0 (Vernier) with a sample obtained every 30 seconds for a period of two weeks for US, and for four days for MCXR. Power consumption of computers and monitors in the imaging control rooms was obtained from manufacturers' published data.

5.4.6 Data analysis

To calculate power usage for CT, MRI, US and CXR, power usage was divided into two states: active power (including positioning a patient or scanner, and imaging the patient), and standby power for all other times. Additionally, two distinct standby power states were identified for CT, MRI and US imaging devices; passive standby, when the scanner was in a

deep low-power mode overnight, and active standby, for the time the imager was in-between patients during operational hours (Supplementary materials Figure 5-3).

For the ALCA, the average power consumed by each modality was estimated as the sum of the average active power (per minute for US, CT, and MRI, or per image for CXR) added to its respective proportion of standby power on a per minute basis, including computers and monitors. For the CLCA, power usage of scanners was estimated as being the difference between the average active power and active standby power per minute. The impacts of computers and monitors were not included in the CLCA analysis, as these were running regardless of an image being ordered.

As the MCXR operates on battery power, two charging modes were identified: active charging, when the mobile unit was first plugged back into the charger after performing imaging, and trickle charging when the unit's battery was fully charged. For the ALCA, power usage per MCXR was estimated as the sum of the total power divided by the total number of MCXRs performed. For the CLCA, power usage was estimated as the difference per minute in active and passive charging, multiplied by the time per MCXR, calculated as being the total time unplugged from the charger divided by the total number of MCXRs.

Carbon emissions from all parts of the life cycle were modelled using SimaPro 9.0.0.27 (PRé Sustainability, Amersfoort the Netherlands). Background data on the environmental impacts of materials and energy used, such as plastics and electricity, was obtained from the attributional and consequential versions of the ecoinvent 3.5 database (ecoinvent, Zurich Switzerland).¹⁷ Australian electricity generation mixes and emission factors are available in

Supplementary materials Table 5-4. The impact assessment was modelled using the ReCiPe 2016 (H) impact assessment model.¹⁸ Details of the LCA processes and data sources, including conversion factors, are provided in Supplementary material 5.8.1.

5.5 Results

All imaging devices spent considerably more time in standby mode compared to active mode (Table 5-1), ranging from 67% time in standby for MRI through to 99·6% for X-ray. Mean examination time was longest for MRI imaging at almost 27 minutes, followed by US (20 min), CT (8·4 min) and CXR (1·5 min). MCXR's time per scan was 6·9 min, as this included all the time the scanner was being moved between patients. So as to focus primarily on the four most common modalities, further results for the MCXR can be found in the Supplementary materials Table 5-5.

ALCA power consumption was higher than both mean power consumption (total power divided by total time in a given mode) and CLCA power consumption due to the high proportion of time spent in standby for all modalities (Table 5-1). Whilst an MRI scanner has the highest mean power consumption per minute of operation in all modes (active and standby) of all the imaging modalities due to its superconducting magnets needing to be constantly cooled to approximately -270°C by liquid nitrogen, it had a lower attributional power consumption compared to the CT scanner. This difference was due to the CT scanner being in standby mode for considerably longer than the MRI scanner (92% of total time vs. 67%), resulting in each active minute of the CT scanner having a greater number of standby minutes attributed to it.

Table 5-1: Electrical power consumed, and time spent in each operating mode, with calculated attributional (ALCA) and consequential (CLCA) power use.

	Total time spent - hrs	Total scans	Average scans per week	Average time (min) per scan (95% CI)	Total power kWh	Average power Wh/min	ALCA power Wh/min	CLCA power Wh/min
CT Active	28.2	399	200	8.4±0.2	278	164	939	64
CT Active standby	145.6				927.5	106		
CT Passive standby	162				280.7	29		
MRI Active	110.5	245	122	26.7±2.5	1749.3	265	605	91
MRI Active standby	63.4				660.1	174		
MRI passive standby	163.1				1473.6	151		
US Active	48.4	146	69	19.9±2.1	25.5	9	23	0.85
US Active standby	69.2				33.4	8		
US passive standby	237.6				5.2	0.4		
	Total time spent - hrs	Total scans		Average time (min) per CXR (95% CI)	Total power - kWh	Average power Wh/CXR	ALCA power Wh/CXR	CLCA power Wh/CXR
CXR Active	1.2	47	24	1.5±0.3	0.7	10	171	5
Total X-ray Standby	321.3				114	6		

For carbon emissions, focusing firstly on ALCA, MRI and CT had the highest emissions of the imaging modalities at 17.5 and 9.2 kg CO₂e per scan respectively (Table 5-2, Figure 5-2), with the majority of this impact (MRI - 94%, CT - 91%) resulting from electricity use (Figure 5-2). For MRI, the impact of consumables came predominantly from the cotton drawsheets (0.7kg CO₂e, or 4% of total impact), whilst for the CT it originated primarily from the contrast tubing, the cotton sheet and pillowcase (both 0.4 kg CO₂e, 4%) and the contrast tubing (0.3 kg CO₂e, 3%)(Supplementary materials Table 5-6). US and CXR had similar carbon impacts (0.76 and 0.53 kg CO₂e respectively). Notably, whilst the dominant source of emissions for US (as for MRI and CT) is electricity (87%), the major source of impacts for the CXR is the washing and drying of the cotton sheet and pillowcase (0.67 kg CO₂e, 88%), with electricity only contributing 0.02 kg CO₂e, or 3% of the total impact.

Carbon emissions for MRI, CT and US were 84% to 94% lower in CLCA compared to ALCA, due to the exclusion of standby power in the calculated impact. MRI and CT remained the imaging modalities with the largest impacts (1.1 and 1.09 kg CO₂e respectively). For CXR, the impact fell only slightly from 0.8 to 0.6 kg CO₂e compared to ALCA, as the main source of impact that originated from sheet and pillowcase laundering remained the same.

Table 5-2: Carbon emissions for each imaging modality, kg CO₂e/scan

	Attributional LCA per scan (mean) Total CO ₂ e/No.of tests ordered (i.e. average)				Consequential LCA per additional scan Additional CO ₂ e used for one more scan			
	MRI	CT	CXR	US	MRI	CT	CXR	US
	27 min	8 min	2 min	20 min	27 min	8 min	2 min	20 min
Consumables	1.0	1.1	0.74	0.07	0.8	1.02	0.58	0.084
Electricity	16.5	8.1	0.02	0.46	0.3	0.07	0.002	0.002
Total	17.5	9.2	0.76	0.53	1.1	1.09	0.58	0.09

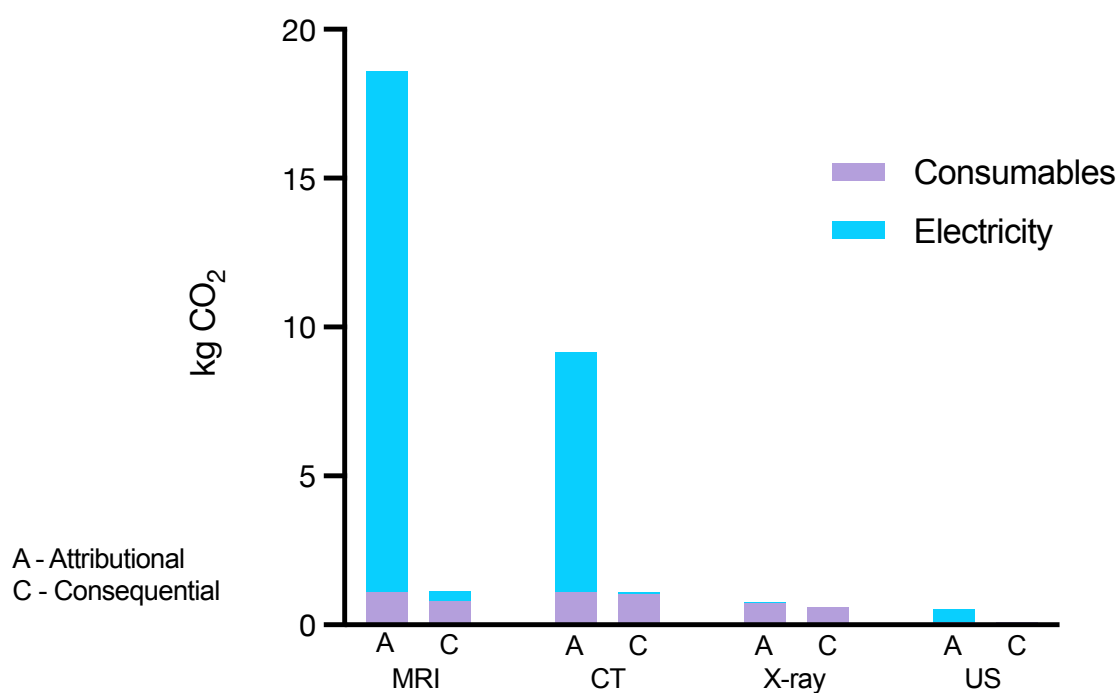


Figure 5-2: Carbon emissions from electricity and consumables (in kg CO₂e) of imaging modalities, as estimated by ALCA and CLCA

5.6 Discussion

5.6.1 Statement of principal findings

We report for the first time the life cycle carbon footprint of all major diagnostic imaging modalities. Magnetic resonance imaging (MRI) and computerised tomography (CT) have large carbon footprints compared to the “traditional” imaging modalities of X-rays and ultrasound. This finding was observed when emissions were calculated per scan (ALCA) and when calculated per additional scan (CLCA), but was most marked using the attributional approach (ALCA), with high emissions per scan for MRI and CT (MRI – 17·5 kg CO₂e, CT – 9·2 kg CO₂e,) compared to chest X-ray and ultrasound (0·76 and 0·53 kg CO₂e respectively). As a comparison, a MRI scan has equivalent carbon emissions to driving a new European car 145km, a CT scan 76 km, a chest X-ray 6 km, and a US scan 4 km.¹⁹ The majority of MRI’s and CT’s large carbon footprints are due to electricity use, and in particular, their standby power use.¹⁷

Emissions calculated per additional scan (CLCA approach) were smaller in absolute magnitude, particularly for MRI and CT, due to the effect of excluding standby power, but the same pattern remained.

5.6.2 Strengths and limitations

A key strength of our study is that we used process-based LCA to measure carbon emissions released by all energy and materials consumed in the process of imaging, as defined by our system boundary. Process-based LCA provides an accurate estimate of emissions at the level of individual healthcare activities, in this case imaging modalities, which allows for these

activities to be compared, and for targeted mitigation strategies to be developed. As such, our study cannot be directly compared to LCA studies which estimate carbon emissions of the healthcare sector, or parts of it, by using economic models (Environmental Input-Output LCA).

A further strength is that our study calculated emissions per scan and per additional scan (using ACLC and CLCA approaches, respectively). The benefit of providing both measures is the insights afforded by these complementary data. ALCA provides information on the current contribution from each type of imaging to healthcare's carbon footprint, whilst CLCA estimates the actual change in emissions that will occur from either ordering one more or one less additional scan.

Our study has limitations. We excluded the environmental impact of the manufacture of radiological equipment due to the amortised impact per scan being known to be very small²⁰, and because it cannot be estimated with precision without detailed manufacturer's data about the weights and composition of all of a scanner's components (generally not available for commercial in confidence reasons). Nonetheless, to explore this issue we used publicly available data (Supplementary material 5.8.2) together with the usual duration of a machine life of 10 -15 years to estimate this impact. We estimate an impact of manufacturing in the range 0.00007 to 0.043 kg CO₂e per scan, resulting in no important changes to our results. Another limitation is that we only investigated a single scanner of each modality in a public hospital setting in one country. Large differences in scanner energy consumption have been reported, due to both differences in actual scanners as well as usage patterns.^{21,22} Because of this variability, absolute levels of emissions at other sites may differ. Our study, however,

does show their expected relative magnitude. We therefore recommend that further studies be undertaken to measure a range of scanners of varying ages, sizes, and manufacturers, as well as in different settings (e.g. private radiology, general hospital, or emergency department).²² Lastly, we did not include the cooling energy required to keep CT and MRI scanners in a cool ambient temperature room as it is heavily dependent on external temperature and humidity, and difficult to separate from the overall building energy demand of the hospital. The effect of this omission, however, is only to underestimate the total environmental impact of these imaging modalities.

5.6.3 Findings in context

There have been only a few dozen process-based LCA studies of specific healthcare items or activities in the world. Only one study calculated the carbon impact of common imaging modalities, finding that the attributional carbon footprint of an MRI was 22.4 kg CO₂e, similar to our 17.9 kg CO₂e.²² There are other studies that have focussed primarily on the power consumption of scanners, with our study's results on consumption falling broadly in line in comparison to these other studies.²³

Of note, our results should draw attention to the carbon impacts of imaging in comparison to other carbon hotspots which have received much attention. For example, anaesthesia is a recognised carbon hotspot²³, yet one MRI has approximately equivalent emissions to one gaseous general anaesthetic.²⁴ Thus far, however, the carbon emissions from imaging have received little attention.

5.6.4 Implications for policy and practice

There are three main opportunities to reduce the carbon emissions associated with diagnostic imaging. Firstly, imaging is currently often overutilised in clinical care. As an example, a review investigating the overuse of testing in Australia found studies showing 34–62% of computed tomography scans of pulmonary arteries in suspected pulmonary thromboembolism, 36–40% of imaging tests in patients with low back pain, and 54% of imaging tests in patients with abdominal pain were unnecessary.²⁵ There are therefore likely opportunities for clinicians to reduce their use of low-value scans, or to substitute high-carbon modalities for low ones, to substitute high-carbon modalities for low ones, such as using US in place of MRI when it is clinically appropriate to do so. For example, US is clinically preferred over MRI for shoulder impingement/rotator cuff symptoms²⁶, and echocardiography has advantages over cardiac MRI when investigating asymptomatic patients in the context of inherited heart conditions.²⁷ Clinicians may identify further opportunities to evaluate whether less intensive imaging may provide better health outcomes with less environmental impact, with further research measuring health outcomes, costs and environmental impacts of low carbon clinical care options being urgently needed to give clinicians confidence to change their practice when it is clinically appropriate to do so.

Secondly, for all imaging modalities, the difference between ALCA and CLCA reveals the large impacts of standby energy use, when a machine is on but not being utilised, with this also noted by other authors.²⁸ Especially for hospitals where machines are required to be on 24/7 for emergency use, this standby energy use represents the unavoidable impact of operating a machine. Impacts can, however, be decreased by reducing the number of machines that are on to match demand, hence increasing the utilisation rates of the operating machines. As an

example, if the CT scanner in our study spent the same amount of time being utilised as the MRI scanner (8% vs. 33% active scanning time), then its attributional power use would fall from 939 to 237 Wh/min. Overall, further reductions could be seen if scanners were turned off at times of low demand when less elective healthcare is being performed, such as overnight, at weekends or on holidays, especially if there are duplicates of equipment allowing one to be on for emergency use. Whilst MRI scanners cannot be turned off as the magnet needs to be constantly cooled, this is possible for all other scanners.

Thirdly, manufacturers could seek to reduce the power used by scanners in different standby modes, and similarly, hospital administrators could include standby power usage as a decision criterion when seeking to purchase new equipment.

Lastly, given the unavoidable environmental cost of operating particularly MRI and CT scanners, it would be preferable to ensure high utilisation rates of existing scanners in a locale before ordering additional scanners. As an example, in 2019 Australia was second only to Japan in the number of CT scanners per capita (70 scanners per million population), an 85% increase since 2015. The utilisation rate of each of these scanners, is 2,020 scans per year, approximately one third of the USA's 6,199 scans per year, suggesting there is an opportunity for greater utilisation, and hence a reduced environmental impact.²⁹

As the primary carbon impact for imaging results from electricity use, it could be considered that the increases seen in low carbon renewable energy entering electricity grids mean that better utilisation of scanners and reduced ordering of imaging does not need to occur. There

are, however, currently few countries or states that have 100% renewable energy, with renewable energy making up only 28% of global electricity generation.³⁰

Given the need for rapid decarbonisation, reducing the carbon impact from imaging will require input from clinicians to both only order imaging when necessary, and where possible to order X-rays or ultrasound in preference to MRI or CT imaging; from administrators in choosing when to purchase new scanners, and to choose scanners that have low standby power usage; and that non-MRI scanners are turned off wherever possible out-of-hours.

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5.8 Supplementary materials

Table 5-3: Consumables and carbon emissions (CO₂e) as estimated for ALCA and CLCA for each imaging modality

	Weight (g)	Material	ALCA kg CO ₂ e	CLCA kg CO ₂ e
CT Consumables				
Gloves - 8 per patient	26.4	Nitrile rubber	0.06	0.06
Rediwipe®	14	Paper	0.06	0.06
Slide sheet, 2 per patient for 50% of patients (proportion of 100 uses + washing and drying)	172	Polypropylene	0.2	0.2
Cotton sheet (proportion of 200 uses) + washing and drying, 50% of patients	417	Cotton	0.3	0.2
Cotton pillowcase - (proportion of 200 uses) + washing and drying	72.5	Cotton	0.05	0.04
10 mL syringe	8	Polypropylene, rubber	0.02	0.02
23G needle	1	Polypropylene, steel	0.005	0.005
Alcohol swab	1	Alcohol, viscose fibre	0.003	0.003
Contrast tubing	80	PVC	0.3	0.3
Contrast - 270 mg/kg, 75kg patient	20.3	Iodine	0.1	0.1
MRI consumables				
Gloves - 8 per patient	26.4	Nitrile rubber	0.06	0.06
Rediwipe®	14	Paper	0.06	0.06
Slide sheet, 1 per patient for 20% of patients (proportion of 100 uses + washing and drying)	34	Polypropylene	0.03	0.03
Cotton sheet (proportion of 200 uses) + washing and drying	1040	Cotton	0.7	0.5
Cotton pillowcase - (proportion of 200 uses) + washing and drying	140	Cotton	0.1	0.07
10 mL syringe	8	Polypropylene, rubber	0.02	0.02
23G needle	1	Polypropylene, steel	0.005	0.005
Alcohol swab	1	Alcohol, viscose fibre	0.003	0.003
Contrast - 0.1 mmol/kg, 75kg patient	1.17	Gadolinium	0.2	0.3
US consumables				
Gloves - 2 per patient	7	Nitrile rubber	0.01	0.01
Gel - 14% propylene glycol	20	Propylene glycol, deionised water	0.01	0.01
Tissue paper	8	Tissue paper	0.04	0.06

CXR consumables				
Gloves - 2 per patient	7	Nitrile rubber	0.01	0.01
Rediwipe®	14	Paper	0.6	0.6
Cotton sheet (proportion of 100 uses) + washing and drying	814	Cotton	0.6	0.4
Cotton pillowcase - (proportion of 100 uses) + washing and drying	145	Cotton	0.1	0.07
MCXR consumables				
Gloves - 2 per patient	7	Nitrile rubber	0.01	0.01
Rediwipe®	14	Paper	0.6	0.6

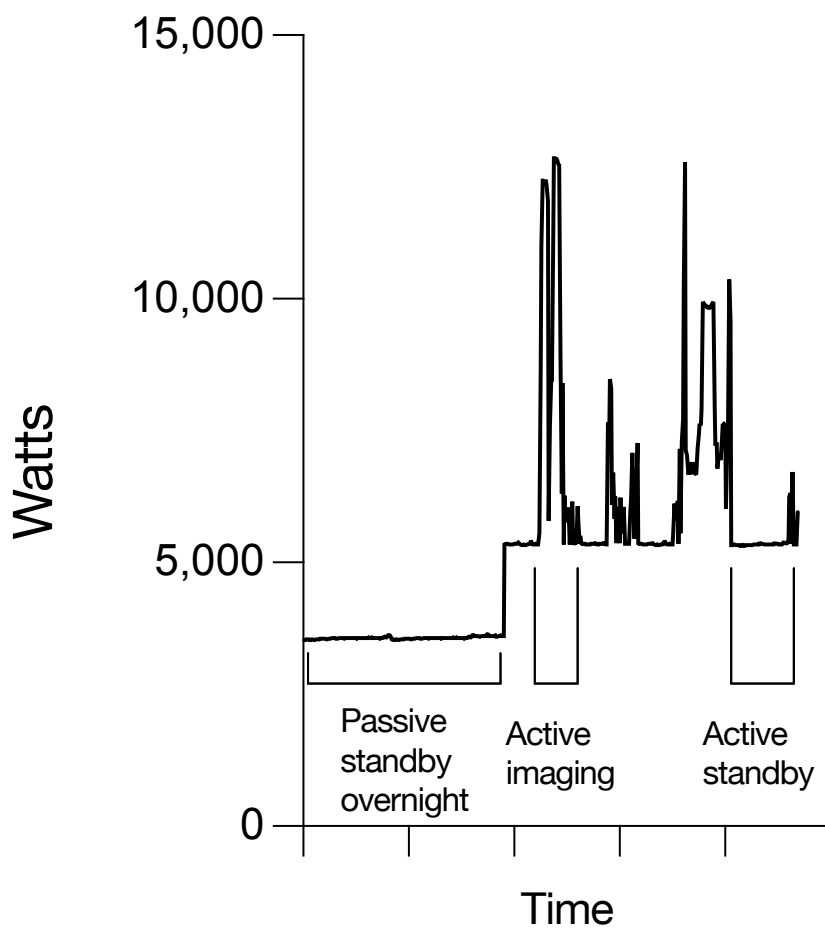


Figure 5-3: Example of scanner showing deep standby (overnight), active standby, and active states

Table 5-4: Generation source and emission factors for Australian attributional and consequential electricity, from ecoinvent 3.5

Attributional electricity 1.02 kg CO ₂ e / kWh		Consequential electricity 0.127 kg CO ₂ e / kWh	
Black coal	43.9%	Solar	85.9%
Brown coal	22.6%	Gas	7.4%
Natural gas	17%	Wind	4.9%
Hydro	6.4%	Coal	2.0%
Wind	5.4%		
Solar	2.6%		
Bioenergy	1.8%		

Table 5-5: MXCR electrical power consumed, and time spent in each operating mode, with calculated attributional (ALCA) and consequential (CLCA) power use

	Total time spent - hrs	Total scans	Average time (min) per CXR (95% CI)	Total power - kWh	Average power Wh/CXR	ALCA power Wh/CXR	CLCA power Wh/CXR
MCXR	6.3	559	6.9			395	4
MCXR - charging	55.1			14	4		
MCXR - trickle charging	38.6			8	4		

Table 5-6: Source of carbon emissions per average scan for each imaging modality, in kg CO₂e

Average scan time	Attributional					Consequential				
	MRI 27 min	CT 8 min	CXR 2 min	US 20 min	MCXR	MRI 27 min	CT 8 min	CXR 2 min	US 20 min	MCXR
Gloves and wipes	0.06	0.06	0.07	0.05	0.07	0.06	0.06	0.08	0.07	0.08
Ultrasound gel				0.01					0.01	
Contrast	0.2	0.11				0.02	0.11			
Contrast equipment	0.03	0.34				0.03	0.34			
Slide sheet	0.03	0.25				0.07	0.25			
Laundered cotton	0.8	0.34	0.67			0.62	0.26	0.50		
Electricity	16.5	8.1	0.02	0.46	0.40	0.3	0.06	0.002	0.002	0.0005
Total	17.6	9.2	0.76	0.53	0.47	1.1	1.09	0.58	0.09	0.08

5.8.1 Process life cycle assessment

Process life cycle assessment uses a series of interlinked processes to model the system under investigation. Each process consists of inputs (energy, raw materials, or outputs from other processes), outputs (what the process produced) and emissions to the environment (land, water or air). Multiple processes are then interlinked together to make a process tree, with a typical process tree consisting of hundreds up to thousands of individual processes, including resource extraction, manufacture, transport, use and end-of-life.

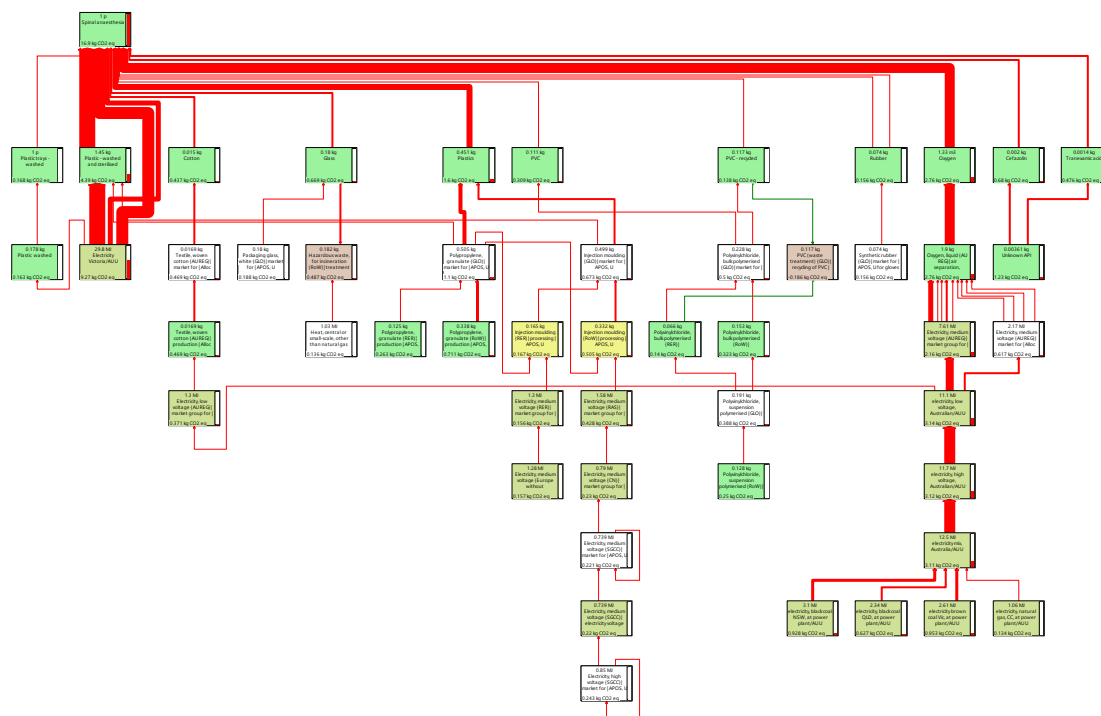


Figure 5-4: Example of process tree for spinal anaesthesia, in kg CO₂e. The tree has been heavily truncated to allow for easy visualisation of the main impacts.

It would be both impractical and prohibitively expensive to determine all the inputs and outputs of processes in a process tree every time an LCA is undertaken. For this reason, studies collect as much *foreground* data, such as the electricity used by a scanner, as possible

to reduce uncertainty. *Background* data, such as for electricity generation or plastic manufacture, are then used for the remaining processes.

Large international databases are routinely used to provide background data. As an example, the Swiss-based ecoinvent used in this study has more than 10,000 individual processes consisting of both attributional and consequential datasets. Databases typically have data available at the national, regional, or international level for individual processes (e.g steel manufactures in a blast furnace as an Australia, European, or global average).

All the modelling was performed in specialist life cycle assessment software called SimaPro. SimaPro calculates all the emissions of a given chemical to the environment and converts them to a reference unit using conversion factors contained in an impact assessment method. As an example, the reference unit for greenhouse gases is kg of carbon dioxide, given as carbon dioxide equivalents (CO₂e), with 1 kg of the gaseous anaesthetic being equivalent to 1,790 kg CO₂e, while 1kg of the anaesthetic sevoflurane is equivalent to 216 kg CO₂e. This study used an impact assessment method called ReCiPe,(2016), which itself uses the Intergovernmental Panel of Climate Change's (IPCC) conversion factors for greenhouse gases.

5.8.2 Estimation of impact of scanner manufacture

- the average weight of a scanner, and magnet for a MRI, from manufacture's datasheets
 - CT scanner – average gantry weight 2,030 kg (from <https://www.oncologysystems.com/resources/ct-scanner-simulator-guides/philips-ct-scanners-comparison-chart>)
 - 1.5 Tor MRI scanner – Gantry weight 4,600 kg, magnet weight 3,863 kg (from <https://www.philips.com.au/healthcare/product/HC781341/ingenia-15t-mr-system#documents>)
 - X-ray machine – 900 kg (from <https://www.orveemedical.com/x-ray-machine.html>)
 - Mobile X-ray machine – 490 kg including 9 12v batteries (from <https://www.somatechnology.com/pdfFiles/GE-AMX-IV-Plus-Portable-X-ray-Machine.pdf>)
 - Ultrasound machine – 140 kg (from <https://www.ultrasoundsupply.com/products/ultrasound-machines/ge-ultrasound/ge-logiq-e9/>)
- an estimate of the impact of the MRI magnet of 1,714 kg CO₂e per ton of NbTi wire.
based on *A comparative life-cycle assessment between NbTi and copper magnets* (2004) by Hartikainen et al (IEEE Transactions on Applied Superconductivity 14(2):1882-1885)
- the remaining weight of the scanner being estimated as being 60% steel (1.67 kg CO₂e per kg, from ecoinvent) and 40% copper (3.99 kg CO₂e per kg, from ecoinvent) as a conservative estimate, based on *Environmental impact of cardiac imaging tests for the diagnosis of coronary artery disease* (2011), by Marwick and Buonocore (Heart 14(97):1128-1131)

- the usual life of a scanner being 10 years, based on the radiology's department records showing that a scanner lasts between 10-15 years before it is replaced

Chapter 6 Unnecessary pathology testing and carbon emissions

Carbon emissions and hospital pathology stewardship: a retrospective cohort analysis

Accepted and in press, Internal Medicine Journal, accepted 13 November 2021

6.1 Abstract

6.1.1 Background

As healthcare is responsible for 7% of Australia's carbon emissions, it was recognised that a policy implemented at St George Hospital, Sydney to reduce non-urgent pathology testing to two days per week and on other days only if essential, would also result in a reduction in carbon emissions. The aim of the study was to measure the impact of this intervention on pathology collections and associated carbon emissions and pathology costs.

6.1.2 Methods

The difference in the number of pathology collections, carbon dioxide equivalents (CO₂e) for five common blood tests, and pathology cost per admission were compared between a 6-month reference period and 6-month intervention period. CO₂e were estimated from published pathology CO₂e impacts. Cost was derived from pathology billing records. Outcomes were modelled using multivariable negative binomial, generalised linear, and logistic regression.

6.1.3 Results

In total, 24,585 pathology collections in 5,695 patients were identified. In adjusted analysis, the rate of collections was lower during the intervention period (rate ratio 0.90, 95% CI, 0.86 to 0.95; $P<0.001$). This resulted in a reduction of 53 g CO₂e (95% CI, 24 to 83g; $P<0.001$) and \$22 (95% CI, \$9 to \$34; $P=0.001$) in pathology fees per admission. The intervention was estimated to have saved 132kg CO₂e (95% CI, 59 to 205kg) and \$53,573 (95% CI, 22,076 to 85,096).

6.1.4 Conclusions

Reduction in unnecessary hospital pathology collections was associated with both carbon emission and cost savings. Pathology stewardship warrants further study as a potentially scalable, cost-effective, and incentivising pathway to lowering healthcare's greenhouse gas emissions.

6.1.5 Funding

National Health and Medical Research Council, Australia (NHMRC) PhD scholarship.

Healthy Urban Environments (HUE) Collaboratory of the Maridulu Budyari Gumal Sydney

Partnership for Health, Education, Research and Enterprise MBG SPHERE.

6.2 Introduction

Climate change threatens to undo the last 60 years of public health gains, through extreme weather, changing distributions of infectious diseases, and food and water insecurity.¹

Paradoxically, healthcare is itself a major contributor to carbon emissions: in Australia, healthcare is responsible for 7% of national greenhouse gas (GHG) emissions, whilst globally healthcare accounts for approximately 4.4% of the world's emissions.^{2,3} There is growing awareness of climate-health impacts, with medical organisations in Australia describing it as a public health emergency^{4,5} and health organisations, such as the National Health Service (NHS) starting to decarbonise.⁶ In Australia, the Australian Medical Association (AMA) and Doctors for the Environment Australia (DEA) have called for Australia's healthcare sector to become net zero by 2040, with an interim target of 80% reduction by 2030.⁷ Whilst the move towards renewable energy will achieve some of this reduction, there will also need to be changes in clinical care.

In 2020, a life cycle carbon footprint of five commonly used pathology tests in a hospital setting was reported⁸, showing that phlebotomy and collection tubes accounted for most of the impact. As these items are unable to be reused or recycled, the main opportunity to reduce emissions from laboratory tests is to reduce unnecessary testing.⁹ According to a meta-analysis by Zhi et al, between 12 – 44% of ordered pathology tests are not indicated.¹⁰ Given the high number of pathology tests performed in Australian hospitals, there are opportunities to reduce both carbon emissions and financial costs through improved pathology stewardship.

In September 2019, the Division of Medicine (DoM) at St George Hospital introduced a policy to limit non-urgent pathology testing to two days per week (Mondays and Thursdays), with pathology testing on other days only when urgently required. Whilst the initial driver was to reduce patient harm and economic costs, it was subsequently recognised that it could also reduce carbon emissions, which may in future further motivate clinicians to reduce unnecessary testing. The objective of this retrospective cohort study was to measure the difference in the number of pathology collections between the intervention period and a reference period, along with the corresponding difference in GHG emissions (in carbon dioxide equivalents (CO₂e)), financial costs and any adverse events.

6.3 Methods

6.3.1 Study setting

St George Hospital is a 653-bed tertiary referral hospital in metropolitan Sydney. The DoM comprises the Departments of Cardiology, Endocrinology, Gastroenterology and Hepatology, Infectious Diseases and Immunology, Nephrology, Neurology, Respiratory, and Rheumatology. Approval for this project was obtained from the South Eastern Sydney Local Health District (SESLHD) Human Research Ethics Committee: 2020/ETH01470.

6.3.2 Study design

6.3.2.1 Intervention

The DoM's policy to limit testing to Mondays and Thursdays was developed in conjunction with heads of department, and a junior doctor interest group that designed posters promoting the policy change (e.g. "Twice weekly ordering" and "More is not always better", see Supplementary Figure 6-1). The policy was communicated via department meetings, staff

orientations, and strategic placement of posters in areas frequented by junior doctors. The policy was implemented on 1 September 2019 and is ongoing.

6.3.2.2 Study periods

Two periods were determined for the primary comparative analysis. The intervention period was defined as 1 September 2019 to 29 February 2020. A corresponding 6-month period from the previous year, 1 September 2018 to 28 February 2019, was selected as the reference period to minimise seasonal effect. Data from the intermediate period (1 March 2019 to 31 August 2019) was also analysed and included in all multivariable models.

6.3.2.3 Study population

All admissions under the care of a DoM consultant for 24 hours or longer, insured by Medicare, Department of Veterans Affairs, or compensation schemes were included. Admissions covered by private health funds were excluded, as pathology is billed separately. Emergency Department (ED) and Intensive Care Unit (ICU) pathology tests were excluded as ordering is not directed by DoM staff. Any admissions that stretched over two study periods were split by date, with each portion analysed under their corresponding study period.

6.3.3 Data sources

The following de-identified DoM patient admission data for the study periods were extracted from the Health Information Exchange and NSW Health Pathology: patient age, sex, Aboriginal or Torres Strait Islander (ATSI) status, medical specialty, length of stay (LOS),

emergency or planned admission, ICU admission, patient acuity measured by National Weighted Activity Unit 2019 (NWAU19), and in-hospital mortality.

Billing records were retrieved within the study periods for commonly ordered tests: full blood count (FBC), coagulation profile (activated partial thromboplastin time (aPTT) and international normalised ratio (INR)), urea, electrolyte and creatinine (UEC), C-reactive protein (CRP), calcium, magnesium, phosphate (CMP), liver function tests (LFT). Additional tests processed at the same time (d-dimer, fibrinogen, thrombin time, amylase, lipase, lactate, creatine kinase, urate, and ammonia) were also retrieved. Admission and pathology billing data were linked using a de-identified patient and admission identifier.

Environmental impacts were obtained from a previous study investigating the consequential life cycle assessment (LCA) of pathology testing.⁸ Environmental impacts were calculated per collection, and included phlebotomy (collection tubes, tube holders, needles, gloves, alcohol and cotton swabs, specimen bags) and the impacts of laboratory analysis (laboratory consumables, and analyser's electricity and reagent) (Supplementary Table 6-3). The financial costs were derived from the laboratory initiation fee for collection and the cost of test analysis.

6.3.4 Outcomes

The primary outcome was the number of pathology collections per admission in DoM patients, with key secondary outcomes being CO₂e emissions and financial cost resulting from these collections. Additional outcomes were the number of collections and rate of collections (per day admitted under DoM) overall and by medical specialty, the proportion of

collections on a Monday or Thursday (versus other days of the week), and in-hospital mortality. All outcomes were compared between the intervention and reference period.

6.3.5 Statistical analysis

Patient and admission characteristics were summarised overall and by study period.

Categorical variables were summarised by number and percentage; continuous variables (all non-normally distributed) were summarised by median and interquartile limits (IQL).

Between group differences were assessed using the Pearson chi-squared test or Kruskal-Wallis test, as appropriate.

The difference in pathology collections per admission per study period was modelled using negative binomial regression adjusted for age, sex, NWAU19, and type of admission (emergency, planned), with LOS included as an offset variable. Generalised linear regression adjusted for admission length, age, sex, NWAU19, and type of admission (emergency, planned) was used to model the differences in CO₂e and financial costs. To account for hospital admissions that spanned multiple periods, robust variance estimates adjusted for within-admission correlation were used in all models. Bootstrapped estimates of the standard error were obtained from 20 replications, clustered by admission. All models included study period as a categorical variable (reference period, intermediate period, and intervention period). The risk of in-hospital mortality in each study period was compared using multivariable logistic regression, including the same covariables as the generalised linear models described above.

The estimated savings after adjustment for confounding variables for CO₂e and financial costs between the intervention and reference periods (i.e. associated with the intervention), was calculated by multiplying the number of admissions during the intervention period by the coefficient for the intervention period (with respect to the reference period) derived from the CO₂e and financial cost per admission models. The likelihood of a pathology collection occurring on Monday or Thursday (as opposed to other days of the week) in the intervention period was compared to the reference period using univariable logistic regression. To explore differences in testing days by specialty, a likelihood ratio test was used to compare the models with and without an interaction between study period and specialty.

The three periods (reference, intermediate, and intervention) were included in all analyses. However, for simplicity, results from the intermediate period are generally excluded from the main manuscript. They are presented in the appendix. All analyses were conducted using Stata 16.1 (StataCorp, TX).

6.4 Results

A total of 7,603 admissions in 5,695 patients were included in the analysis, of which 134 spanned more than one study period, resulting in a total of 7,738 analysable episodes. The median patient age was 70 years (IQL 55-80), 46.3% were female and 1.1% identified as ATSI. The median length of admission was 4.0 days (IQL 2.2-7.6), 87.7% were unplanned, 9.2% included time in the ICU and the median NWAU19 was 1.21 (IQL 0.67-2.09). Patient and admission characteristics were similar during all periods, with the exception of more patients

of ATSI identity in the intervention period, and higher median NWAU19 and longer time under DoM in the reference period (Table 6-1, Supplementary Table 6-4).

Table 6-1: Characteristics of Division of Medicine admissions and collections during study periods

	Reference period	Intervention period	P-value
Admissions	2,590	2,486	
Female – n (%)	1,204 (46.5)	1,114 (44.8)	0.30
Age (years) – median (Q1-Q3)	70 (56-80)	70 (54-80)	0.08
Aboriginal or Torres Strait Islander – n (%)	24 (0.9%)	37 (1.5%)	0.07
Admission type – n (%)			
Emergency	2,169 (83.7%)	2,131 (85.7%)	0.051
Planned	421 (16.3%)	355 (14.3%)	
NWAU19 – median (IQL)	1.31 (0.73-2.14)	1.21 (0.67-2.09)	0.007
ICU during admission – n (%)	255 (9.9%)	214 (8.6%)	0.13
LOS (days) – median (IQL)	4.2 (2.2-8.1)	4.0 (2.2-7.8)	0.04
Div. Medicine time per admission (within each period; days)	4.0 (2.1-7.1)	3.7 (2.1-7.0)	0.01

A total of 24,585 pathology collections were identified (15,685 in the reference and intervention period), with 75.8% of admissions being linked to at least one pathology collection (admissions without collections were typically short, being elective admissions for procedures or where pathology testing was ordered in the ED only and so not included in the present analysis). The number of admissions without a collection was higher in the intervention period, whilst the median number and rate of collections was lower (Table 2, Supplementary Table 6-5).

Table 6-2: Pathology collection characteristics, and associated CO₂e emissions and fees per study period.

	Reference period	Intervention period	P-value
Collections (n) in admissions (N)	8,752 / 2,590	6,933 / 2,486	
Admissions with no collections – n (%)	585 (22.6%)	629 (26.1%)	0.02
Collections per admission – median (IQL)	2 (1-4)	2 (0-3)	<0.001
Collections per patient day	0.53 (0.14-0.85)	0.45 (0.00-0.82)	<0.001
Total CO ₂ e (kg)	1,443	1,126	
CO ₂ e per admission (kg) – median (IQL)	0.34 (116, 685)	0.22.4 (0, 550)	<0.001
Total pathology cost (AUD)	\$641,316	\$503,341	
Pathology cost per admission (AUD) – median (IQL)	\$137 (\$50, \$304)	\$106 (\$0, \$253)	<0.001

The total GHG emissions was 4,038 kg CO₂e. The median CO₂e was 337.9g per admission (IQL 97.3, 677.8), and 81.1g per day (IQL 14.3, 138.3). Median pathology fee per admission was \$125.42 (IQL 32.74, 293.36), or \$34.91 per day, totalling \$1,144,656. The median CO₂e and fees per admission were lower in the intervention period compared to the reference period (P<0.001) (Table 2) and the intermediate period (Supplementary Table 6-5).

In multivariable analysis, the intervention period was a significant predictor of CO₂e, fees and pathology collections (Supplementary Table 6-6). CO₂e per admission were estimated to be 53 g (95% CI, 24 to 83g; P<0.001) lower during the intervention period than during the reference period. Similarly, fees per admission were \$22 (95% CI, \$9 to \$34; P=0.001) lower, and the incidence rate ratio comparing number of collections per admission was 0.90 (95% CI, 0.86 to 0.95; P<0.001), consistent with a 10% reduction in the rate of pathology collections. Savings associated with the intervention period were estimated as 132 kg CO₂e

(95% CI, 59 to 205 kg), equivalent to driving an average passenger vehicle between Melbourne and Adelaide (733km¹¹; and a cost saving of \$53,573 (95% CI, 22,076 to 85,096).

There were 217 in-hospital deaths during the 18-month period, including 65 in the reference period and 58 in the intervention period. In hospital mortality did not differ between the two study periods (OR for intervention period 1.09 (95% CI 0.75 to 1.59), although it was higher during the intermediate period, OR 1.61 (95% CI 1.15 to 2.25), which covered winter. (Supplementary Table 6-7).

The change in collection rates within specialities across the study periods was variable, with four of eight showing significant reductions between the intervention and reference periods and one showing a significant increase (Supplementary Table 6-8). Overall, there was evidence of effect modification by specialty on the relationship between collection rate and study period (P-interaction<0.001). There was evidence of a change in pathology collection pattern by day of the week, with the odds of a pathology collection occurring on a Monday or Thursday being higher in the intervention period compared to the reference period (odds ratio 1.08, 95% CI 1.01 to 1.16; P=0.024). This association was not modified by specialty (P-interaction=0.58).

6.5 Discussion

6.5.1 Principal findings

All Australian states and territories have net-zero 2050 targets, which will have to include healthcare.¹² The UK's National Health service has suggested that healthcare's path to net-zero will require multiple small interventions¹³, such as from this study. The 10% decrease in the number of pathology collections in the intervention period resulted in a 132 kg decrease in greenhouse gas emissions, alongside a financial saving of \$53,573, with no apparent increase in adverse health outcomes during the intervention period. Whilst not captured in this study, additional reductions in GHG emissions could potentially occur through the reduction of iatrogenic anaemia, or from avoiding the clinical cascade of post-hospital care that can result from unnecessary testing.^{14,15}

The DoM contributes to 20% of hospital pathology activity, and if a similar 10% reduction were achieved over the whole hospital, annual savings would be approximately 1,300 kg CO₂e, and \$500,000. Extrapolated nationally¹⁶, this could lead to savings in the vicinity of 135,000 kg CO₂e and \$56 million. We are unable, however, to give this potential saving as a percentage of healthcare's total footprint. The carbon footprint of Australian healthcare was calculated using the top-down methodology of input-output, which includes the indirect carbon impacts of all purchases made by the healthcare sector (e.g. legal or labour supply sectors), and additionally uses the average electricity grid (primarily coal) from 2014 when the input-output tables were calculated. By comparison, our study used a consequential analysis to calculate the impact of pathology, which only included the things that change as a consequence of a test being performed, such as the difference in power when an analyser

moves from standby to active, and similarly used the current electricity suppliers that respond to an increased demand, which is renewables and gas.

In terms of behaviour change, consistent with the intervention's testing policy there was a significant increase in the odds of a test being performed on a Monday or a Thursday, accompanied by a decrease in the number of tests performed overall. The pattern of change was not uniform between specialties, with overall testing decreasing for some specialties but not others, while the increase in Monday or Thursday testing was statistically the same between specialties. This is consistent with different specialties responding to the request in different ways. "Cultural" differences in testing behaviour may also vary widely between the same department at different hospitals, as demonstrated by a recent Australian study of ED departments.¹⁷

Whilst the incidence of further unnecessary testing during the intervention period is unknown, there are potential opportunities to further reduce unnecessary testing, especially if environmental considerations are a policy driver. Studies have shown that providing the cost of tests to practitioners can reduce testing rates ^{18,19}, and that outside of healthcare, carbon labelling can change consumer behaviour.²⁰ Junior doctors, who belong to an age cohort that strongly supports climate action were involved in this policy and medical associations now have clear goals to decarbonise healthcare.²¹ Given these factors, providing information about the carbon costs of tests to doctors may be an additional motivation to reduce unnecessary testing. This could be enhanced by an ongoing multi-faceted behaviour change program, using implementation science methodology, including educational initiatives, changing computer ordering systems, and promoting benchmarking ²²; and

including both ED and ICU within the program, as both have been shown to have high rates of unnecessary testing.^{17,23}

6.5.2 Comparison with other studies

Whilst other studies have shown comparable reductions of 11-12% due to interventions reducing unnecessary pathology testing^{24,25}, this study is the first to estimate the associated reduction in greenhouse gas emissions.

6.5.3 Strengths and limitations of the study

This study did have some limitations. It was performed at a single site in Sydney, although the results are comparable with similar interventions in other tertiary teaching hospitals^{24,25}. The time period was short and so subject to fluctuations, even though a comparable seasonal reference period was used. We were unable to examine potential unintended harms in detail, although these are considered likely to have been minimal, given the opportunity for pathology tests to be ordered on any day if clinically indicated. Lastly, the study was not controlled, and therefore there are potentially other confounders which may have influenced the results.

6.6 Conclusion

This study has demonstrated that institutional initiatives can effectively reduce GHG emissions and healthcare costs associated with pathology testing whilst not adversely affecting patient care. The intervention is both scalable and sustainable. Prospective interventional studies are required to determine if doctors may be influenced by environmental benefits to safely reduce unnecessary pathology testing, as efforts to develop and expand such programs would likely result in substantial environmental and financial benefits.

6.7 References

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6.8 Supplementary materials

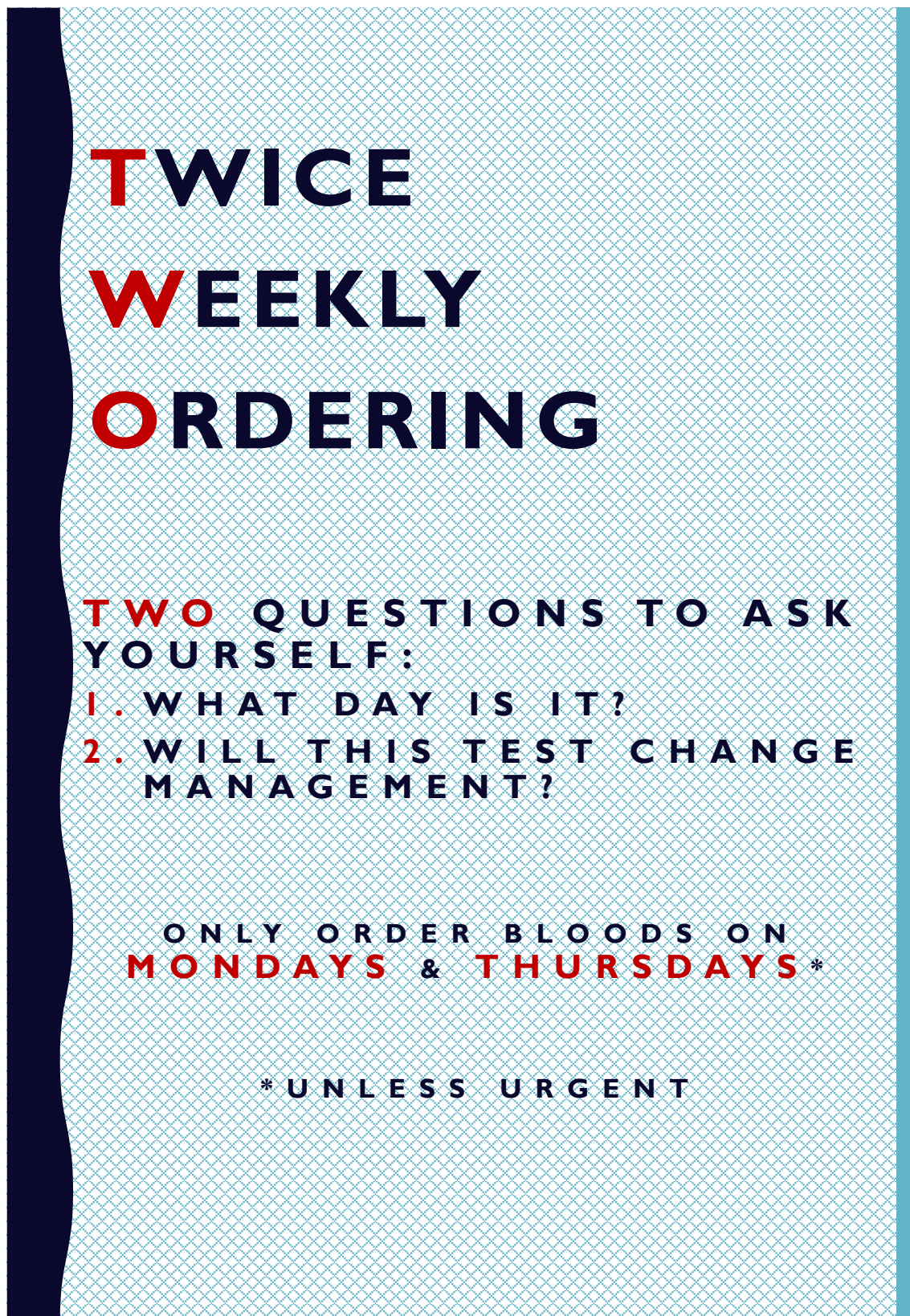


Figure 6-1: Poster communicating policy change

Table 6-3: Carbon emissions (g CO₂e) associated with the collection and laboratory analysis of blood samples

	Ordered test	Test emissions	Tube emissions	Phlebotomy emissions
Biochemistry	(LFT) albumin, alkaline phosphatase, alanine transferase, aspartate transferase, bilirubin, gamma glutyltransferase, protein; (non-LFT biochemistry) amylase, lipase, urate, lactate, ammonia, C-reactive protein, creatine kinase	0.51	50.3	46.5
	(EUC) sodium, potassium, chloride, bicarbonate, urea, creatinine	2.33		
Coagulation studies	D-dimer, fibrinogen, prothrombin time, activated partial thrombin time, thrombin time	3.9	31.5	
Full blood count	Haemoglobin and red cell parameters, white cell count and differential, platelets	42.8	27.0	

The total CO₂e for a pathology order is equal to the sum phlebotomy (tube holders, needles, gloves, alcohol and cotton swabs, and specimen bags); collection tubes; and the impacts of laboratory analysis (reagent and electricity use of analysers). For UEC, coagulation studies and FBC, impacts were recorded per collection and consisted of phlebotomy, collection tube and laboratory emissions. For non-UEC biochemistry tests, we assumed that they were collected in conjunction with a UEC. For these tests, only laboratory impacts per individual test were recorded, as the impacts of phlebotomy and collection tubes fell on the accompanying UEC. For example, the standard 'liver function test' consists of seven individual tests (albumin, alkaline phosphatase, alanine transferase, aspartate transferase, bilirubin, gamma glutyltransferase, protein), with laboratory emissions as a result being 3.57g CO₂e (7 x 0.51g CO₂e).

Table 6-4: Characteristics of admissions and collections during study periods

	Reference period	Intermediate period	Intervention period	Overall *	P-value (All periods)	P-value (Reference vs. Intervention)	P-value (Intermediate vs. Intervention)	P-value (Reference vs. Intermediate)
Admissions	2,590	2,662	2,486	7,603				
Female – n (%)	1,204 (46.5)	1,254 (47.1)	1,114 (44.8)	3,519 (46.3)	0.30	0.30	0.10	0.54
Age (years) – median (Q1-Q3)	70 (56-80)	70 (55-81)	70 (54-80)	70 (55-80)	0.12	0.08	0.07	0.90
Aboriginal or Torres Strait Islander – n (%)	24 (0.9)	22 (0.8)	37 (1.5)	82 (1.1)	0.048	0.07	0.03	0.35
Admission type – n (%)					0.13	0.051	0.13	0.64
Emergency	2,169 (83.7)	2,242 (84.2)	2,131 (85.7)	6,429 (84.6)				
Planned	421 (16.3)	420 (15.8)	355 (14.3)	1,174 (15.4)				
NWAU19 – median (IQL)	1.31 (0.73-2.14)	1.17 (0.67-2.09)	1.21 (0.67-2.09)	1.21 (0.67-2.09)	0.002	0.007	0.53	<0.001
ICU during admission – n (%)	255 (9.9)	254 (9.5)	214 (8.6)	696 (9.2)	0.29	0.13	0.24	0.71
LOS (days) – median (IQL)	4.2 (2.2-8.1)	4.1 (2.2-8.0)	4.0 (2.2-7.8)	4.1 (2.2-7.8)	0.10	0.04	0.53	0.14
Div. Medicine time per admission (within each period; days)	4.0 (2.1-7.1)	4.0 (2.1-7.2)	3.7 (2.1-7.0)	3.9 (2.1-7.0)	0.03	0.01	0.02	0.79
Collections	8,752	8,900	6,933	24,585				
Admissions with no collections – n (%)	585 (22.6)	623 (24.0)	629 (26.1)	1,837 (24.2)	0.02	0.02	0.11	0.46
Collections per admission – median (IQL)	2 (1-4)	2 (1-4)	2 (0-3)	2 (1-4)	<0.001	<0.001	<0.001	0.43
Collection per patient day	0.53 (0.14-0.85)	0.52 (0.13-0.84)	0.45 (0.00-0.82)	0.50 (0.11-0.83)	<0.001	<0.001	<0.001	0.56

* Sum of each period may exceed overall value due to admissions covering multiple periods

Table 6-5: Multivariable model of in-hospital mortality

	Odds ratio	P-value
Study period (ref=Reference period)		
Intermediate period	1.61 (1.14 to 2.25)	0.006
Intervention period	1.09 (0.75 to 1.59)	0.63
Age (per year)	1.06 (1.04 to 1.07)	<0.001
NWAU	1.00 (0.99 to 1.01)	0.88
Female (ref=Male)	0.71 (0.53 to 0.95)	<0.001
Non-emergency (ref=Emergency)	0.89 (0.60 to 1.34)	0.59
ICU admission (ref=No)	8.21 (5.94 to 11.38)	<0.001
Length of stay (per day)	1.02 (1.01 to 1.03)	0.004

Table 6-6: CO₂e emissions and fees per period.

	Reference period	Development period	Intervention period	Overall *	P-value (All periods)	P-value (Reference vs. Intervention)	P-value (Intermediate vs. Intervention)	P-value (Reference vs. Intermediate)
Collections (n) in admissions (N)	8,752 / 2,590	8,900 / 2,662	6,933 / 2,486	24,585 / 7,603				
Total CO ₂ e (kg)	1,443	1,470	1,126	4,038				
CO ₂ e per admission (g) – median (IQL)	339.4 (116.3, 684.9)	337.9 (97.3, 686.9)	215.4 (0, 550.4)	337.9 (97.3, 677.3)	<0.001	<0.001	<0.001	0.42
Total cost (AUD)	641,316.08	662,581.93	503,340.55	1,807,238.56				
Cost per admission (AUD) – median (IQL)	137.06 (49.98, 304.00)	129.50 (32.80, 313.68)	106.21 (0, 253.32)	125.42 (32.74, 293.36)	<0.001	<0.001	<0.001	0.41

Table 6-7: Effect of study period on CO₂e , fees, and pathology collections

	CO ₂ e (Difference per admission, g)	P-value	Fees (Difference per admission, AUD)	P-value	Collections (Collection rate ratio)	P-value
Study period (ref=Reference period)						
Intermediate period	13.9 (-10.0 to 37.8)	0.26	10.05 (-0.36 to 20.46)	0.059	1.004 (0.959 to 1.051)	0.87
Intervention period	-53.2 (-82.5 to -23.9)	<0.001	-21.55 (-34.23 to -8.88)	0.001	0.904 (0.862 to 0.948)	<0.001
Age (per 20 years)	23.3 (3.3 to 43.4)	0.023	4.25 (-6.13 to 14.64)	0.422	1.027 (1.004 to 1.050)	0.02
NWAU	-4.1 (-18.6 to 10.4)	0.58	-1.97 (-8.69 to 4.76)	0.567	0.998 (0.993 to 1.003)	0.37
Female (ref=Male)	-47.5 (-66.3 to -28.8)	<0.001	-21.40 (-30.90 to -11.89)	<0.001	0.896 (0.866 to 0.926)	<0.001
Non-emergency (ref=Emergency)	-11.0 (-72.1 to 50)	0.72	1.93 (-28.67 to 32.53)	0.901	1.074 (1.012 to 1.139)	0.018
Length of stay (days)	13.9 (-10.0 to 37.8)	0.26	10.05 (-0.36 to 20.46)	0.059	(offset)	

Table 6-8: Number of collections per day per admission according to speciality and period (median, IQL)

Specialty	reference	intermediate	intervention	P-value for overall difference
Speciality 1	0.41 (0.00, 0.72)	0.35 (0.00, 0.63)	0.21 (0.00, 0.46)	<0.001
Speciality 2	0.60 (0.17, 0.87)	0.37 (0.00, 0.67)	0.30 (0.00, 0.50)	0.001
Speciality 3	0.59 (0.40, 0.80)	0.60 (0.35, 0.95)	0.34 (0.13, 0.68)	0.002
Speciality 4	0.66 (0.35, 0.94)	0.67 (0.33, 0.93)	0.59 (0.25, 0.90)	0.023
Speciality 5	0.55 (0.00, 0.88)	0.66 (0.30, 0.98)	0.41 (0.00, 0.97)	0.47
Speciality 6	0.70 (0.28, 1.25)	0.80 (0.25, 1.48)	0.66 (0.25, 1.12)	0.34
Speciality 7	0.90 (0.62, 1.28)	0.93 (0.53, 1.28)	0.97 (0.69, 1.42)	0.021
Speciality 8	0.23 (0.00, 0.60)	0.32 (0.00, 0.68)	0.33 (0.00, 0.62)	0.10

Chapter 7 Prevalence of unnecessary routine preoperative testing at Western Health

7.1 Introduction

There are many reasons why preoperative testing is ordered, including predicting adverse perioperative outcomes, and the identification of otherwise unknown conditions that may require changes in either surgical or anaesthetic management.¹ As an example, there is strong evidence that identifying anaemic patients through preoperative testing Low haemoglobin concentrations in patients undergoing both cardiac and non-cardiac surgery is associated with increased mortality.^{2–7} Low preoperative haemoglobin concentrations are also associated with the need for perioperative blood transfusions^{8,9}, postoperative complications^{10,11}, and adverse cardiac events.¹² Similarly, preoperative creatinine levels indicating an estimated glomerular filtration rate below 60ml per minute per average body surface area(1.73 m²) have been shown to be associated with increased postoperative mortality¹³, although this relationship was not seen in other studies.^{14–17}

Other preoperative tests have, however, not shown any predictive value in both well and unwell patients. In unwell patients, preoperative sodium levels and white blood cell counts are not predicative of adverse outcomes^{12,14}, while in well patients, coagulation profiles are similarly not predictive of adverse outcomes.^{18–20} Instead, the major predictors of adverse outcomes are age, surgery type, and existing patient comorbidities.^{21,22}

Many authors, therefore, have questioned the use of routine preoperative testing for low-risk patients.^{23–26} Additionally, even when an unindicated routine test is abnormal, there is often little or no change in patient management as a result.^{27–31} Due to abnormal tests not changing perioperative management in their study, Bryson et al (2013) noted, “... that no case was delayed, cancelled, or rescheduled lends support to the relatively low impact of testing on clinical decision making”.³²

To address unnecessary testing, guidelines for preoperative testing have been written by American, Canadian, and German anesthesiologists societies.^{33–35} Whilst these guidelines are quite general in nature, more specific guidelines have been written by the UK’s National Institute for Health and Care excellence (NICE).³⁶ The NICE guidelines were developed for patients undergoing elective surgery who are over the age of sixteen; who weren’t pregnant; who weren’t having cardiothoracic surgery or neurosurgery; and only suffered from diabetes, obesity, or cardiovascular, respiratory, or renal comorbidities.

The NICE guidelines use the American Society of Anesthesiologists Physical Status (ASA-PS), a 6-point severity scale for a patient’s physical fitness for surgery (

Table 7-1), in combination with the complexity of surgery (Table 7-2), in a “traffic light” system, where red indicates don’t routinely offer test, orange is to consider the test in patients with specific conditions, and green is to offer the test (Table 7-3).

Table 7-1: American Society of Anesthesiologists Physical Status (ASA-PS), from Sobrie et al (2016)³⁷

ASA	Definition
1	Healthy person
2	Mild systemic disease
3	Severe systemic disease
4	Severe systemic disease that is a constant threat to life
5	A moribund person who is not expected to survive without surgery
6	A declared brain-dead person whose organs are being removed for donor purposes

Table 7-2: Surgery grades and examples, from NICE (2016) Clinical guideline NG45³⁶

Minor	Intermediate	Major or complex
Excising skin lesion Draining breast abscess	Primary repair of inguinal hernia Excising varicose veins in the leg Tonsillectomy or adenotonsillectomy Knee arthroscopy	Total abdominal hysterectomy Endoscopic resection of prostate Lumbar discectomy Thyroidectomy Total joint replacement Lung operations Colonic resection Radical neck dissection

Table 7-3: Example of “traffic light” system for full blood count from NICE (2016) Clinical guideline NG45³⁶

	Surgery grade		
ASA grade	Minor	Intermediate	Major or complex
ASA 1	Do not routinely offer	Do not routinely offer	Offer
ASA2	Do not routinely offer	Do not routinely offer	Offer
ASA3 or ASA4	Do not routinely offer	Consider for people with cardiovascular or renal disease if any symptoms not recently investigated	Offer

Using the previous earlier 2003 version of these guidelines as a reference, Clair et al (2010) found that that none of the coagulation profiles or liver function tests ordered for gynaecological patients were indicated, nor were 83% of the metabolic profiles or 71% of the

full blood counts.³⁸ Several other studies using the 2003 NICE guidelines also found unindicated ordering of coagulation profiles^{39,40}, whilst Leung et al (2017) found that 69% of preoperative tests were deemed unnecessary, and in particular clotting profile (99.2%), U+E (63.5%) and FBE (63.5%).³¹ This study additionally found that only 0.5% of the unnecessary tests were abnormal, that they were all clotting profiles, and these abnormal results were all clinically insignificant.

Reducing unnecessary routine preoperative testing is one way that carbon emissions could be reduced without adversely affecting patient care. We hypothesised that the rates of unnecessary testing at a Victorian public hospital would be similar to those seen in the studies of Clair et al (2010) and Leung et al (2017). The aim of this study, therefore, is to determine the prevalence of unnecessary testing at Western Health, Melbourne, by using the 2016 NICE guidelines to ascertain whether a test is indicated.

7.2 Methods

7.2.1 Study setting

The study is a retrospective audit performed at Western Health, a university-affiliated public health service that operates three acute hospitals (Sunshine Hospital, Footscray Hospital, and Williamstown Hospital), along with Sunbury Day Hospital that offers day surgery. Western Health ethics committee gave the study approval (QA2020.36_65648). Western Health has guidelines on ordering preoperative testing that are solely based on type of surgery (minor, intermediate, major), with no consideration on the ASA of the patient (Appendix 1)

7.2.2 Data audit

Preoperative testing data for the 2019 calendar year were provided by the Western Health Performance Unit. Records were selected only for patients who underwent elective surgery and were both over the age of 16 and were ASA 1 or 2. Data obtained from Western Health iPm and Cerner data systems were:

- Demographic data (age, sex, gender, postcode, spoken language and whether the patient needed an interpreter)
- Admission date and time
- Date and type of any tests ordered 30 days prior to the elective surgery
- The unit who ordered the test
- The Australian Medical Benefit Scheme (MBS) item that identifies the principal surgery performed
- The date of the surgery date, and
- Whether a MET (Medical Emergency Team) call was required for the patient

The patient data was de-identified, before being analysed using Excel (Microsoft, Redmond USA). Identification of the whether a surgery type fell into the Minor, Intermediate or Major or complex categories of the NICE guidelines was made by a Western Health anaesthetist (Appendix 2). They provided further advice whether those patients who underwent multiple tests over multiple days in the 30 days prior to surgery were deemed “complex cases” and were therefore the testing they were receiving was not considered to be routine preoperative testing.

Results

The Performance unit provided data on 8,629 patients who underwent elective surgery

(Figure 2-1).

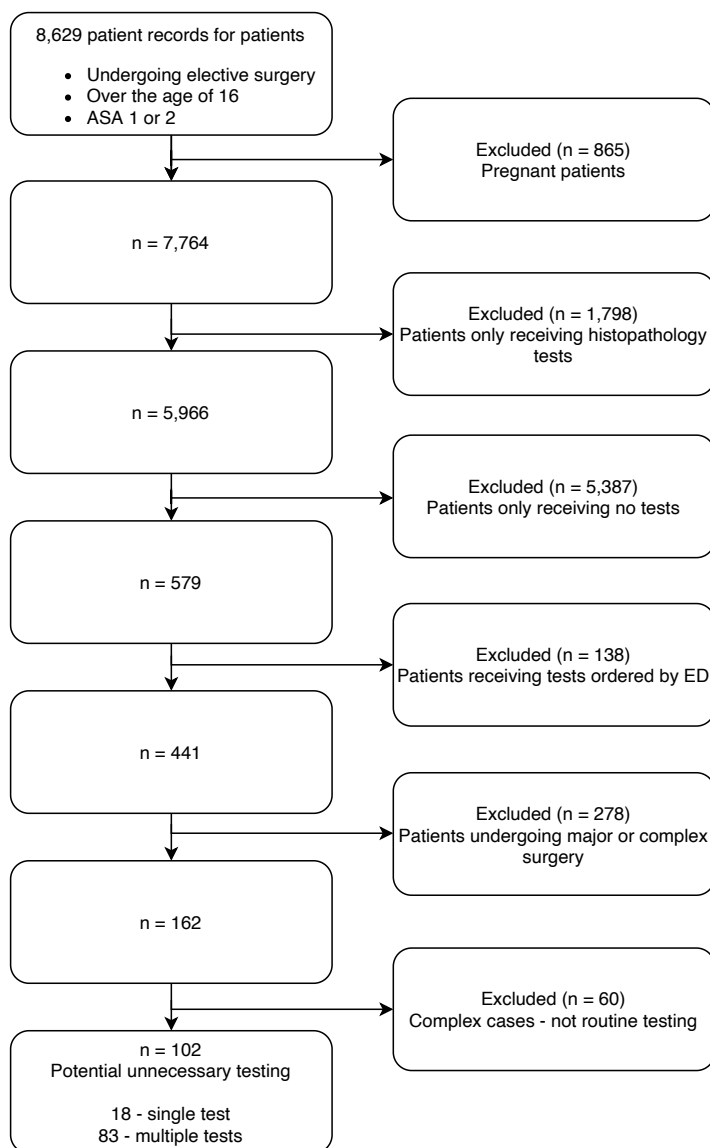


Figure 7-1: Unnecessary testing selection flow diagram

Data for 865 patients were removed from data set due to being pregnant, identified through the principal MBS items of *Management of laboured birth*, or *Uterus, Curettage of*. A further 1,798 patients' data were removed because they underwent only histological pathology testing, which is not included in the NICE guidelines.

Of the remaining 5,966 patients, 5,387 (90%) had no pathology tests ordered in the 30 days prior to the surgery and were therefore removed. 138 patients of the remaining cohort were likewise removed because the testing was ordered by the Emergency Department and was therefore deemed to have not been ordered due to their upcoming elective surgery, but rather was for an unrelated medical emergency.

Data for another 278 patients were removed because they were undergoing Major or complex surgery, with the NICE guidelines considering that for these patients preoperative testing should be offered. Lastly, 61 patients' data were removed because the testing they deemed to be "complex cases", and not receiving routine preoperative testing.

18 of the remaining 101 patients that underwent potential unnecessary testing had a single pathology test (12 full blood examinations, and 6 general biochemistry), while 83 patients had multiple tests (74 full blood examinations, 73 general biochemistry and 26 C-Reactive protein). Of note, six patients had a repeat of the same test on the same day, in what in four patients appeared to be duplicate test ordering as they moved between wards and specialties (e.g. from inpatient to urology). The odds of a patient within this study cohort of having a potential unnecessary test was 0.017.

7.3 Discussion

I identified potential unnecessary testing in only 102 patients out of a total sample size of 5,966 patients, an odds of only 0.017. This was contrary to the original hypothesis that Western Health would be similar to previous studies that showed a >50% rate of unnecessary routine preoperative testing. Instead, Western Health appears to be faithfully following their own preoperative test guidelines.

These guidelines are similar to the NICE guidelines, in that testing should not be offered for minor surgery, testing should be offered for major surgery, and testing should sometime be offered for intermediate surgery, dependent on a patient's health status (e.g. any haematological disorder or significant disease for a full blood examination). Where they differ from the NICE guidelines is that these recommendations are irrespective of a patient's ASA.

While there appears to be little unnecessary routine testing at Western Health, I did however identify in the data instances where patients received multiple of the same test (e.g. full blood examination, urea and electrolytes, or C-reactive protein) within hours of each other on the same day, especially when it appeared they were being transferred between medical units. While I didn't study the prevalence of multiple tests being ordered on the same day, this overutilisation of testing through repeat testing should be further investigated.

Western Health's low prevalence of routine preoperative testing is not generalisable to other health services. It has been shown that there can be wide inter-hospital variability in pathology test ordering.⁴¹ Further research, therefore, should be done to determine whether other health services have similarly low rates of unnecessary preoperative testing.

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7.5 Supplementary materials

7.5.1 NICE guidelines for preoperative testing

Preoperative tests (update)
Guideline summary

1 Guideline summary

1.1 Full list of recommendations

Communication

1. When offering tests before surgery, give people information in line with recommendations (including those on consent and capacity) made in the NICE guideline on patient experience in adult NHS services.
2. Ensure that the results of any preoperative tests undertaken in primary care are included when referring people for surgical consultation.

Considering existing medicines

3. Take into account any medicines people are taking when considering whether to offer any preoperative test.

Resting ECG

4. Resting ECG

	Surgery grade		
ASA grade	Minor	Intermediate	Major or complex
ASA 1	Do not routinely offer	Do not routinely offer	Consider for people aged over 65 if no ECG results available from past 12 months
ASA 2	Do not routinely offer	Consider for people with cardiovascular, renal or diabetes comorbidities	Offer
ASA3 or ASA4	Consider if no ECG results available from past 12 months	Offer	Offer

Resting echocardiography

5. Do not routinely offer resting echocardiography before surgery.
6. Consider resting echocardiography if the person has:
 - a heart murmur and any cardiac symptom (including breathlessness, pre-syncope, syncope or chest pain) or
 - signs or symptoms of heart failure.

Before ordering the resting echocardiogram, carry out a resting electrocardiogram (ECG) and discuss the findings with an anaesthetist.

Chest X-ray

7. Do not routinely offer chest X-rays before surgery.

Lung function tests and arterial blood gas analysis

8. Do not routinely offer lung function tests or arterial blood gas analysis before surgery.
9. Consider seeking advice from a senior anaesthetist as soon as possible after assessment for people who:
- are ASA grade 3 or 4 due to known or suspected respiratory disease and
 - are having intermediate or major or complex surgery.

Full blood count test

10. Full blood count test

	Surgery grade		
ASA grade	Minor	Intermediate	Major or complex
ASA 1	Do not routinely offer	Do not routinely offer	Offer
ASA2	Do not routinely offer	Do not routinely offer	Offer
ASA3 or ASA4	Do not routinely offer	Consider for people with cardiovascular or renal disease if any symptoms not recently investigated	Offer

Kidney function tests

11. Kidney function tests

	Surgery grade		
ASA grade	Minor	Intermediate	Major or complex
ASA 1	Do not routinely offer	Do not routinely offer	Consider in people at risk of AKI ^a
ASA2	Do not routinely offer	Consider in people at risk of AKI ^b	Offer
ASA3 or ASA4	Consider in people at risk of AKI ^c	Offer	Offer

Haemostasis tests

12. Do not routinely offer haemostasis tests before surgery.
13. Consider haemostasis tests in people with chronic liver disease having intermediate or major or complex surgery.
 - If people taking anticoagulants need modification of their treatment regimen, make an individualised plan in line with local guidance.
 - If clotting status needs to be tested before surgery (depending on local guidance) use point-of-care testing.^d

Glycated haemoglobin (HbA1c) test in people with diagnosed diabetes

14. People with diabetes who are being referred for surgical consultation from primary care should have their most recent HbA1c test results included in their referral information.
15. Offer HbA1c testing to people with diabetes having surgery if they have not been tested in the last 3 months.

Glycated haemoglobin (HbA1c) test in people without diagnosed diabetes

16. Do not routinely offer HbA1c testing before surgery to people without diagnosed diabetes.

Sickle cell disease or sickle cell trait tests

17. Do not routinely offer testing for sickle cell disease or sickle cell trait before surgery.

^a See recommendation 1.1.8 in NICE CG169: Acute kidney injury: prevention, detection and management (2013)

^b See recommendation 1.1.8 in NICE CG169: Acute kidney injury: prevention, detection and management (2013)

^c See recommendation 1.1.8 in NICE CG169: Acute kidney injury: prevention, detection and management (2013)

^d Note that currently the effects of direct oral anticoagulants (DOACs) cannot be measured by routine testing.

18. Ask the person having surgery if they or any member of their family have sickle cell disease.
19. If the person is known to have sickle cell disease and has their disease managed by a specialist sickle cell service, liaise with this team before surgery.

Urinalysis

20. Do not routinely offer urine dipstick tests before surgery.
21. Consider microscopy and culture of midstream urine sample before surgery if the presence of a urinary tract infection would influence the decision to operate.

Pregnancy testing

22. On the day of surgery, sensitively ask all women of childbearing potential whether there is any possibility they could be pregnant.
23. Make sure women who could possibly be pregnant are aware of the risks of the anaesthetic and the procedure to the fetus.
24. Document all discussions with women about whether or not to carry out a pregnancy test.
25. Carry out a pregnancy test with the woman's consent if there is any doubt about whether she could be pregnant.
26. Develop locally agreed protocols for checking pregnancy status before surgery.
27. Make sure protocols are documented and audited, and in line with statutory and professional guidance.

1.2 Key research recommendations

Polysomnography

1. Does preoperative screening of people who are at risk of obstructive sleep apnoea (OSA) with polysomnography identify those at higher risk of postoperative complications?
2. Does treating OSA perioperatively improve outcomes?

Glycated haemoglobin (HbA1c) test

3. Does optimisation of HbA1c in people with poorly controlled diabetes improve surgical outcomes?

1.3 How this clinical guideline was updated

This guideline is a complete update of NICE clinical guideline 3: 'Preoperative tests: The use of routine preoperative tests for elective surgery'.⁷¹ This update replaces the 2003 guideline, which will be stood down.

The update was commissioned to include and update the results of the 2012 Health Technology Assessment 'What is the value of routinely testing full blood count, urea and electrolytes, and lung function tests before elective surgery in patients with no apparent clinical indication and in

subgroups of patients with common comorbidities: a systematic review of the clinical and cost-effective literature'.²⁴

In the areas where new evidence was identified as part of the NICE review update, full searches were undertaken and systematic reviews conducted. No systematic reviews were undertaken for areas where the NICE review update found no new evidence. Formal consensus methods, in the form of a modified Delphi survey, were used in addition to the updated evidence reviews to support the development of recommendations, and for those areas where no evidence review was to be conducted.

Clinical tests not in the original guideline that were included in the update are:

- Cardiopulmonary exercise test (CPET)
- Resting echocardiography
- Polysomnography
- Glycated haemoglobin (HbA1c)

Random blood glucose was included in the original guideline, but removed from the update and replaced by the glycated haemoglobin (HbA1c) test. This reflects the change in current practice.

Children, pregnant women and people having cardiothoracic or neurosurgery were excluded from the scope of the update.

All recommendations in the original guideline have been replaced by the recommendations in this update.

- The original guideline made recommendations for specific age bands, whereas the update considers ASA grade only (with an assumption that age is indirectly reflected within the ASA grade)
- The original guideline made individual recommendations for single comorbidities, whereas the update combines all comorbidities within recommendations
- The update does not use surgery grades as in the original guideline, but instead uses the terms 'minor', 'intermediate' and 'major or complex' to refer to increasing complexity of surgical procedures
- Where tests are recommended for consideration, the update provides clarification on the populations or circumstances in which doing the test would have value.

7.5.2 Medicare items of surgery deemed to be Major or complex

30023: Wound of soft tissue. traumatic. deep or extensively contaminated. debridement of. under general anaesthesia or regional or field nerve block. including suturing

30024: Wound of soft tissue. debridement of extensively infected post surgical incision or Fournier's Gangrene. under general anaesthesia or regional or field nerve

30223: Large haematoma. large abscess. carbuncle. cellulitis or similar lesion. requiring admission to a hospital. incision with drainage of (excluding aftercare)

30296: Thyroidectomy. total

30318: Open parathyroidectomy. exploration and removal of 1 or more adenoma or hyperplastic glands via a cervical incision including thymectomy and cervical exploration

30336: Lymph nodes of axilla. complete excision of. to level II or level III (Anaes.) (Assist.)

30375: Caecostomy. enterostomy. colostomy. enterotomy. colotomy. cholecystostomy. gastrostomy. gastrotomy. on a person 10 years of age or over. reduction of intussuscept

30439: Operative cholangiography or operative pancreatography or intra operative ultrasound of the biliary tract (including 1 or more examinations performed during the

30445: Laparoscopic cholecystectomy (Anaes.) (Assist.)

30446: Laparoscopic cholecystectomy when procedure is completed by laparotomy (Anaes.) (Assist.)

30448: Laparoscopic cholecystectomy. involving removal of common duct calculi via the cystic duct (Anaes.) (Assist.)

30448: Laparoscopic cholecystectomy. involving removal of common duct calculi via the cystic duct (Anaes.) (Assist.)

30484: Endoscopic retrograde cholangiopancreatography (Anaes.)

30485: Endoscopic sphincterotomy with or without extraction of stones from common bile duct (Anaes.)

30491: Bile duct. endoscopic stenting of (including endoscopy and dilatation) (Anaes.)

30566: Small intestine. resection of. with anastomosis. on a person 10 years of age or over (Anaes.) (Assist.)

32003: Large intestine. resection of. with anastomosis. including right hemicolectomy (Anaes.) (Assist.)

32024: Rectum. high restorative anterior resection with intraperitoneal anastomosis (of the rectum) greater than 10cm from the anal verge excluding resection of sigmoid colon

32028: Rectum. low or ultra low restorative resection. with peranal sutured coloanal anastomosis. with or without covering stoma (Anaes.) (Assist.)

32030: Rectosigmoidectomy (Hartmann's operation) (Anaes.) (Assist.)

32033: Restoration of bowel following Hartmann's or similar operation. including dismantling of the stoma (Anaes.) (Assist.)

35630: Hysteroscopy. with endometrial biopsy. performed in the operating theatre of a hospital

35653: Hysterectomy. abdominal. sub total or total. with or without removal of uterine adnexae (Anaes.) (Assist.)

35657: Hysterectomy. vaginal. with or without uterine curettage

35664: Radical hysterectomy with radical excision of pelvic lymph nodes (with or without excision of uterine adnexae) for proven malignancy

35667: Radical hysterectomy without gland dissection (with or without excision of uterine adnexae) for proven malignancy

35754: Laparoscopically assisted hysterectomy which requires dissection of endometriosis. or other pathology. from the ureter. one or both sides

36528: Nephrectomy. radical with en bloc dissection of lymph nodes. with or without adrenalectomy. for a tumour less than 10 cms in diameter (Anaes.) (Assist.)

36845: Cystoscopy. with diathermy. resection or visual laser destruction of multiple tumours in more than 2 quadrants of the bladder or solitary tumour greater than 2cm in diameter

37203: Prostatectomy (endoscopic. using diathermy or cold punch). with or without cystoscopy and with or without urethroscopy.

38418: Thoracotomy. exploratory. with or without biopsy (Anaes.) (Assist.)

38421: Thoracotomy. with pulmonary decortication (Anaes.) (Assist.)

38424: Thoracotomy. with pleurectomy or pleurodesis. or enucleation of hydatid cysts (Anaes.) (Assist.)

38436: Thoracoscopy. with or without division of pleural adhesions. including insertion of intercostal catheter where necessary. with or without biopsy (Anaes.)

38440: Lung. wedge resection of (Anaes.) (Assist.)

38441: Radical lobectomy or pneumonectomy including resection of chest wall. diaphragm. pericardium. or formal mediastinal node dissection (Anaes.) (Assist.)

42702: Lens extraction and insertion of artificial lens. excluding surgery performed for the correction of refractive error except for anisometropia greater than 3 dioptres following removal of cataract in first eye

45665: Lip. eyelid or ear. full thickness wedge excision of. with repair by direct sutures (Anaes.)

48918: Shoulder. total replacement arthroplasty of. including any associated rotator cuff repair (Anaes.) (Assist.)

49318: Hip. total replacement arthroplasty of. including minor bone grafting (Anaes.) (Assist.)

49321: Hip. total replacement arthroplasty of. including major bone grafting. including obtaining of graft (Anaes.) (Assist.)

49324: Hip. total replacement arthroplasty of. revision procedure including removal of prosthesis (Anaes.) (Assist.)

49517: Knee. hemiarthroplasty of (Anaes.) (Assist.)

49518: Knee. total replacement arthroplasty of (Anaes.) (Assist.)

49521: Knee. total replacement arthroplasty of. requiring major bone grafting to femur or tibia. including obtaining of graft (Anaes.) (Assist.)

49527: Knee. total replacement arthroplasty of. revision procedure. including removal of prosthesis (Anaes.) (Assist.)

51011: Spinal decompression or exposure via partial or total laminectomy. partial vertebrectomy or posterior spinal release. one motion segment.

7.5.3 Western Health's guidelines for preoperative testing

Guidelines for Nursing and Junior Medical Staff Ordering Basic, Non-Surgical Pre-operative Investigations for Elective Surgery											
Procedure code: OG-CC3	Current version: June 2019										
Previous version: May 2016	Next review date: June 2022										
Section: Connecting Care	Sub-section: Investigation										
1. Overview <p>An investigation should only be ordered if there is a reasonable likelihood that the result is going to be abnormal and/or there is a probability that the result will affect the perioperative management of the patient. Investigations should have an indication that takes into account issues raised from the history, examination and the likely effect of the physiological disturbance of the procedure. An investigation done in the last 3 months may be sufficient if there is unlikely to have been any change since then. Patients may require investigations for issues not covered by these guidelines.</p>											
2. Applicability <p>This procedure is for the guidance of nursing and junior medical staff responsible for ordering basic investigations before elective surgery.</p> <p><u>This protocol only includes the following investigations:</u> FBE, U&E, ECG, TFT, LFT, Ca, Mg, PO4, Coagulation studies, HbA1C, Fe Studies.& CRP.</p> <p>These guidelines do not cover specific surgical investigations such as an x-ray for an orthopaedic procedure or more advanced and less common investigations that should be ordered following consultation with a specialist Anaesthetist or other member of Senior Medical Staff.</p>											
3. Responsibility <p>The Director of Anaesthesia and Pain Medicine has the initial responsibility for introducing and implementing this guideline into clinical practice.</p>											
4. Authority <p>These are guidelines only and exceptions are allowed based on the clinical judgement of appropriately qualified staff. Nursing and Junior Medical Staff should consult with Specialist Anaesthetists and other Senior Medical Staff if ordering investigations counter to these guidelines.</p>											
5. Associated Documentation <p>In support of this procedure, the following Manuals, Policies, Instructions, Guidelines, and/or Forms apply:</p> <table> <thead> <tr> <th>Code</th><th>Name</th></tr> </thead> <tbody> <tr> <td>OP-GC6</td><td>Peri-operative Management of Diabetes in Non-pregnant Adults</td></tr> <tr> <td>OP-GC8</td><td>Blood Group Testing and Pretransfusion Tests</td></tr> <tr> <td>OP-GC8</td><td>Requesting Blood and Blood Products</td></tr> <tr> <td>Surgery DP-CM5</td><td>Ordering Basic Non-Surgical Pre-operative Investigations for Adult Elective Surgery Within the Electronic Medical Record</td></tr> </tbody> </table>		Code	Name	OP-GC6	Peri-operative Management of Diabetes in Non-pregnant Adults	OP-GC8	Blood Group Testing and Pretransfusion Tests	OP-GC8	Requesting Blood and Blood Products	Surgery DP-CM5	Ordering Basic Non-Surgical Pre-operative Investigations for Adult Elective Surgery Within the Electronic Medical Record
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Surgery DP-CM5	Ordering Basic Non-Surgical Pre-operative Investigations for Adult Elective Surgery Within the Electronic Medical Record										
6. Definitions and Abbreviations <p>For purposes of this procedure, unless otherwise stated, the following definitions/abbreviations shall apply:</p> <table> <tbody> <tr> <td>Physiological Disturbance</td><td>Tissue damage leads to inflammation, pain and release of a number of mediators that can cause fluid shifts and put a strain on physiological systems, in particular cardiovascular, respiratory, immune and renal. This accounts for many of the complications that occur in the post-operative period.</td></tr> <tr> <td>ABG</td><td>Arterial Blood Gases</td></tr> <tr> <td>Ca</td><td>Calcium</td></tr> <tr> <td>ECG</td><td>Electrocardiogram</td></tr> </tbody> </table>		Physiological Disturbance	Tissue damage leads to inflammation, pain and release of a number of mediators that can cause fluid shifts and put a strain on physiological systems, in particular cardiovascular, respiratory, immune and renal. This accounts for many of the complications that occur in the post-operative period.	ABG	Arterial Blood Gases	Ca	Calcium	ECG	Electrocardiogram		
Physiological Disturbance	Tissue damage leads to inflammation, pain and release of a number of mediators that can cause fluid shifts and put a strain on physiological systems, in particular cardiovascular, respiratory, immune and renal. This accounts for many of the complications that occur in the post-operative period.										
ABG	Arterial Blood Gases										
Ca	Calcium										
ECG	Electrocardiogram										

FBE	Full Blood Examination
G&H	Group and Hold (also known as Group and Screen)
HbA1C	Haemoglobin A1C
LFT	Liver Function Tests
Mg	Magnesium
PO4	Phosphate
RFT	Respiratory Function Tests
TFT	Thyroid Function Tests
U&E	Urea and Electrolytes
Urine MSC	Urine Micro Sensitivity and Culture

7. Procedure Detail

7.1 Steps

Follow these 5 steps:

1. Determine if the patient could be pregnant and if so seek consent and arrange a pregnancy test.
2. Determine the type of surgery using the table below.
3. Determine the likelihood of the procedure being done under local anaesthesia with minimal sedation (no investigations required for minor surgery).
4. Determine investigations to be ordered from the table below. No = don't order, Yes = do order, otherwise consider the indications in the box.
5. Check if indicated investigations have already been **done in the last 3 months** and if there has been a significant clinical change since then. If not, these **do not need to be repeated**.

		Minor	Intermediate	Major
Define Type of Surgery	Tissue damage	None or minimal	Minor and localized	Extensive
	Physiological disturbance	Nil	Minor and lasting a short duration	Significant and lasting days
	Hospital recovery period	Day case	Day or overnight	2 or more days
	Require transfusion	No	Unlikely	Potential
	Examples	Excision of a skin lesion; dilatation and curettage; cone biopsy; endoscopy; cystoscopy; cataract surgery; carpal tunnel release	Mastectomy; laparoscopic cholecystectomy; tubal ligation; inguinal hernia repair; excision of varicose veins; tonsillectomy; thyroidectomy; arthroscopy	Total major joint replacement; hysterectomy; caesarean section; transurethral resection of prostate; multi-level back surgery; carotid endarterectomy; femoral popliteal bypass surgery; free flap surgery; breast reconstruction; major head and neck resections; liver resection, whipple procedure, oesophagectomy
Determine Investigations to be Ordered	FBE	No	Any haematological disorder, history of recent bleeding, significant cardiac disease	Yes
	U&E	Known renal disease or at high risk i.e. long standing diabetes, poorly controlled hypertension ¹	As in the box on the left and/or age > 50 years	Yes
	ECG	No	Known coronary heart disease, significant arrhythmia, peripheral arterial disease, cerebrovascular disease or other significant structural heart disease	As in the box on the left and/or age > 50 years
	G&H	No	No	Yes ²
	LFT, Ca, Mg, PO4	No	No	Known liver disease or at high risk i.e. heavy alcohol intake, jaundice
	Coagulation studies	No	No	Known bleeding disorder, severe liver disease
	HbA1C	A recent (3 months or less) HbA1c should be documented for all patients with diabetes mellitus whenever possible		
	TFT	No	On thyroid replacement therapy and have not had function checked for 6 months or express symptoms of dysfunction or poor compliance	

	Fe Studies & CRP	No	No	Major joint arthroplasty, colectomy and major gynaecological surgery if not done in last 6 months
	Urine MSC	All Urology procedures except trans perineal prostate biopsy		

1 Not required if procedure does not require general anaesthesia.
2 Consideration of cross match should be given to cases done at the Williamstown hospital where the transport of blood from Footscray Hospital will take at a minimum 30 minutes.

8. Document History

Number of previous revisions: 1

Previous issue dates: May 2016

9. References

Routine preoperative tests for elective surgery. NICE guideline Published: 5 April 2016
<https://www.nice.org.uk/guidance/ng45>

Cardiac Risk Stratification for Noncardiac Surgery, Grasso AW, Cleveland Clinic Centre for Continuing Education Published date: June 2014 <http://www.clevelandclinicmeded.com/medicalpubs/diseasemanagement/cardiology/cardiac-risk-stratification-for-noncardiac-surgery/>

2014 ACC/AHA Guideline on Perioperative Cardiovascular Evaluation and Management of Patients Undergoing Noncardiac Surgery. Journal of the American College of Cardiology. Vol 64, No 22, 2014

10. Sponsor

Director of Anaesthesia and Pain Medicine

11. Authorisation Authority

Clinical Services Director of Perioperative and Critical Care Services

Chapter 8 Conclusion

Towards the end of my PhD, world leaders attending the United Nations Climate Change Conference COP26 in Glasgow (31 October to 12 November 2021) gave a global commitment to limit global warming to 1.5° Celsius compared to pre-industrial levels. They committed to do this by urgently accelerating action on climate change and agreeing to increase their 2030 greenhouse gas reduction targets by the end of 2022.¹ Additionally, the conference called for coal power and fossil fuel subsidies to be phased down², and there was an agreement to halt and reverse deforestation.³

Recognising the need for healthcare to be part of this decarbonisation, the COP26 Health Programme led to fifty countries making a commitment to develop low-carbon health systems, with fourteen countries (including the United Kingdom (UK), Spain and Jordan) setting a deeper target of being carbon neutral by 2050.⁴ There was little discussion or detail during COP26, however, on how these commitments will be achieved.⁵

There are two main challenges to overcome in achieving low-carbon or net-zero health services. The first is that we don't know the carbon footprint of most medical devices and consumables, nor of medical interventions. As the business maxim states, however "What gets measured gets managed".⁶ The greatest understanding we currently have on the source of carbon emissions arising from healthcare has come from the UK's National Health Service's Sustainable Development Unit (SDU), formed in 2008 with the remit of establishing a carbon neutral health service. Using the top-down approach of environmental input-output (EIO) life cycle assessment (LCA), the SDU has established that 67% of the NHS's carbon

emissions arise from the procurement of pharmaceuticals, medical and non-medical equipment, anaesthetic gases, and metered dose inhalers (Figure 8-1).⁷ There is no data, however, on the footprint of individual items within these broad groups.

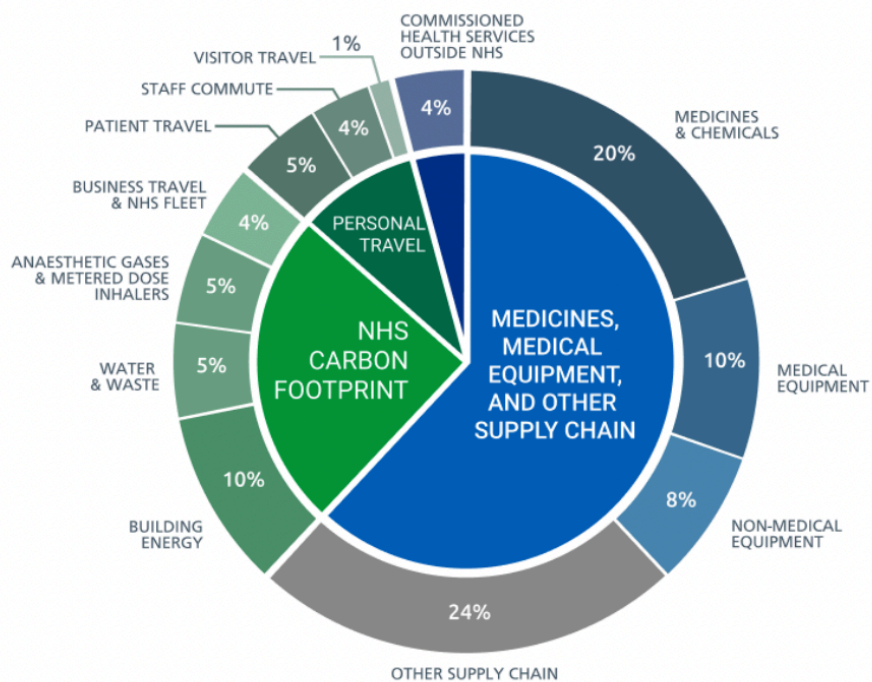


Figure 8-1: Source of carbon emissions by proportion of NHS Carbon Footprint, from NHS “Delivering a ‘Net Zero’ National Health Service” (2020)⁷

Undoubtedly, some of these emissions from procurement will naturally decrease as the world moves away from fossil fuels towards renewable energy, thus reducing emissions created during manufacture. Only 26% of global energy in 2020, however, is generated from renewable energy⁸. This means that if healthcare wants to rapidly decarbonise it can’t just wait for global energy systems to gradually reduce reliance on fossil fuels. Instead, it will require changes in clinical practice.

This need for changes in clinical practice has been reinforced by the SDU's 2020 report on delivering a net-zero health service, which identified that a range of initiatives including digital care pathways, increased preventative medicine, low-carbon substitutions and innovations, rather than any “silver bullet”, was needed to achieve a net-zero health service (Figure 8-2). As an example, many healthcare activities such as pathology testing have low individual impacts but are performed billions of times globally each year. A change in the rates of ordering of tests, therefore, can cumulatively result in a large reduction in overall emissions.

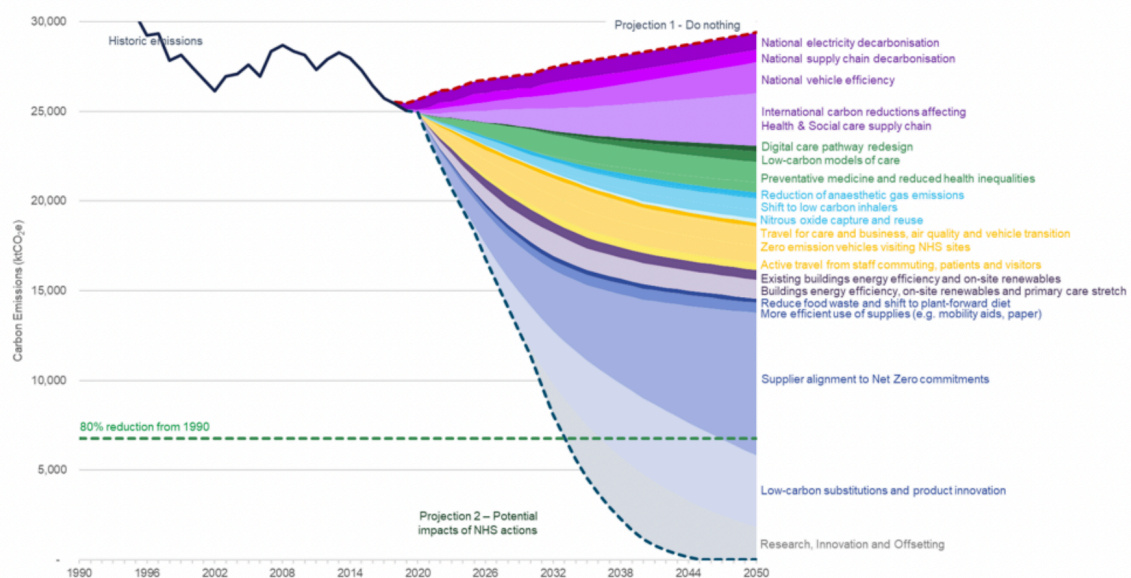


Figure 8-2: Pathway to net zero for the NHS Carbon Footprint, from NHS “Delivering a ‘Net Zero’ National Health Service” (2020)

The second major challenge, therefore, is how to include carbon emissions in the decision-making process when evaluating changes to clinical care or new interventions, such that there are no adverse health or economic outcomes. When deciding on which healthcare interventions to implement, or whether to change current clinical behaviour, Health Technology Assessments (HTAs) form an important part of clinical and policy guidance. This

guidance can be used by both individual healthcare payers and national agencies such as the National Institute of Health and Care Excellence (NICE) in the UK. HTAs determine whether the economic cost of a healthcare intervention is justified compared to the health benefit it provides. There is currently no method for carbon emissions to be taken into consideration HTAs, alongside economic costs, when comparing differing models of clinical care.

To solve these challenges will require a multi-disciplinary approach that includes sustainability and LCA practitioners, clinicians, and health economists working iteratively together to:

1. Measure carbon emissions resulting from the delivery of individual healthcare interventions
2. Identify carbon hotspots or areas of low-value care where safe clinical changes can occur
3. Model the changes using HTA with integrated carbon emissions to ensure that they are effective for carbon, cost and health outcomes
4. Model any new interventions using HTA with integrated carbon emissions

My thesis provides a framework for the multi-disciplinary approach required to decarbonise healthcare. It does so by theorising the three components introduced in Chapter 1: methodology, measurement, and mitigation. For the remainder of this chapter, I will be summarising the key findings of each of these three components, along with providing commentary on how I addressed the challenges in completing each one. Finally, I will suggest future research that needs to be undertaken so that healthcare can achieve net-zero carbon

emissions. While this research has been undertaken in the context of the Australian healthcare system, beyond the availability of resources there is no underlying reason why this framework could not be undertaken in other countries as HTAs and LCAs are performed in low-, middle- and high-income countries.⁹⁻¹²

8.1 Methodology

8.1.1 Key findings from Chapter 3, Incorporating carbon into healthcare's future: adding carbon emissions to health technology assessments

Chapter 3, (paper entitled *Incorporating carbon into healthcare's future: adding carbon emissions to health technology assessments* (in progress)) investigated the ways by which LCA can be incorporated into HTA. The paper found that carbon emissions are best quantified by process LCA, and that emissions could be integrated into HTAs as: a decision modifier when two or more technology alternatives are clinically and economically similar; as a criterion in a multi criteria decision analysis (MCDA); monetized and included in a cost-benefit (CBA) analysis; or as an additional cost in a cost-effectiveness analysis (CEA).

While there are no technical challenges to this occurring, the main challenge is the lack of LCAs that have been undertaken in healthcare. LCA practitioners utilise both general background databases on materials and processes to enable complex supply chains to be modelled, reducing time and cost, as well as sector-specific databases such as for agriculture. It was the paper's recommendation, therefore, that a healthcare-specific database be established that contains common items such as syringes and processes such as sterilisation, so as to enable expeditious and accurate modelling. The paper recognised that this will initially be costly and time consuming, but that, as the knowledge base is built up, it will

become increasingly quick and inexpensive to quantify the carbon emissions of individual healthcare interventions.

8.1.2 Challenges

8.1.2.1 Health technology assessment methods

To enable this integration, there were a number of methodological considerations that had to be solved. Firstly, there is no unified way by which HTAs are performed by different payers, organisations, or jurisdictions. While cost effectiveness analysis is the most commonly used method for HTAs, other methods that are used include cost benefit analysis, and using economic costs as a simple decision modifier or as part of a multi criteria decision analysis. The integration of carbon emissions, therefore, had to be flexible to enable decision makers to use any method of HTA.

8.1.2.2 Life cycle assessment methods

The second challenge was determining the best LCA approach. The paper found that process-based LCAs rather than environmental input-output LCAs (EIO) should be used, as they can provide the granular level of detail to enable comparisons between individual interventions in an HTA. Process-based LCAs typically, however, temporally aggregate emissions from across the life cycle (raw material production, manufacture, use and disposal) into a single figure. By doing so, emissions that may be separated by decades (e.g the life cycle of a car, going from mining, to use, through to end-of-life) are aggregated into a single figure. The temporal aggregation is problematic if the LCA component was to integrate with multi-year HTAs, as monetised emissions arising from the LCA need to be discounted on a yearly basis along with all other economic costs. This therefore required that emissions be assigned to the year in which they are produced.

There has been a small but increasing number of papers published using dynamic LCA, where emissions rather than being temporally aggregated are instead assigned to single years.⁹ Fortuitously in healthcare, many items have a short life cycle from manufacture through to use and disposal so that items do not lose sterility. Additionally, the majority of items used in healthcare are plastics and metals¹⁰, and therefore produce no greenhouse gas emissions when placed in landfill. This means that there are only limited long-term methane emissions from materials such as cotton and paper as they biodegrade that need to be accounted for far into the future. Together this means that it is possible to assign emissions to specific years using dynamic LCA with a relative degree of accuracy.

Additionally, in performing the LCAs on pathology and imaging that make up the middle chapters of this thesis, I recognised the importance of performing both attributional and consequential LCAs for healthcare, as together they provide information on both the total impacts of healthcare activities. This combination also gives some clarity on actual expected changes in emissions that would occur with a change in clinical behaviour, as these are often very different. It is preferable, therefore, to perform both attributional and consequential LCA for inclusion in a HTA.

8.1.2.3 Embedding LCA results into economic software models

The next consideration was how to physically embed the results of a LCA into economic software models such as a Markov model. Creating a multi-year Markov model using TreeAge Pro® (TreeAge Software LLC, Massachusetts USA), I recognised that it was possible to include CO₂e emissions in both their natural units of kg CO₂e, and monetised (dollars per kg of CO₂e)

as an additional economic cost, with the software resolving both of these separately. Having both natural units and monetised costs created the flexibility to be able to integrate the results with all the HTA methods.

8.1.2.4 Monetising emissions

The final consideration was how to best monetise emissions. In 2018, the Dutch Ministry of Agriculture, Nature and Food Quality commissioned CE Delft to produce the Environmental Prices Handbook EU28 version.¹¹ The Handbook provided the methodology for how to monetise all life cycle emissions in their midpoint reference units, including impacts in addition to carbon such as particulate matter (in kg PM10-eq), ozone depletion (in kg CFC-eq) and ecotoxicity (in kg 1,4 DB-eq). In addition to providing a cost in Euros for these midpoint emissions, the Handbook also provided a cost for the endpoint unit for health of a Value of a Life Year (VOLY).

In the interests of creating a flexible methodology, I had initially considered including all LCA emissions concerned with human health, such as particulate matter and toxicity, as part of the methodology in addition to carbon. Similarly, I had considered using all monetisation methods contained in the EU28 Handbook, such as using contingent valuation and a willingness-to-pay for avoiding air pollution in cities as a way of calculating VOLYs. Whilst flexibility was important so that LCA results could be included in any method of HTA, having both too many environmental impacts and approaches to monetisation meant the methodology started to lack clarity, especially when carbon emissions have become the primary focus of decision makers. I decided to focus purely on carbon, taking into account

that the other major contributor to human health impacts, particulate matter emissions, tracks carbon emissions due to the burning of fossil fuels.

Focussing on carbon emissions, I had initially only considered using the Social Cost of Carbon, and Marginal Abatement Cost models as ways to monetise emissions. It was only at the start of 2021, when health services started to talk about achieving carbon neutrality, that I realised that carbon offsetting would have to play a big role in healthcare. Health services may be able to reduce their emissions, but they will still have to use consumables such as hypodermic needles, dressings and sutures, and these will be associated with some level of emissions that will have to be offset. Due to this realisation, I included the cost of offsetting as an additional method of carbon monetisation.

8.1.3 Conclusion

Having studied, and applied practicable solutions to all the methodological considerations, there appears to be no technical barrier to stopping carbon impacts being included in multiple methods of HTA. The main barrier is that very few process-based LCAs of healthcare have been performed.

Given the pathway to low carbon healthcare will require multiple changes in all areas of clinical practice, the healthcare sector needs to rapidly commission LCA studies over every health discipline so that these changes can be accurately modelled in HTAs. Results of LCAs, and more specifically the life cycle inventories that contain all the power consumed and the weights of materials used to calculate an LCA, should go to a central repository to enable rapid and accurate modelling by researchers.

8.2 Measuring

This measuring part of the thesis was in recognition of the paucity of LCAs that have been performed in healthcare. Pathology testing and diagnostic imaging are ubiquitous in all parts of healthcare, and so form an important component when determining the carbon impacts of differing pathways of care.

8.2.1 Key findings – pathology testing

Chapter 4, entitled *The carbon footprint of pathology testing* (published in the Medical Journal of Australia) was a consequential LCA of pathology testing, while Chapter 5, entitled *An LCA of hospital pathology testing* (published in the International Journal of Life Cycle Assessment), was an attributional study that additionally included urinalysis. When taken together, the two papers show how attributional and consequential LCA provide complementary information about the best ways to mitigate emissions.

8.2.1.1 Chapter 4 – A consequential LCA of pathology testing

In Chapter 4, the consequential analysis investigated the impacts of the five most common hospital pathology tests: full blood examination (FBE); urea and electrolyte levels (U+E); coagulation profiles; C-reactive protein concentrations (CRP); and arterial blood gases (ABG). The results showed that the majority of the impact originated from sample collection and phlebotomy (range 60% for full blood examination to 95% for coagulation profile). After collection there was a small addition in emissions due to analyser power consumption as a sample was being analysed, and then again when very small volumes of reagent get used for all tests except for FBE.

CO₂e emissions were 116 g/test for FBE, 99 g/test for U+E, 82 g/test for coagulation profile, 49 g/test for ABG, and 0.5 g/test for CRP. This last result for CRP demonstrates how the impacts of the test are primarily due to collection and phlebotomy; how an additional biochemistry test has a very low impact in the laboratory; and lastly how changes in ordering behaviour may not necessarily result in big changes in emissions. CRP samples use the same biochemistry collection tube as U+E samples. While U+E tests are often ordered as a stand-alone item, CRPs very rarely are, and are instead most often ordered in conjunction with a U+E. The consequence of ordering a CRP isn't that an additional biochemistry collection tube is used. Rather, the CRP "piggybacks" on the U+E's collection, with the U+E carrying the full impact of collection.

The hierarchy of reduce, re-use and recycle is often used when describing environmental sustainability. There are limited opportunities in pathology testing, and indeed for much of healthcare, to re-use and recycle due to infection control concerns, and what can be recycled, such as the outer boxes of reagents or phlebotomy equipment, often currently is. Rather, this consequential study showed that the main way to reduce pathology emissions is by reducing the ordering of unnecessary tests, and hence the main source of emissions arising from collection and phlebotomy.

8.2.1.2 Chapter 5 – An attributional LCA of pathology testing

In Chapter 5, the attributional analysis provided a different story on the source of emissions, as the analysis includes the standby power of analysers when they are operating but are not actively running samples. This impact from standby power is especially important when looking at emissions arising from hospitals, where equipment is often left running 24/7 so

that it is immediately available to use in the case of emergencies. Impacts using an attributional approach, therefore, were higher compared to the consequential. CO₂e emissions were 274 g/test for U+E, 233 g/test for coagulation profile, 148 g/test for CRP, 117 g/test for FBE and 74 g/test for ABG. In addition, the paper included the impact of urinalysis (538 g CO₂e/test).

For all the tests, the inclusion of a proportion of stand-by power to each test was the primary cause of the higher emissions compared to the consequential analysis. For some analysers, such as the coagulation profiler and the biochemistry analysers, this standby power usage was high, while the FBE analyser had a minimal standby power usage. Additionally, compared to the consequential analysis, CRP was modelled as having its own collection tube, with this being the primary cause of it having a higher impact. Urinalysis had the highest impact of all the tests due to the electricity required to keep samples heated to 30° Celsius, the compressed air that the analyser required, and the agar plates required to plate samples.

As with the consequential analysis, reducing unnecessary testing is an important way to reduce emissions. The attributional analysis, however, by calculating the impacts of testing as a proportion of total emissions, provides some further insights for potential mitigation strategies. Given the importance of standby power in the overall impact, moving to renewable energy will play an important role in reducing carbon emissions, as will choosing to purchase analysers that have a low standby power consumption.

An increased utilisation of analysers would also result in emissions per test being reduced, and this could be achieved either through centralising non-urgent hospital testing, or by reducing the financial barriers for hospitals to engage in non-hospital pathology testing. There may also be opportunities in the future for point-of-care analysers, and especially the development of biosensors and microfluidics that require pin-pricks of blood rather than whole collection tubes, to further reduce the impacts of pathology testing.

8.2.1.3 Challenges from Chapters 4 and 5

For these papers on pathology testing, I decided to take the approach of one paper targeted at medical professionals and the other at life cycle assessment practitioners, for two main reasons. The first was the basic recognition that, given the multi-disciplinary nature of the healthcare LCAs, it was important to reach both medical professionals and LCA practitioners. Medical professionals are the ones best able to instigate behaviour change in their workplace that will lead to reduced emissions, and LCA practitioners, are going to be increasingly called upon in the upcoming years to undertake LCAs in healthcare. Previous healthcare LCAs have been published overwhelmingly in medical journals, so I felt it was important to start publishing in LCA journals, and begin the process of forming a body of research on healthcare with the methodological considerations for, and in the language of, LCA practitioners.

The second reason was pragmatic. It is difficult to succinctly explain differences in both methodology and results between attributional and consequential LCA, especially in a system where emissions are occurring from both phlebotomy consumables, and from electricity consumption of analysers. As the Medical Journal of Australia had a limited word count, and not wanting the paper to have a major focus on LCA methodology and thus make it less likely

to be published by a general medical journal, I made the decision to submit the consequential analysis to the Medical Journal of Australia. This then meant I could submit the attributional analysis to The International Journal of Life Cycle Assessment, and include a more detailed life cycle inventory section as supplementary information where it would be most beneficial for LCA practitioners. Additionally, in this attributional paper I included all environmental impacts that have an influence on human health (climate change, ozone depletion, ozone formation, fine particulate matter, carcinogenic and non-carcinogenic toxicity, and water consumption), and calculated an endpoint in disability adjusted life years (DALYs), as LCA practitioners have experience in working with and understanding multiple environmental impacts.

8.2.2 Key findings from Chapter 6 – The carbon impact of diagnostic imaging

Chapter 6, *The carbon impact of diagnostic imaging* (in progress) analyses both the consequential and attributional impacts of diagnostic imaging. Five types of imaging were investigated: chest X-ray (CXR); mobile chest X-ray (MCXR); computerised tomography (CT); magnetic resonance imagery (MRI); and ultrasound (US). I decided to combine attributional and consequential approaches in the single paper for two reasons. The first is that, unlike pathology testing, where each test had a range of relative contributions arising from phlebotomy consumables and electricity consumptions for attributional and consequential approaches, thereby potentially increasing confusion for a non-LCA readership, for imaging the primary cause of emissions is electricity. Furthermore, the high electricity consumption of the CT and MRI scanners, and the resultant large variance between attributional and consequential emissions, provides some clarity to understanding the two approaches, unlike for CXR and US where the differences are less pronounced.

The main result from the paper was that MRI and CT have higher emissions for both attributional and consequential approaches compared to the more “traditional” imaging modalities of X-ray and ultrasound, resulting in similar emissions to the known carbon hotspot of anaesthesia. It is preferable, therefore, to either avoid unnecessary ordering of MRIs and CTs, especially for conditions where there is a known overutilisation of imaging such as for lower back pain; and if imaging is required to diagnose a condition, to preference wherever possible either X-ray or US over MRI and CT.

The other results from the paper are very similar to those from the pathology papers. More importantly, compared to pathology testing, diagnostic imaging scanners should be powered by renewable energy whenever possible given their high power consumption. High utilisation rates for individual scanners are also very important, as operating a scanner is associated with an inherent high standby power consumption, regardless of how often actual imaging is performed. Therefore, ensuring high utilisation rates before an additional scanner is ordered or commissioned will reduce the relative impacts of this standby power usage. Similarly, other actions to help reduce the carbon emissions associated with standby power usage include turning off equipment whenever possible, such as overnight or during weekends and public holidays, and choosing to purchase scanners that have low standby power consumption, which will hopefully encourage manufacturers to pursue further reductions in their scanner’s power usage.

8.2.2.1 Challenges from Chapter 6

The main challenge from Chapter 6 was the recorded power consumption from the MRI machine at St George Hospital in Sydney being less than expected when compared to other studies. This error may have been due to a logger error, or more likely, that the electricians placed the logger solely on the MRI machine and not on the electricity feed that included both the helium chiller and the MRI machine. This error, however, turned out to be fortuitous. Western Health's MRI machine, which I subsequently measured, had a higher utilisation rate compared to St George's MRI machine. This difference clearly very highlighted the importance of utilisation when performing the attributional analysis, and more specifically, that if the CT scanner had the same utilisation as the MRI scanner, then it's attributional power consumption would fall from 939 to 237 Wh/min.

8.2.3 Conclusion

The consequential LCAs of pathology testing shows the importance of only ordering tests when necessary, given phlebotomy is the greatest source of emissions. The attributional LCA additionally shows the impacts of standby power, which can be reduced by moving to renewable energy, and ensuring analysers are highly utilised.

For diagnostic imaging, X-ray and ultrasound have lesser impacts compared to MRI and CT for both consequential and attributional approaches, and therefore should be preferentially used whenever possible in place of CT and MRI. Attributional LCA shows that MRI and CT imaging has a carbon footprint comparable to gaseous anaesthesia, a known carbon hotspot in healthcare. This impact could be reduced with the move to renewable energy, along with and ensuring a high utilisation rate of scanners.

8.3 Mitigation

This last section, on mitigation, investigates whether changes in clinical care can lead to a reduction in carbon emissions. More specifically it focuses on the overutilisation of testing, as reducing unnecessary testing should reduce emissions while not adversely impacting patient health.

8.3.1 Key findings from Chapter 7 – Reducing unnecessary testing reduces carbon emissions and financial costs

Chapter 7 is entitled *Carbon emissions and hospital pathology stewardship: a retrospective cohort analysis* (published in the Internal Medical Journal). This paper reports on the retrospective study at St George Hospital in Sydney that investigated the financial and environmental impacts resulting from an intervention to reduce pathology testing in the Department of Medicine (DoM). The initial driver of the DoM to reduce testing was both financial and a concern for patient wellbeing, but with the publication of my paper on the carbon footprint of pathology testing it was recognised that any reduction in testing that was achieved would also be associated with a reduction in carbon emissions. I was therefore invited to collaborate with the DoM to measure the reduction in carbon emission as a result of their intervention.

The intervention was designed in conjunction with heads of department and junior doctors, as anecdotally it was junior doctors who were predominantly ordering unnecessary tests. The policy developed was to limit non-urgent pathology to only two days a week (Mondays and Thursdays), with testing on other days only when urgently needed. The testing policy was

communicated through staff meetings and during orientations for new staff, alongside posters promoting the change (“Twice weekly ordering” and “More is not always better”).

Two 6-month periods were compared; a pre-intervention period from 1 September 2018 to 28 February 2019, and the intervention period a year later from 1 September 2019 to 28 February 2020, with these being chosen to reduce the seasonal effects of changing admissions over winter. While there was a preference to have extended the study so the comparison was a year instead of six months, the change in admissions due to COVID in March of 2020 meant that this was not feasible.

Pathology tests included in the analysis were full blood examination (FBE), coagulation profiles, and the following biochemistry tests: urea, electrolyte and creatinine (CUE) C-reactive protein (CRP), calcium, magnesium, phosphate (CMP), liver function tests (LFT), d-dimer, fibrinogen, thrombin time, amylase, lipase, lactate, creatine kinase, urate, and ammonia.

Financial costs of this testing were taken directly from the billing records for each patient, with these costs including both the initiation fee which covered the cost of collection, and the cost of test analysis. The environmental impacts of each test were taken from the paper *The carbon footprint of pathology testing* (Chapter 4). The impacts for FBE and coagulation profiles were taken directly from the paper, with the impacts for the biochemistry tests being the same as those for CRP in the pathology paper; the impacts of collection fell to CUE, as this was almost always ordered, with each additional biochemistry test therefore only having

an impact of 0.5 g CO₂e (as per the CRP in the consequential paper) due to reagent use, and the small change in power consumption as the analyser performed an additional test.

The differences in pathology collection between the two study periods was analysed with negative binomial regression adjusted for age, sex, type of admission (emergency or planned) and the National Weighted Activity Unit (NWAU) that is used to calculate activity-based funding for hospitals. The differences in CO₂e emissions and financial costs were modelled using generalised linear regression, adjusted for the same variables.

In this multivariable analysis, the intervention period was a significant predictor of a reduction in pathology collections, financial cost and CO₂e emissions. The 10% decrease in the number of pathology collections during the intervention period, which is of a similar magnitude to similar interventions in other studies, was associated with a reduction in carbon emissions of 132 kg CO₂e, and a financial saving of \$53,573 over the six-month intervention. Importantly, these savings were achieved without there being any apparent increase in adverse health outcomes, determined through in-hospital mortality (65 in the reference period and 58 in the intervention period).

If the same 10% reduction in pathology tests occurred in each department of St George Hospital, then annual savings would be approximately 1,300 kg CO₂e and \$500,000.

Extrapolated nationally, a 10% reduction could result in saving of approximately 135,000 kg CO₂e and \$56 million. This study demonstrates the potential of focusing reducing low-value care, in this case the overutilisation of testing, as environmental and financial savings can be realised with just a change in behaviour without any apparent adverse health outcomes.

Additionally, there may be opportunities to further reduce rates of unnecessary testing, by the use of implementation science methodology, changing computer ordering systems, promoting benchmarking, and promoting the reduction in carbon emissions as a driver for behaviour change.

8.3.2 Key findings Chapter 8 – prevalence of unnecessary routine preoperative testing at Western Health

Chapter 8 investigated whether there is an overutilisation of routine pre-operative testing for elective surgery, as this may be an area of focus for healthcare decarbonisation.

8.3.2.1 Key findings

Preoperative testing data for elective surgery was obtained for the 2019 calendar year for patients that were over the age of 16 and were ASA 1 or 2. Data obtained included demographic data, type of surgery, tests ordered 30 days prior to surgery, and which unit of the hospital ordered the tests.

From an initial data record of 8,629 patients, both 865 patients were removed from the analysis because they were pregnant, and 1,798 patients were removed because the only test they received was histopathology, as neither are included in the NICE guidelines. A further 5,387 patients received no testing at all, leaving only 579 patients. 477 patients were then removed because: they received testing in the Emergency Department, with this testing not being due to their upcoming elective surgery; from patients undergoing major or complex surgery, as the NICE guidelines state that testing is indicated for these patients; and those patients who were undergoing a large number of tests over the 30 days prior to surgery, and so the testing they received was not routine.

This left 102 patients who may have potentially received an unnecessary test. The odds of receiving an unnecessary preoperative test in this context, therefore, was only 0.017. While there are no opportunities at Western Health to reduce unnecessary preoperative testing, this may not be true of other services.

8.3.2.2 Challenges

Initially, the intention was to determine the prevalence of unnecessary pre-operative testing at both Western Health, and at Austin Health, both university-affiliated health services in Melbourne. While the data systems at Western Health recorded patient ASA, meaning that patient testing could be compared to the NICE guidelines for preoperative testing, ASA at Austin Health is only recorded manually on a paper sheet on the day of surgery, and this is not subsequently entered into any computer database. The Charleston Comorbidity Index (CCI), however, was recorded at Austin, and I therefore considered using it as a proxy for ASA. A search of the literature showed unfortunately that there was no direct correlation between CCI and ASA, and hence there was a risk of wrongly identifying patients as undergoing unnecessary testing. I therefore chose only to analyse patient data from Western Health, which is a weakness of this chapter as other hospitals may have differing preoperative testing guidelines.

8.3.3 Conclusion

The study at St George showed that reducing unnecessary testing of medical patients under physician care reduces both carbon emissions and financial costs without resulting in adverse patient outcomes. This type of intervention resulting in a 10% reduction in testing is easily implementable at other hospitals, and if extrapolated nationally, would lead to savings in the vicinity of 135,000 kg CO₂e, and \$56 million.

By comparison, the study of routine preoperative testing of perioperative patients being ordered by anaesthetists at Western Health showed no real opportunities to reduce emissions by reducing unnecessary testing, given that minimal amounts of preoperative testing currently occurs for those patients who are ASA 1 and 2 and undergoing minor or intermediate surgery.

8.4 Future research

With the move of health services towards decarbonisation, there is a huge body of future research performing life cycle assessments on all aspects of healthcare that is urgently required, so that carbon emissions can be included in HTAs, carbon hotspots can be identified, and mitigation strategies can be developed. What also needs to be identified is how this research can be performed most efficiently, given the need for rapid action.

Ideally, procurement departments of hospitals, health services and governments should demand LCAs from suppliers showing the carbon footprint of their products. Ideally, this will be under the structure of Environmental Product Declarations (EPDs), which use specific Product Category Rules (PCRs) that define functional units and life cycle inclusions and

exclusions, so products using the same PCR can be accurately compared. Examples of existing PCRs include *Nonwoven wipes*, *Ceramic tiles (EN 17160)* and *Disposable surgical drapes, gowns and air suits*.¹² By making it part of procurement requirements, LCA responsibilities, and costs, are shifted onto manufacturers rather than onto LCA practitioners specialising in healthcare. For these LCA practitioners, it is preferable to use their skills to interact with clinical staff so that they can perform LCAs of specific healthcare activities or models of care, such as an LCA of a lung biopsy, a coronary artery bypass graft, or differing models of palliative care.

LCAs on healthcare activities and models of care should ideally focus on those activities that have been identified in the literature as resulting in overdiagnosis and overtreatment. As I found in the paper on testing at St George Hospital in Sydney, it is possible to reduce low-value care without adverse impacts on patients, and reach both a reduction in carbon emissions and financial costs. As an example, the overdiagnosis literature has identified cancer screening programs¹³, Vitamin D testing¹⁴, and imaging for lower back pain¹⁵ as low value care. Results from the pathology and imaging LCAs undertaken as part of this thesis are able to be rapidly integrated into further attempts to reduce their incidence, hopefully leading to lower carbon emissions.

In terms of the integration of HTA with LCA, this research provides a potential framework. Proof of concept studies using real world data and pathways of care, therefore, need to be performed with a multidisciplinary team of clinicians, health economists and environmental scientists using the methodology outlined in Chapter 3, to determine how feasible the integration is in practice. Furthermore, if the methodology is feasible, then additional studies

will need to be undertaken to ascertain whether the inclusion of carbon emissions will be sufficient to change clinical practice in the same way as economic costs. As a specific example for a cancer screening program that has been identified as leading to overdiagnosis, performing a HTA that goes from a patient receiving a positive Prostate-specific Antigen (PSA) blood test that then leads to various pathways that may include further investigation with MRI imaging or undergoing a prostate biopsy, treatments such as radiation therapy or radical prostatectomy, or newer proposed treatment pathways such as a delayed referral to a specialist with decision support of patients.

While not discussed in the St George paper, the study highlighted the dangers in using Environmental Input-Output (EIO) to calculate healthcare carbon emissions, and therefore potential savings. The financial savings identified in the study (\$53,573), if analysed using EIO would result in a carbon saving of 9,429 kg CO₂e compared to the 132 kg calculated in the paper. Anecdotally, health services are starting to use EIO to identify their carbon emissions, due to a combination of low cost and speed compared to performing process-based LCAs. The concern is that the promised emission reductions based on EIO and the actual reductions based on consequential LCA are significantly different leading to potentially problematic outcomes, especially if areas with high mitigation potential are not correctly identified. Further research is urgently required to examine why there are such large differences in the two approaches for healthcare.

The Hippocratic Oath states, “First do no harm”. Yet, in treating people today, emissions from the healthcare sector result in deaths and lost life years into the future. The decade to 2030 will be vital in stopping irreversible climate change. Healthcare will have to play an important

role in the decarbonisation needed, and there are many challenges that will need to be addressed for this to occur. Nevertheless, as I observed as a scientist working in a clinical setting during the COVID-19 pandemic, if there is a will and appropriate resourcing, then the healthcare sector can be nimble and act quickly.

8.5 References

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