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Climate effect on the incidence of kidney failure patients in Australia

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Abstract

Background Australia's diverse geography and climate conditions may influence the substantial burden of kidney failure. Understanding current climate impacts on kidney health is critical amid ongoing climate change. This study examines geographical variations and associations with climate conditions in kidney failure incidence among patients initiating kidney replacement therapy (KRT).

Methods Data were sourced from the Australian and New Zealand Dialysis and Transplant Registry, the Bureau of Meteorology, and the Australian Bureau of Statistics. Climate conditions, remoteness, socioeconomic index, age, BMI, ethnicity, and state of residence were analysed using a spatial Bayesian regression model to estimate their effects on kidney failure incidence among patients initiating KRT.

Results Among 49,363 patients, 61.5% were male, 74.3% were Caucasian, and 40.5% were former smokers. Kidney failure patients receiving KRT are clustered across Australia (Moran's $I = 0.38$). The incidence rate of kidney failure patients receiving KRT was high in the "hot dry summer, warm winter" (714.2 per 100,000) and "hot humid summer, warm winter" (607.1 per 100,000) climate zones. The risk was high in "hot humid summer, warm winter" (relative risk [RR] = 1.70, 95% credible interval [CI]: 1.30–2.21) compared to "mild to warm summer, cold winter" zone. The risk was attenuated after adjusting for geographical and demographic covariates. Very remote areas had a threefold risk compared to major cities (RR = 3.00, 95% CI: 2.43–3.71).

Conclusions This study revealed substantial regional variations in kidney failure incidence among patients initiating KRT, related to differences in climate conditions, notably hot, humid environments. These incidence patterns also accounted for factors including remoteness, socioeconomic status, and state of residence, highlighting the need to address climate-related health disparities in the context of ongoing climate change.

Keywords Bayesian modelling, Environmental risk factors, Kidney failure, Spatial analysis, Remoteness

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Background

Kidney disease impairs the ability of the kidneys to filter blood and remove waste products [1]. According to the Global Burden of Disease report in 2017, kidney diseases impacted more than 10% of the global population, equivalent to over 800 million cases. When the glomerular filtration rate of a patient falls to less than 15 ml/min/1.73 m^2, kidney disease is considered to be in its end stage, at which point kidney replacement therapy (KRT) with either dialysis or a transplant is required for the patient to continue living [2, 3]. Kidney failure poses a substantial health burden by elevating mortality rates and worsening complications in other conditions, and it demands life-saving interventions [2], underscoring the critical need for effective management and treatment strategies. This condition is marked by a reduced quality of life and an elevated risk of premature death [4].

Kidney failure substantially impacts the Australian population. As of the end of 2018, the prevalence rate of individuals with kidney failure on dialysis was 536 per one million people [5]. Australia experienced a 60% increase in the number of individuals beginning KRT over the past 10 years, rising from 18,536 cases in 2009 to 25,652 cases in 2018 [6, 7]. Australia is one of the largest countries in the world, featuring diverse geographical and climatic zones [8]. Regional variation in kidney failure incidence underscores disparities, with individuals living in remote areas facing noteworthy barriers to accessing dialysis, transplantation, and specialist care due to high costs and limited services [9, 10]. The incidence of kidney failure patients receiving KRT refers to the number of new cases in a population, where a new case is defined by kidney function declining to the point of requiring KRT for survival. Understanding geographical variations in kidney failure patients receiving KRT and their contributing factors is crucial for developing effective prevention and management strategies, offering a rich context for examining the impact of environmental factors on kidney failure [11, 12].

Given Australia's diverse climate, from the hot, humid regions of the north to the mild to warm summer and cold winter areas in the south [13], it is important to examine the relationship between climate conditions and the kidney failure patients receiving KRT. One such important factor driving geographical variations that warrants comprehensive investigation is the role of climate characterised by temperature and humidity [14, 15]. A comprehensive assessment of these factors to evaluate the geographical variations in the kidney failure patients receiving KRT has yet to be conducted.

The Australian and New Zealand Dialysis and Transplant (ANZDATA) registry collects and tracks data for patients with kidney failure receiving KRT in Australia and New Zealand [5], associating factors including age, residence, and socioeconomics with kidney diseases [16, 17]. Despite studies linking socioeconomic factors to kidney failure incidence, the findings remain limited in addressing geographical disparities and the role of climate in its distribution. Some studies have explored the effect of temperature on kidney diseases [8, 18] and their geographical variations [8]. However, insufficient attention has been given to assessing their impact on the incidence of kidney failure patients receiving KRT in the context of broader climate factors. Moreover, the relative risk of kidney failure patients receiving KRT across Australia, which could provide valuable insights into geographical disparities, has not yet been estimated.

This research is motivated by the need to understand the impact of climate on the geographical disparity of incidence of kidney failure patients receiving KRT across Australia. Variations in remoteness, socioeconomic status, and ethnicity across Australia may also be linked with the spread of the incidence of kidney failure patients receiving KRT [19]. This study first assesses geographical patterns of kidney failure incidence among patients initiating KRT, then examines climate condition associations with kidney failure incidence among patients initiating KRT and estimates regional relative risks across varied climates in Australia.

Methods

Study area and participants

This study encompassed all kidney failure patients aged 18 years and above who started their first KRT in Australia between January 1, 2000, and December 31, 2020. Initially, the dataset included 52,113 patients, but after excluding missing location and covariates, the final analysis included 49,363 patients (Fig. 1).

Data source

The data in this study were obtained from the ANZDATA registry [20], which collects information on all kidney failure patients receiving KRT across Australia and New Zealand. The Australian Bureau of Statistics (ABS) was the second data source for this study, from which the estimated resident population (ERP) [21], remoteness area [22], and the socio-economic indexes for areas (SEIFA) [23] were obtained. Climate zone classifications were obtained from the Australian Bureau of Meteorology [13].

Geographical unit

Australia is divided into a hierarchy of statistical areas according to the Australian Statistical Geography Standard (ASGS) used by the Australian Bureau of Statistics (ABS) [24]. This study focuses on the Statistical Area

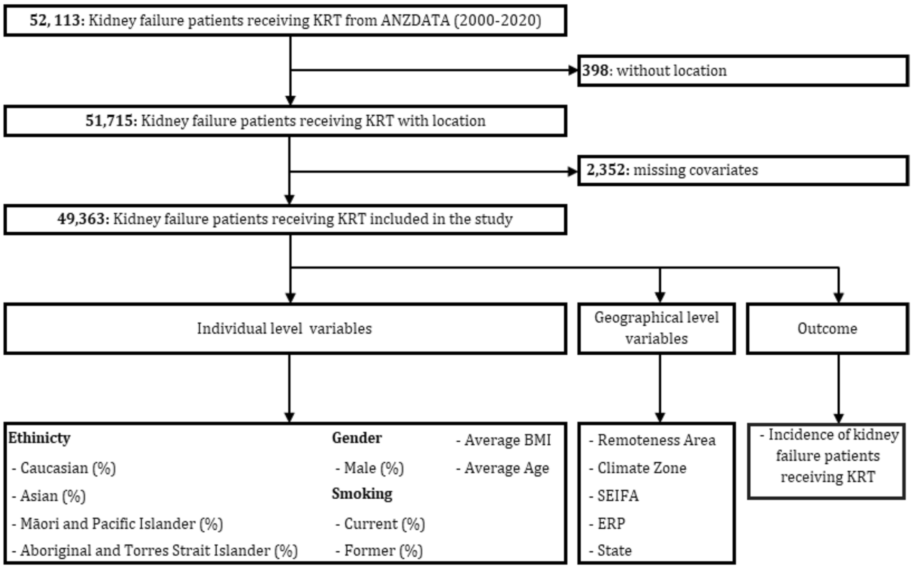

Fig. 1 Data management flow chart

Level 3 (SA3) regions of Australia, which are visually represented by the 340 mutually exclusive polygons designed to reflect regional communities with shared social and economic characteristics. All exploratory analyses, comparisons, and modelling of kidney failure patients receiving KRT in this study were based on SA3 regions, which served as the primary geographical units for investigating geographical variations. National-scale maps of Australia across SA3 regions often obscure patterns within cities due to the dense clustering of smaller regions along the coast, contrasted with larger, sparsely populated regions in remote areas (Additional file 1: Fig. S1). To enhance visibility of smaller regions in city areas, this study also used greater capital city outer boundaries defined by ABS [25].

Outcome variable

The outcome variable of this study was the incidence of kidney failure patients receiving KRT, counted in each SA3 region between January 2000 and December 2020. The annual corresponding ERP between 2000 and 2020 was used in this analysis. For exploratory analysis, the outcome variable was calculated per 100,000 population using the ERP at each SA3 region. In the statistical modelling, expected incidence was incorporated to account for population size differences across SA3 regions.

Exposure variable

In this study, the climate zone was the exposure being investigated for its potential effect on the geographical variations of the incidence of kidney failure patients receiving KRT. We used the Bureau of Meteorology's categorical climate classification, which integrates long-term temperature and humidity patterns to provide a nationally consistent and spatially comprehensive framework for assessing the climate effect on kidney failure incidence across Australia [13]. This classification method identifies six climate zones across Australia based on definitions relating to summer and winter conditions. These are zone 1 (hot humid summer, warm winter); zone 2 (warm humid summer, mild winter); zone 3 (hot dry summer, warm winter); zone 4 (hot dry summer, cold winter); zone 5 (warm summer, cold winter); and zone 6 (mild to warm summer, cold winter) (Fig. 2). Each category of the climate zone is described metrologically for better clarification in Additional file 1: Table S1.

Covariates

Sex (male/female), ethnicity (Caucasian/Aboriginal and Torres Strait Islander/Asian/Māori and Pacific Islander/others), smoking status (former/current/never), age (years), body mass index (BMI, kg/m^2), Australian states and territories (State, New South Wales/Victoria/Queensland/South Australia/Western Australia/Tasmania/Northern Territory/Australian Capital Territory), remoteness area (major city/inner regional/outer regional/remote/very remote), and SEIFA (most disadvantaged to most advantaged: 1st/2nd/3rd/4th/5th quintiles) were considered as the covariates in this study. Ethnicity was coded according to the Australian Standard Classification of Cultural and Ethnic Groups (ASCCEG) [26]. The remoteness areas were defined to measure the relative access to services based on the Accessibility/Remoteness Index of Australia (ARIA+) [22]. The SEIFA in this analysis is the Index of Relative

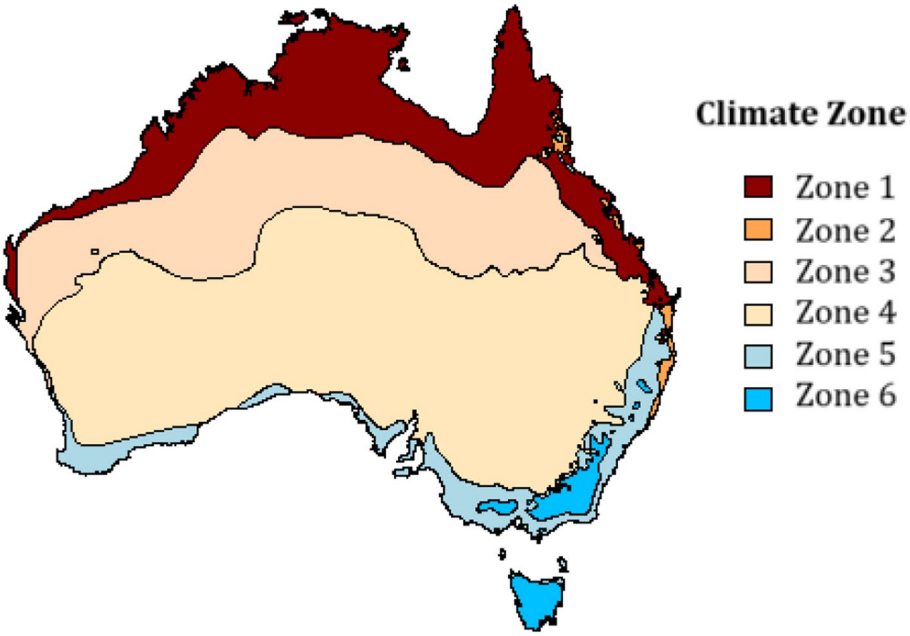

Fig. 2 Climate zone classification of Australia according to temperature and humidity properties across the country, adopted from (BOM, 2023). Zone 1—hot humid summer, warm winter; zone 2—warm humid summer, mild winter; zone 3—hot dry summer, warm winter; zone 4—hot dry summer, cold winter; zone 5—warm summer, cold winter; and zone 6—mild to warm summer, cold winter

Socio-economic Advantage and Disadvantage (IRSAD) scores reported by the ABS in 2021 [23].

Data management

To examine geographical variations, individual-level covariates were spatially aggregated at each SA3 regional level. Categorical covariates (sex, ethnicity, and smoking status) were represented as percentages within each SA3 region, with the percentage of males, for example, serving as a predictor for sex. Numerical covariates (age and BMI) were expressed as averages for each SA3 region (Fig. 1). Climate zones were assigned to each SA3 region via a spatial join using the highest coverage proportion. The same method was applied to remoteness areas. SEIFA and ERP data were obtained at the SA2 level and transformed to the SA3 level.

Exploratory spatial data analysis

Choropleth maps were used to visualise the distribution of the incidence of kidney failure patients receiving KRT (per 100,000) across SA3 regions in Australia (Additional file 1: Fig. S2). To determine whether the distribution of kidney failure patients across regions exhibited clustering, random distribution, or dispersion, we employed global Moran's *I* as a measure of spatial autocorrelation [27]. The study applied the Local Indicator for Spatial Association (LISA) [28] to pinpoint local clusters and spatial outliers in SA3 regions where the incidence of kidney failure patients receiving KRT is located (Additional file 1: Fig. S3).

The distribution of the incidence of kidney failure patients receiving KRT (per 100,000) across climate zones in Australia was explored using descriptive statistics (minimum, maximum, mean, standard deviation, and Moran's *I*). A similar exploratory analysis has been done for remoteness areas, SEIFA categories, and state.

Statistical models

A spatial Bayesian regression model was applied to assess how climate affects the incidence of kidney failure patients receiving KRT, with spatial relationships between neighbouring SA3 regions modelled using random effects via conditional autoregressive modelling within the Integrated Nested Laplace Approximation (INLA) framework and a penalised complexity prior distribution [29]. We used a spatial Bayesian regression model to account for spatial dependence and quantify uncertainty. This approach enables (i) accounting for the influence of neighbouring regions on kidney failure incidence, (ii) producing more stable and reliable estimates, particularly in regions with smaller populations or fewer cases, and (iii) capturing both local variation and broader regional patterns. This model was implemented in three forms: model 1 conducted separate univariable analyses of the exposure variable and each covariate; model 2 expanded on model 1's exposure analysis by integrating all geographical characteristics, specifically remoteness areas, SEIFA, and state; and model 3 included all model 2 variables and the remaining covariates: sex, age, BMI, ethnicity, and smoking status.

For model 3, the incidence of kidney failure patients receiving KRT in the SA3 region i, denoted Y_i, is assumed to follow a Poisson distribution [30], given by,

$$Y_i|E_i, RR_{Geo_i} \sim Poisson\left(E_i * RR_{Geo_i}\right);\ i = 1,2\ldots326,$$

where E_i is the expected incidence in the SA3 region i based on its ERP. The relative risk RR_{Geo_i} indicates how much the observed incidence deviates from the expected incidence in the geographical area (SA3 region) i and is modelled as,

$$\begin{aligned}\log\left(RR_{Geo_i}\right) = \alpha + \sum_{c=2}^{5}\beta_{1c}\text{Climate Zone}_c + \sum_{r=2}^{5}\beta_{2r}\text{Remotness Area}_r + \sum_{z=2}^{5}\beta_{3z}\text{SEIFA}_z \\ + \sum_{m=2}^{7}\beta_{4m}\text{State}_m + \beta_5\text{Male}(\%) + \sum_{k=2}^{4}\beta_{6k}\text{Ethnicity}_k(\%) \\ + \sum_{s=2}^{3}\beta_{7s}\text{Smoking}_s(\%) + \beta_8\text{Average age} + \beta_9\text{Average BMI} + S_i,\end{aligned}$$

where α is an intercept (overall log risk at the reference categories of all categorical variables in the model and at zero for all continuous variables), β terms are coefficients of the corresponding covariates, and S_i captures the total spatial random effect, combining a structured effect based on neighbouring SA3 regions and an unstructured effect with random variation.

In the model, the climate zone 3 (hot dry summer, warm winter) and zone 4 (hot dry summer, cold winter) categories were merged into a single category, zone 3/4 (hot dry summer, warm/cold winter). This was made because only 1.5% of SA3 regions are in zone 3, making it less feasible to model separately. The climate zones in this model consist of zone 2 (c = 2), zone 3/4 (c = 3), zone 4 (c = 4), and zone 5 (c = 5).

The statistical models produce two types of relative risks. The coefficients of the exposure variable and covariates generate a covariate-based relative risk, RR. The spatial component yields a geographical relative risk, RR_{Geo}, specific to each geographical area (SA3 region). The RR_{Geo} values for SA3 regions in each greater capital city are combined to estimate a city-wide relative risk [31].

To assess the robustness of the results, a sensitivity analysis was conducted by replacing the penalised complexity prior distribution with a log-gamma prior distribution.

All the analyses were performed using R statistical software version 4.2.

Results

This study analysed 49,363 kidney failure patients who received kidney replacement therapy, of which 30,349 (61.5%) were male, 36,652 (74.3%) were Caucasian, and over one-third of the patients, 19,982 (40.5%), were former smokers. Most kidney failure patients (65.4%) live in regions with warm summers and cold winters, while a tiny proportion, 0.9% (459), live in zone 3 (hot dry summer, warm winter). On average, the age and BMI of kidney failure patients who started kidney replacement therapy were 60.8 years and 28.1 kg/m^2, respectively (Table 1).

There is evidence of clustering in Australia, as indicated by a Moran's I of 0.38, suggesting that the incidence of kidney failure patients receiving KRT in one SA3 region often mirrors that of nearby regions. Figure 3 visually depicts the geographical distribution of the incidence of kidney failure patients receiving KRT (per 100,000) across SA3 regions in each greater capital city in Australia. The related greater capital city summaries are shown in Additional file 1: Table S2.

Zone 1 (hot humid summer, warm winter) has an average incidence of kidney failure patients receiving KRT of approximately 607 per 100,000, while zone 3 (hot dry summer, warm winter), zone 4 (hot dry summer, cold winter), and zone 5 (warm summer, cold winter) have an average incidence of 714, 402, and 285 per 100,000, respectively (Table 2). The SA3 regions belonging to zone 1 (hot humid summer, warm winter) climate exhibited the most substantial spatial clustering of incidence of kidney failure patients receiving KRT (Moran's $I = 0.34$), followed by zone 4 ("hot dry summer, cold winter", 0.28) and zone 2 ("warm humid summer, mild winter", 0.20). In contrast, zone 6 (mild to warm summer, cold winter) and zone 3 (hot dry summer, warm winter) showed minimal clustering, suggesting more evenly distributed incidence. The overall summary statistics of individual-level variables across SA3 regions were presented in Additional file 1: Table S3.

Table 1 Descriptive statistics of variables

Covariates/exposure	*N* = 49,363 (%)
Sex	
Male	30,349 (61.5)
Female	19,014 (38.5)
Ethnicity	
Caucasian	36,652 (74.3)
Aboriginal and Torres Strait Islander	4995 (10.1)
Asian	4843 (9.8)
Māori and Pacific Islander	1682 (3.4)
Others	1191 (2.4)
Smoking	
Former	19,982 (40.5)
Current	5948 (12.0)
Never	23,433 (47.5)
Remoteness area	
Major city	27,413 (55.5)
Inner regional	10,904 (22.1)
Outer regional	6306 (12.8)
Remote	1211 (2.5)
Very remote	3529 (7.1)
SEIFA (disadvantage score)	
1st quintile group (most disadvantaged)	12,427 (25.2)
2nd quintile group	8771 (17.8)
3rd quintile group	11,105 (22.5)
4th quintile group	9089 (18.4)
5th quintile group (most advantaged)	7971 (16.1)
Age (year)	
Mean (SD)	60.8 (15.3)
BMI (kg/m^2)	
Mean (SD)	28.1 (6.9)
Climate zone	
Zone 1 (hot humid summer, warm winter)	4368 (8.8)
Zone 2 (warm humid summer, mild winter)	5385 (10.9)
Zone 3 (hot dry summer, warm winter)	459 (0.9)
Zone 4 (hot dry summer, cold winter)	4409 (8.9)
Zone 5 (warm summer, cold winter)	32,298 (65.4)
Zone 6 (mild to warm summer, cold winter)	2444 (4.9)
State	
New South Wales	16,273 (33.0)
Victoria	11,245 (22.8)
Queensland	9711 (19.7)
South Australia	3543 (7.2)
Western Australia	5338 (10.8)
Tasmania	999 (2.0)
Northern Territory	1687 (3.4)
Australian Capital Territory	567 (1.1)

Table 3 summarises the estimated results from all three models. In model 1, the risk of kidney failure patients receiving KRT was higher in zone 1 (hot humid summer, warm winter; RR = 1.70, 95% CI: 1.30–2.21) compared to zone 6 (mild to warm summer, cold winter). However, after adjusting for geographical (model 2) and additional covariates (model 3), this elevated risk diminishes (RR = 1.13 and 0.92, respectively). The risk for zone 3/4 (hot dry summer, warm/cold winter) was one and a half times more likely than for zone 6 (mild to warm summer, cold winter) in model 1 (RR = 1.45, 95% CI: 1.15–1.82). Very remote regions consistently showed a higher risk of kidney failure patients receiving KRT compared to major cities in model 1, where these regions were three times more likely to experience kidney failure incidence (RR = 3.00, 95% CI: 2.43–3.71). This elevated risk attenuated to a two times higher risk in model 2 (RR = 2.04, 95% CI: 1.57–2.65) after adjusting for geographical factors and further diminished in model 3 (RR = 1.26, 95% CI: 0.86–1.86).

Incidence of kidney failure patients receiving KRT is highest in the most disadvantaged socio-economic areas, with a mean of 534.3 cases per 100,000 population. It declines steadily with increasing advantage, reaching the lowest mean of 227.8 cases in the most advantaged. The most disadvantaged socio-economic regions displayed strong clustering across SA3 regions (Moran's $I = 0.48$) (Table 2). Table 3 shows that individuals in the most disadvantaged socio-economic group had double the risk of kidney failure (RR = 2.01, 95% CI: 1.72–2.34) than the most advantaged group (model 1). This risk was 1.8 times higher in model 2 (RR = 1.77, 95% CI: 1.51–2.07) and declined to 1.5 in model 3 (RR = 1.48, 95% CI: 1.25–1.76).

The Northern Territory had the highest average incidence of kidney failure receiving KRT of 1085 patients per 100,000 population across the SA3 regions compared to other states in Australia. At the state level, the clustering was observed in Western Australia, followed by the Northern Territory and New South Wales, with Moran's I values of 0.80, 0.36, and 0.32, respectively. In contrast, Tasmania (Moran's $I = -0.21$) exhibited spatial dispersion (Table 2). Individuals residing in the Northern Territory had 2.5 times the risk of kidney failure compared to those in New South Wales and the Australian Capital Territory (RR = 2.47, 95% CI: 1.73–3.51) (model 1). However, this association attenuated to 1.5 times in model 2 (RR = 1.49, 95% CI: 1.05–2.13) and further declined to 1.4 times in model 3 (RR = 1.39, 95% CI: 0.94–2.05) (Table 3).

Age and BMI are associated with the incidence of kidney failure patients receiving KRT across SA3 regions, particularly after adjusting for all geographical covariates, ethnicity, and gender. Each unit increase in average BMI was associated with a 9% higher incidence of kidney

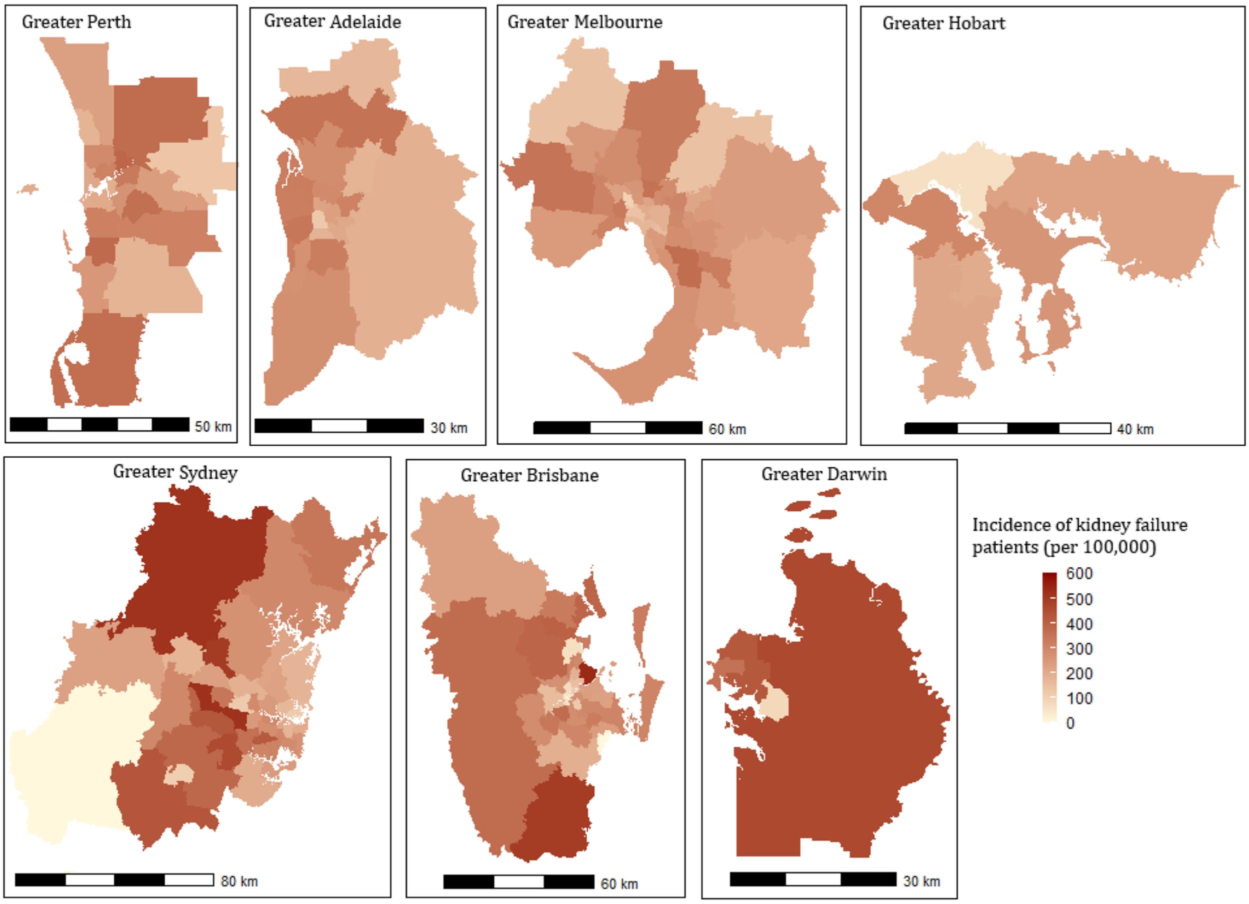

Fig. 3 Incidence of kidney failure patients receiving KRT (per 100,000) across the SA3 regions in each greater capital city

failure patients receiving KRT in model 3 (RR = 1.09, 95% CI: 1.04–1.14). For each year increase in average age, model 3 showed a 4% increase in incidence of kidney failure patients receiving KRT (RR = 1.04, 95% CI: 1.02–1.05).

The spatial effect shown in Table 3 highlights the proportion of variability of incidence of kidney failure patients receiving KRT that can be attributed to spatial dependency across SA3 regions: 13% in model 1 (climate zone only; 0.13, 95% CI: 0.03–0.29), 13% in model 2 (climate zone and geographical variables; 0.13, 95% CI: 0.07–0.30), and 10% in model 3 (all covariates; 0.10, 95% CI: 0.01–0.28). A sensitivity analysis with log-gamma prior yielded results similar to those in Table 3 (results not shown).

The relative risk (RR_{Geo}) for each SA3 region is shown in Fig. 4. The SA3 regions in the northern part of Australia displayed a higher estimated relative risk ($RR_{Geo} > 1$). Most SA3 regions with the highest risk of kidney failure incidence were in very remote areas, falling within zone 1 (hot humid summer, warm winter), zone 3 (hot dry summer, warm winter), and zone 4 (hot dry summer, cold winter) climate zones. Figure 5 displays city-wide RR_{Geo} estimates for greater capital cities, combining RR_{Geo} values from their SA3 regions by climate zone. It reveals substantial variation in kidney failure risk within and between cities.

Discussion

Australia's vast geographical and climatic diversity is linked to disparities in the incidence of kidney failure. This study investigates the influence of temperature/humidity-based climate zones on the geographical variations in the incidence of kidney failure patients receiving KRT across Australia and estimates the relative risk. Variations in incidence across SA3 regions were observed, consistent with other studies highlighting geographical disparities [32, 33]. Notable clustering was found in the central and northern part of Australia, where the hot humid and hot-dry climate likely limits hydration and makes it challenging for residents to maintain the recommended urine volume of 2.0 to 2.5 l per day [34].

Table 2 Summary of incidence of kidney failure patients receiving KRT (per 100,000) across SA3 regions for geographical variables

	No. of SA3 regions (%)	**Min, max**	**Mean (SD)**	**Moran's *I***
Climate zone				
Zone 1 (hot humid summer, warm winter)	24 (7.4)	83, 2437	607.1 (630.1)	0.34
Zone 2 (warm humid summer, mild winter)	47 (14.4)	49, 661	322.7 (120.8)	0.20
Zone 3 (hot dry summer, warm winter)	5 (1.5)	321, 1337	714.2 (389.6)	0.04
Zone 4 (hot dry summer, cold winter)	34 (10.4)	73, 2638	402.2 (421.6)	0.28
Zone 5 (warm summer, cold winter)	184 (56.4)	98, 1516	284.9 (140.1)	0.07
Zone 6 (mild to warm summer, cold winter)	32 (9.8)	63, 593	265.0 (112.1)	0.04
Remoteness area				
Major city	157 (48.2)	49, 561	263.0 (97.0)	0.19
Inner region	78 (23.9)	63, 1516	300 (180.8)	0.15
Outer region	57 (17.5)	83, 1085	287.7 (141.5)	−0.19
Remote	15 (4.6)	73, 581	318 (134.3)	−0.38
Very remote	19 (5.8)	240, 2638	949 (755.8)	0.22
SEIFA				
1st quintile group (most disadvantaged)	63 (19.3)	63, 2638	534.3 (502.3)	0.48
2nd quintile group	67 (20.6)	63, 1086	313.5 (131.5)	−0.02
3rd quintile group	67 (20.6)	68, 661	272.4 (95.6)	−0.26
4th quintile group	65 (19.9)	98, 1516	273.7 (180.5)	0.15
5th quintile group (most advantaged)	64 (19.6)	49, 612	227.8 (88.2)	0.15
State				
New South Wales	88 (27.0)	107, 753	308.0 (112.4)	0.32
Victoria	66 (20.2)	98, 1085	274.3 (128.3)	0.01
Queensland	79 (24.2)	49, 2094	323.8 (281.8)	0.24
South Australia	31 (9.5)	126, 750	273.2 (106.4)	0.12
Western Australia	31 (9.5)	129, 1454	351.4 (246.7)	0.80
Tasmania	15 (4.6)	63, 574	264.7 (103.8)	−0.21
Northern Territory	9 (2.8)	83, 2638	1085.1 (956.2)	0.36
Australian Capital Territory	7 (2.1)	81, 276	190.0 (65.5)	0.25

With limited studies on the impact of climate on kidney failure, we drew comparisons to the broader association between climate zones and kidney disease [35]. Research from the USA [36], Taiwan [37], and worldwide [38] underscores the impact of extreme heat on kidney disease incidence and severity. Remote and very remote regions experience hot dry and humid summers, which lead to excessive sweating and result in the loss of water and sodium. This may result in inadequate hydration and electrolyte imbalance, increasing kidney stress and potentially accelerating the progression to kidney failure [15]. Living in remote and hot climate zones may pose the additional burden of reduced access to healthcare facilities, which may further exacerbate the risk of developing kidney failure. These factors may help to explain why certain communities, including Aboriginal and Torres Strait Islander Australians living in remote and very remote areas, are disproportionately affected by kidney failure [19, 39].

Hot climatic factors may not only contribute to the risk of developing kidney failure, but also increase hospital admissions and deaths among kidney failure patients [40]. The overall risk of kidney failure in hot humid summers is over 10% higher than in mild to warm summers with cold winters. Patients with chronic medical conditions who depend on access to functioning health services are particularly vulnerable during extreme weather events. For patients requiring kidney replacement therapy, the impact of missed dialysis or transplant can be life-threatening. Therefore, the vulnerability of these patients highlights the critical need for reliable healthcare access and preparedness in the face of extreme weather conditions [41]. Advances in kidney replacement therapies have improved survival rates. Still, the increasing number of individuals requiring these treatments highlights the need to implement effective preventive strategies, including exercise, diet, and environmental exposures [4]. The elevated risk of kidney failure incidence among disadvantaged and

Table 3 Estimated relative risk (RR) and 95% credible intervals

	Model 1[a]	Model 2[b]	Model 3[c]
Climate zone			
Zone 6 (mild to warm summer, cold winter) (ref.)	1.00	1.00	1.00
Zone 1 (hot humid summer, warm winter)	1.70 (1.30, 2.21)	1.13 (0.82, 1.54)	0.92 (0.68, 1.25)
Zone 2 (warm humid summer, mild winter)	0.98 (0.78, 1.25)	0.94 (0.70, 1.25)	0.83 (0.62, 1.01)
Zone 3/4 (hot dry summer, warm/cold winter)	1.45 (1.15, 1.82)	0.88 (0.68, 1.15)	0.83 (0.64, 1.07)
Zone 5 (warm summer, cold winter)	1.07 (0.89, 1.30)	1.01 (0.82, 1.25)	0.99 (0.80, 1.21)
Remoteness area			
Major city (ref.)	1.00	1.00	1.00
Inner region	1.10 (0.98, 1.24)	1.03 (0.92, 1.16)	1.07 (0.94, 1.22)
Outer region	1.17 (1.03, 1.34)	0.95 (0.81, 1.11)	0.94 (0.78, 1.12)
Remote	1.21 (0.96, 1.53)	1.05 (0.82, 1.34)	1.01 (0.79, 1.30)
Very remote	3.00 (2.43, 3.71)	2.04 (1.57, 2.65)	1.26 (0.86, 1.86)
SEIFA			
5th quintile group (most advantaged) (ref.)	1.00	1.00	1.00
4th quintile group	1.16 (1.00, 1.34)	1.17 (1.02, 1.34)	1.11 (0.97, 1.27)
3rd quintile group	1.21 (1.04, 1.40)	1.21 (1.05, 1.65)	1.13 (0.98, 1.31)
2nd quintile group	1.39 (1.20, 1.62)	1.41 (1.21, 1.65)	1.24 (1.05, 1.46)
1st quintile group (most disadvantaged)	2.01 (1.72, 2.34)	1.77 (1.51, 2.07)	1.48 (1.25, 1.76)
State			
New South Wales/Australian Capital Territory (ref.)	1.00	1.00	1.00
Victoria	0.94 (0.76, 1.20)	0.94 (0.77, 1.14)	0.96 (0.80, 1.16)
Queensland	0.93 (0.75, 1.15)	0.89 (0.71, 1.12)	0.98 (0.77, 1.22)
South Australia	0.87 (0.65, 1.14)	0.85 (0.66, 1.08)	0.90 (0.66, 1.21)
Western Australia	1.14 (0.84, 1.60)	1.00 (0.76, 1.33)	0.95 (0.74, 1.24)
Tasmania	0.90 (0.67, 1.20)	0.77 (0.56, 1.06)	0.89 (0.66, 1.21)
Northern Territory	2.47 (1.73, 3.51)	1.49 (1.05, 2.13)	1.39 (0.94, 2.05)
Sex			
Male (%)	0.98 (0.97, 1.00)		1.00 (0.99, 1.01)
Ethnicity			
Caucasian (%)	0.99 (0.98, 1.00)		0.99 (0.98, 1.00)
Aboriginal and Torres Strait Islander (%)	1.00 (0.99, 1.01)		1.00 (0.99, 1.02)
Asian (%)	0.98 (0.97, 1.00)		0.99 (0.97, 1.01)
Māori and Pacific Islander (%)	1.00 (0.99, 1.02)		1.00 (0.99, 1.03)
Smoking			
Current (%)	1.03 (1.02, 1.04)		1.00 (0.99, 1.01)
Former (%)	1.00 (1.00, 1.01)		1.00 (1.00, 1.01)
Average age	0.97 (0.96, 1.00)		1.04 (1.02, 1.05)
Average BMI	1.09 (1.04, 1.14)		1.06 (1.00, 1.11)
Spatial effect[d]	0.13 (0.03, 0.29)	0.13 (0.07, 0.30)	0.10 (0.01, 0.28)

[a] Separate univariable analyses of the exposure variable and each covariate

[b] Expanded on model 1's exposure analysis by integrating all geographical characteristics, specifically remoteness areas, SEIFA, and state

[c] Included all model 2 variables and the remaining covariates: sex, age, BMI, ethnicity, and smoking status

[d] The spatial effect represents the proportion of variance explained by the spatial random effect

remote populations in hotter climates underscores public health inequities and calls for targeted interventions to expand prevention, improve access, and ensure equitable kidney care.

The incidence of kidney failure patients receiving KRT is more prevalent and clustered in remote and very remote areas. A report in Australia [9] supported this finding, showing higher kidney failure rates in remote areas than in major cities, primarily due to healthcare

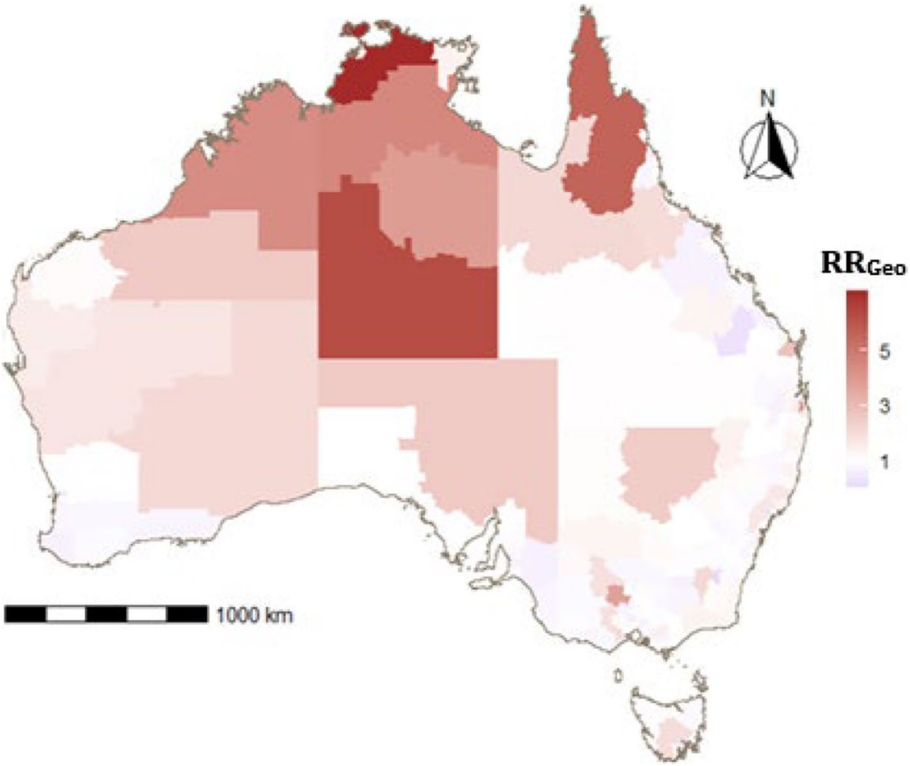

Fig. 4 Estimated geographical relative risk (RR_{Geo}) of incidence of kidney failure patients receiving KRT across SA3 regions in Australia

access and resource challenges, which can delay the diagnosis and treatment. A semi-structured interview study highlighted the important economic, logistical, and psychological challenges faced by individuals in very remote areas seeking dialysis and transplantation services [10]. Similarly, a study conducted in the USA showed that community health behaviours and access to clinical care influence improvements in the estimated glomerular filtration rate (eGFR) [42]. Kidney failure incidence also varies widely across Australian states and territories, with a higher risk in the Northern Territory, which also has a higher proportion of Aboriginal and Torres Strait Islander Australians. The increased risk may in part be explained by the higher proportions of remote communities, lower socioeconomic status, and limited healthcare access [39]. Individuals living in remote regions may have reduced access to early diagnosis and treatment, increasing the risk of kidney failure [43]. The hot and humid climate of the territory can cause dehydration and kidney strain, and likely contribute to higher rates of kidney disease, particularly among individuals engaged in outdoor labour, where extreme heat has been linked to kidney function deterioration [44].

Studies have also reported associations between the geographical variation of kidney failure incidence and demographic as well as socioeconomic factors [45–47]. The higher kidney failure incidence observed in males in this study [48] may be attributed to evidence suggesting that, while females have a greater prevalence of chronic kidney disease (CKD), they progress to kidney failure more slowly than males [49]. A nationwide cohort study conducted on the Korean population demonstrated [50] that smokers have a higher incidence of kidney failure compared to non-smokers. Older individuals are more likely to experience higher risks of kidney failure and related mortality, supporting the finding that the number of kidney failure cases increases with age [49]. Similar to our study, a study [51] observed differences in the number of kidney failure incidences among ethnic groups, supported by findings [52] linking race and ethnicity to CKD development and progression to kidney failure. The risk of kidney failure incidence was over one-third higher among individuals with lower economic status than those with higher economic status, as measured by SEIFA. Likewise, another study reported that lower socioeconomic status and limited access to healthcare in sparsely populated areas increase the risk of kidney failure [53].

The clustering of kidney failure incidence in central and northern Australia, geographically associated with hot-humid (northern) and hot-dry (central) climate conditions, and influenced by remoteness and low SEIFA, as these regions often align with socioeconomically

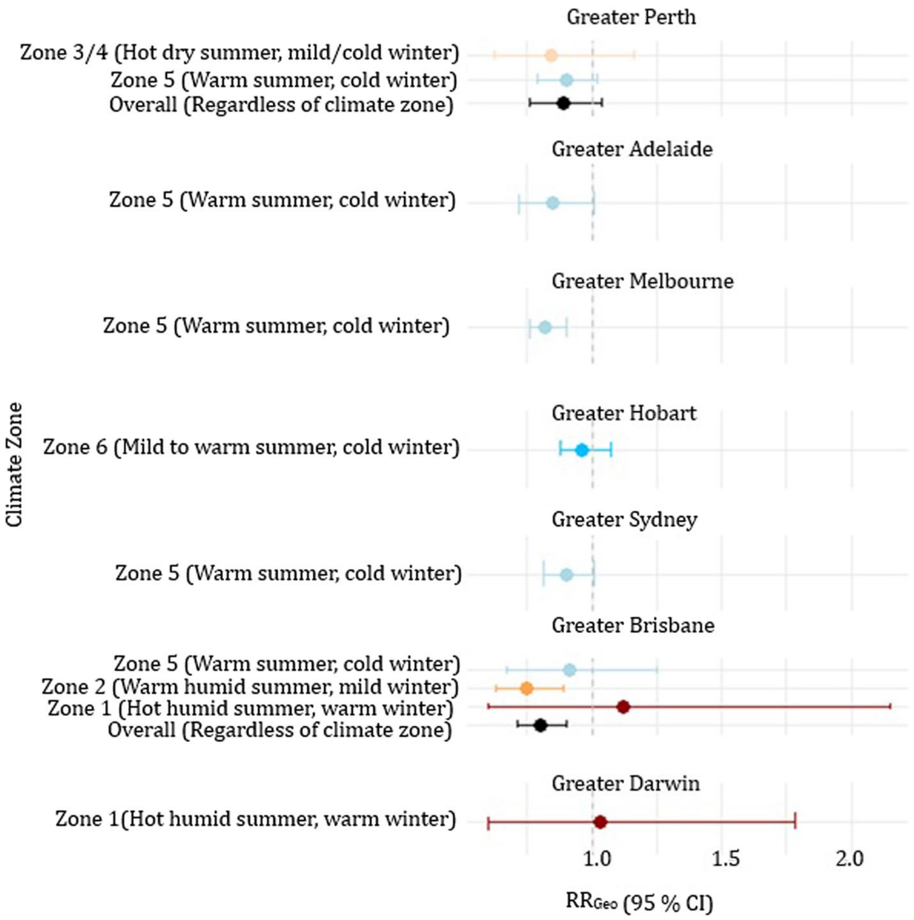

Fig. 5 Estimated relative risk (RR_{Geo}) for greater capital cities by their corresponding climate zones

disadvantaged populations with limited healthcare access. Much of the apparent climate effect was attenuated once SEIFA and remoteness were considered. Persistent hot-humid environments can amplify the risk of kidney failure beyond physiological adaptation [54]. These findings indicate a complex interplay of climate, socioeconomic, and regional factors on kidney failure incidence.

The strengths of this study include using a comprehensive 2000–2020 dataset of kidney failure patients on KRT to pioneer research into the climate's influence on the incidence of kidney failure patients. By analysing patients across this two-decade period, the study captures the significance of geographic and climatic factors on kidney failure incidence and provides a baseline to guide future research incorporating more recent data. The findings are applicable to Australia's adult population aged 18 and over. This study used statistical methods to smooth clustering of kidney failure patients on KRT across Australia's SA3 regions, enhancing risk estimates.

This study has several limitations. In the ANZDATA registry, important information was unavailable, including genetic data, patients managed conservatively without KRT, lifestyle, or other factors such as blood pressure, physical activity, alcohol intake, occupation, and fluid intake. There may also be potential underreporting because participation is voluntary for some centres. The study further did not consider individuals under 18 years or temporal changes in kidney failure incidence and was restricted to KRT initiation without follow-up. Although it covered 2000–2020, more recent data would be valuable to capture current trends and further examine geographic and climatic influences on kidney failure incidence. Relocation to access dialysis services in remote regions potentially misrepresents long-term climate exposure. While our climate classifications capture much of the variation that a heat index would reflect, given their strong correlation with temperature, incorporating continuous measures of heat extremes would strengthen future analyses. The data on acute exposures, such as wildfires, were not considered, and the study's coarse spatial resolution and potential temporal changes in climate conditions within regions remain limitations.

Conclusions

Climate, alongside geographical factors (state, remoteness, and SEIFA) and individual factors (BMI and age), is a key predictor of geographical variations in kidney failure incidence among KRT patients in Australia.

Abbreviations

ABS	Australian Bureau of Statistics
ANZDATA	Australia and New Zealand Dialysis and Transplant
BOM	Australian Bureau of Meteorology
ERP	Estimated resident population
INLA	Integrated Nested Laplace Approximation
KRT	Kidney replacement therapy
LISA	Local Indicator for Spatial Association
SA3	Statistical Area Level 3
SEIFA	Socio-economic indexes for areas

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12916-025-04532-x.

Additional file 1. Fig. S1 The boundaries of Australian states and territories, with polygons representing SA3 regions. Fig. S2 Geographical distribution of incidence of kidney failure patients receiving KRT (per 100,000) in Australia across SA3 regions from 2000 to 2020. Fig. S3 Local indicators of spatial association (LISA). Table S1 Metrological values of each climate zone. Table S2 Incidence of kidney failure patients receiving KRT (per 100,000) across SA3 regions at each greater capital city in Australia. Table S3 Summary statistics of individual-level variables across SA3 regions.

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Authors' contributions

L.M.T. wrote the original draft, conducted coding using R, and prepared the tables and figures. **D.D.** conceptualised the study and managed the overall project administration. **L.M.T., D.D., and G.W.** developed the methodology and conducted data curation and formal analysis. **D.D., G.W., and N.J.O.** provided supervision throughout the study. **L.M.T., M.K.T., N.J.O., G.W., and D.D.** were all involved in the investigation, writing, review, editing, and validation. All authors read and approved the final manuscript.

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Data availability

Data presented in this study are available from the Australia and New Zealand Dialysis and Transplant (ANZDATA) Registry upon formal request.

Declarations

Ethics approval and consent to participate

This study used de-identified secondary data obtained from a national registry. As no identifiable human subjects were involved, individual patient consent was not applicable. Ethical approval for the study was obtained under institutional guidelines from the University of Queensland in March 2022 (approval number: 2022/HE000606).

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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