Effect of polyester and plaster of Paris casts on determination of volumetric bone mineral density assessed by peripheral quantitative computed tomography (pQCT)

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Abstract

Peripheral quantitative computed tomography (pQCT) is a non-invasive, low radiation tool for measuring volumetric bone mineral density. It has potential for use in fracture healing applications, however the unknown attenuation effects of cast material on peripheral quantitative computed tomography have contributed to its limited use in this area. The effect of two common cast materials, polyester and Plaster of Paris was investigated by performing both *in vitro* and *in vivo* studies. The *in vitro* study tested the effect of increasing

layers of cast material on bone density measurements performed on a hydroxyapatite phantom. Cast thickness was directly associated with a reduction in bone mineral density, with twelve layers of polyester and Plaster of Paris resulting in a 0.55% and 2.21% decrease in bone density measurements. Precision error *in situ* with polyester cast material was 0.71%, and 2.31% with Plaster of Paris cast material. The *in vivo* study comprised a prospective trial with 28 healthy adult participants to evaluate the effect of the two cast materials. Trabecular bone mineral density was increased by 0.5% in the presence of a polyester cast, and decreased 4.22% in the presence of a Plaster of Paris cast. Cortical bone mineral density was decreased 3.46% and 5.54% for polyester and Plaster of Paris respectively. This study quantified the effects of orthopaedic casts on pQCT derived bone parameters. The results suggest applicability of commonly utilised cast materials in combination with pQCT to assess fracture healing.

1. Introduction

Compared to the commonly applied, more widely available dual X-ray absorptiometry (DEXA) which provides areal bone mineral density data, pQCT provides true volumetric density measures which are not affected by size and orientation of the object with respect to the imaging source and, hence, has the ability to distinguish between different bone types, such as dense cortical bone and spongy trabecular bone. pQCT is being increasingly utilised as a non-invasive, low radiation (effective dose 0.72-1.43 μSv) tool for estimating changes in bone mineral density (BMD) in osteoporosis [1, 2], and provides 3D volumetric BMD measurements at a resolution of 0.2mm isotropic voxel size. Moreover, pQCT bone mineral density measurements can also be utilized to calculate the mechanical properties, of bone tissue [3, 4].

At present, fracture healing is assessed by qualitative clinical examination in combination with plain X-ray radiographs of the fracture site. However, this approach remains imprecise contributed by the presence of a stabilizing cast, both polyester and Plaster of Paris, significantly increasing the attenuation of plain radiographs, obscuring bony detail. Limitations of plain film radiography implies that fractures are currently treated based on previous experience with a particular fracture type, rather than being tailored to the healing progress of individuals. For example, fractures of the upper limb are usually immobilised for six weeks, despite the potential for union either side of this time point, yet some fractures may be mobilised inappropriately early, contributing to the risk of re-fracture, which has been shown to occur in 1.4% of forearm fractures [5]. Conversely, immobilising fractures for longer than necessary increases the risk of complications such as pressure areas, disuse muscle wasting and reduction in the range of movement of immobilised joints, in addition to the inconvenience of extended, unnecessary immobilisation.

More modern imaging techniques such as pQCT can provide objective measurements of bone strength, potentially guiding decisions regarding the safe removal of casts, weight bearing restrictions, as well as management of limb-lengthening procedures and removal of metal ware.

The recent work of de Kooter, v Rietbergen *et al* has assessed the reproducibility and reliability of bone morphological and mechanical parameters obtained from measurements using high resolution peripheral quantitative computed tomography (HR-pQCT) of the distal radius in the presence of a polyester cast [6-8], however, very few studies to date have addressed the effects of cast materials on pQCT measurements.

The aim of this study is to evaluate the effect of polyester and Plaster of Paris cast material on the accuracy of bone mineral density (BMD) measurements using pQCT in the presence of orthopaedic cast material in healthy adults, and to thereby validate the potential application of pQCT as a clinical tool for assessment of bone mechanical properties whilst immobilised by a cast.

2. Methods

i. Bone mineral density measurement and calibration

pQCT measurements were performed using a Stratec XCT3000 (Stratec Medizintechnik GmbH, Germany). *Scanner settings:* voltage: 59-61 kV, anode current: 250-400 μ A, mean X-ray energy 42 keV, energy after filtration: 19 keV. The same scan parameters were used for all scans: 2 mm scan slices, 0.4 mm voxels at a speed of 20 mm/s. All scans were performed by the same trained technician. Daily calibration was completed using the Quality Assessment (QA) European Forearm phantom provided by the manufacturer.

ii. Study 1: Effect of cast material on *in vitro* pQCT measurements

A manufacturer provided hydroxyapatite phantom (Stratec Medizintechnik GmbH, Germany - in the following referred to as “QA phantom”), was used to assess the influence of the cast material and thickness on the pQCT measurements. The QA phantom used was of cylindrical shape ($l = 40\text{mm}$, $d = 50\text{mm}$) and comprised three different materials with attenuation properties replicating cortical bone, trabecular bone and soft tissue. The QA phantom was mounted on a rigid “arm” and ten axial scans were performed at 2mm intervals along the length of the QA phantom as a control (Figure 1). The QA phantom is defined by the following nominal values describing the linear relationship between the attenuation and the BMD: $\text{XSlope} = 1484.0$, $\text{XInter} = -337.3$.

A total of twelve layers (typically the number of layers applied to immobilise a fracture in clinical practice would be around four) of cast material were then placed around the QA phantom with pQCT measurements taken between alternate layers. At each cast thickness, five pQCT slices were taken at 1 mm intervals using a 0.4 mm pixel size. This process was repeated using both synthetic polyester cast material and Plaster of Paris, two commonly used casting materials in clinical practice. The polyester cast material described in this paper consists of an open-weave polyester and cotton fabric impregnated with water activated polyurethane resin. Mineral density of the QA phantom used to represent trabecular bone was measured using the standard Stratec image analysis software (Stratec Medizintechnik GmbH, Germany). An automated “region of interest” function was used to select this region with a threshold of 280 mg/cm³.

Figure 1: *In situ* QA phantom scans: with polyester cast material (left) and Plaster of Paris cast material (right)

iii. Study 2: Effect of cast material on *in vivo* pQCT measurements

A prospective study of healthy volunteers aged 18-65 was performed. Ethical approval was obtained (Melbourne Health HREC approval 2014.272). Exclusion criteria included any primary bone disease or risk factors for secondary bone disease. Forearm length was

determined by measuring the distance between the ulnar styloid process and the tip of the olecranon on the dominant forearm to the nearest millimetre.

Participants' non-dominant wrist was sequentially immobilized by a professional plaster technician using a synthetic polyester cast (Delta-Cast Elite, BSN Medical GmbH, Hamburg), which was then removed, followed by the application of a Plaster of Paris cast (Gypsona, BSN Medical GmbH, Hamburg). Each cast was applied from the metacarpal heads to 2 cm proximal to the elbow flexor crease. A coronal computed radiograph (referred to as a "scout view") was used to position the scanner at the distal radial metaphysis at a distance from the distal radial articular surface representing 4% of forearm length, and at the diaphysis at a distance that represents 66% of forearm length. The 66% site has previously been shown to average 99.5% of the maximum circumference of the forearm [9]. A single tomographic slice of 2.0 mm thickness was taken at both the 4% and 66% sites through each cast material. This same scanning protocol was then repeated without a cast. Participants were repositioned between each measurement. Image quality was assessed for motion artefact by the pQCT technician at the time of scan acquisition. Scans deemed to be associated with excessive movement were repeated.

Image analysis was performed using the manufacturer's standard software (Stratec Medizintechnik GmbH, Germany). Analysis of tomographic slices taken at the 4% site included trabecular BMD, total BMD, total cross-sectional area (CSA), and total bone mineral content (BMC). pQCT slices taken at the 66% site were analysed for a range of bone parameters including cortical BMD, cortical CSA, total BMC, marrow BMD, marrow CSA and strength-strain index (SSI). The soft-tissue parameters analysed at this site were muscle CSA,

muscle density and fat CSA. The area of bone for analysis was automatically determined using a 'region of interest' function. Standard density thresholds provided by the manufacturer were used. Trabecular bone mineral density was measured at the 4% site with the outer bone contour of the radius detected at a threshold of 280 mg/cm³. Cortical bone was measured at the 66% site with a threshold of 710 mg/cm³.

iv. Statistical analysis

Statistical analysis was performed using IBM SPSS statistics software Version 21. The absolute and relative precision of repeated measurements was assessed using root mean square standard deviation (RMS-SD) and the root mean square coefficient of variation (RMS-CV) respectively [10]. Data obtained from *in vivo* studies was of parametric nature, and assessed for significance using a paired student t-test. The null hypothesis of pQCT scans without a cast was compared to each alternative hypothesis of scans performed in the presence of either polyester or Plaster of Paris cast on each participant.

3. Results

a. Study 1: Effect of cast material on *in vitro* pQCT measurements

Scans demonstrated a continuous decrease in the measured QA phantom density for each additional layer of cast material *in situ* (Figure 2). The mean density of the phantom without cast material was 322.5 mg/cm³ (SD = 0.3). Four layers of cast material (approximately the thickness of orthopaedic casts) decreased the average phantom density measurement to 321.1 mg/cm³ (SD = 0.7) for polyester and 317.9 mg/cm³ (SD = 0.5) for Plaster of Paris. With twelve layers of cast material *in situ* this was further reduced to 320.7 mg/cm³ (SD = 0.9)

and 315.4 mg/cm³ (SD = 0.8) respectively. Attenuation of the plaster of Paris was greater compared to the polyester cast for all different layer thicknesses.

Figure 2: Study 1 – Effect of cast material on the QA phantom measurements: Percentage change in mean QA phantom density (mg/cm³) measurements with increasing layers of cast material from 0 to 12 *in situ*. Error bars represent the standard deviation. *denotes significance $p = <0.05$ compared to no cast.

Cast Layers	Polyester			Plaster of Paris		
	Mean vBMD	RMS-SD	RMS-CV	Mean vBMD	RMS-SD	RMS-CV
Baseline	322.5			322.5		
2	321.5	1.27	0.39	319.3	3.54	1.11
4	321.2	1.86	0.58	317.9	4.96	1.56
6	321.1	1.71	0.53	316.7	6.10	1.93
8	321.3	1.54	0.48	316.8	6.09	1.92
10	321.0	1.85	0.58	315.3	7.51	2.38
12	320.7	2.27	0.71	315.4	7.47	2.37

Table 1: Study 1 – Effect of cast material on the QA phantom measurements: Precision of phantom volumetric bone mineral density (vBMD) in mg/cm^3 . RMS-SD = root mean square standard deviation (mg/cm^3); RMS-CV = root mean square coefficient of variation (%).

The precision of measurements as represented by the RMS CV is shown in Table 1. Precision with up to twelve layers of polyester cast was less than 0.71%. Comparatively, the presence of a Plaster of Paris cast increased this to 1.11% with two layers *in situ*, up to 2.37% with twelve layers *in situ*.

b. Study 2: Effect of cast material on *in vivo* pQCT measurements

Twenty-eight volunteers (female = 14; male = 14) were recruited with a mean age of 33 years. Participants had a mean forearm length of 265 mm. All 28 participants completed scans with and without a polyester cast *in situ*. One participant was unable to complete follow-up with a Plaster of Paris cast due to time commitments, and two scans from participants with a Plaster of Paris cast *in situ* were unable to be analysed due to an incorrect scanning protocol being used. Thus a total of 25 usable sets of scans (see Figure 3) with a Plaster of Paris cast *in situ* were available.

Figure 3: Example of pQCT images from a single patient with a) no cast, b) polyester cast, and c) Plaster of Paris cast

Figures 4a and 4b summarise the effect of the different cast materials on the listed parameters. The *in vivo* study reproduced the results of the phantom study, with Plaster of

Paris having a greater effect on bone density measurements than polyester. In addition, measurements of cross-sectional area were also influenced by having a Plaster of Paris cast *in situ*. Significant differences for polyester casts were only found for total bone density and total cross-sectional area at the 4% site.

Figure 4a: Percentage change in measured parameters at the 4% site, and soft-tissue measurements compared to baseline with polyester and Plaster of Paris casts *in situ*. D.trab = trabecular bone mineral density; D.tot = total bone mineral density at 4% site; Mass.4% = total mass at 4% site; A.tot.4% = total cross-sectional area at 4% site; A.musc = muscle cross-sectional area; D.musc = muscle density; A.fat = fat cross-sectional area. *denotes significance $p < 0.05$ compared to no cast.

Figure 4b: Percentage change in measured parameters at the 66% site compared to baseline with polyester and Plaster of Paris casts *in situ*. D.cort.r = cortical bone mineral density of the radius; A.cort.r = cortical cross-sectional area of the radius; A.tot.r66% = total cross-sectional area of the radius at the 66% site; D.cort = total cortical bone mineral density; A.cort = total cortical cross-sectional area; A.tot = total cross-sectional area at the 66% site; A.marr = bone marrow cross-sectional area; D.marr = bone marrow bone mineral density; Mass.66% = total mass at 4% site; SSI = strength strain index. *denotes significance $p < 0.05$ compared to no cast.

	Polyester (SD)	Plaster of Paris (SD)
D.trab	0.50 (2.85)	-4.22* (2.58)
D.tot	-2.55* (4.93)	-6.28* (6.04)
Mass	0.20 (1.67)	-5.57* (2.75)
A.tot.4%	3.12* (5.97)	1.05 (7.55)
A.musc	0.34 (4.46)	2.28* (5.23)
D.musc	-0.15 (5.11)	-2.41* (5.27)
A.fat	-5.89 (16.43)	-8.91* (15.19)
D.cort.r	0.23 (2.57)	-1.59* (2.71)
A.cort.r	1.66 (6.44)	-1.63 (6.38)
A.tot.r66%	2.16 (23.21)	1.25 (14.12)
D.cort	-3.46 (18.04)	-5.54 (17.8)
A.cort	0.11 (20.86)	-0.65 (17.02)
A.tot	-2.55 (13.37)	-0.20 (17.1)
A.marr	2.46 (16.24)	0.60 (15.85)
D.marr	-2.72 (101.31)	-6.10 (114.04)
Mass.66%	3.88 (3.91)	-1.49 (6.71)
SSI	7.58 (29.4)	-7.72* (15.95)

Table 2: Mean percentage difference in pQCT parameters and standard deviations compared to baseline. *denotes significance $p = <0.05$.

c) Discussion

To our knowledge, this is the first study to quantify the change in density measurements produced by casting material, which is critical to determine before further exploring the potential application of pQCT in the evaluation of fracture healing. The two most commonly utilized cast materials in orthopaedic practice are polyester and Plaster of Paris. The type of cast material used is based on clinician preference, which has traditionally been Plaster of Paris because it is relatively cheap and easily available. There are now several newer synthetic cast materials available. This material has the advantage of being more lightweight, durable, and more radiolucent than Plaster of Paris.

In the presence of a cast, the X-ray beam is attenuated before entering the forearm, not only increasing noise in the tomographic image, but also modifying the x-ray beam profile before it hits the forearm, as observed in beam hardening cases. It is this phenomenon that is thought to be responsible for the change in BMD measurement. Hence, this effect decreases with use of less radiolucent materials and layers of cast material, as was shown in Study 1, our phantom limb testing study (Figure 2). Both polyester and Plaster of Paris had a statistically significant impact on measured QA phantom vBMD. This effect was more pronounced with Plaster of Paris because of its higher attenuation, and it was observed at even a low number of cast material layers. However the significance of this is likely to be statistically rather than clinically significant, largely because of the low coefficients of variation between repeated measurements. The average absolute difference in measurements was $\leq 2.5\%$ for all layers and types of cast material *in vitro* (Figure 2), compared with the density of healing callus in an animal model being previously shown to increase by around 52% between two and six weeks post injury [11]. This is representative of the transition from soft to hard callus, and is a much greater change in vBMD than the estimated loss of precision of 0.5% due to use of a standard polyester cast (4 layers).

Study 2, the *in vivo* study showed that the presence of a polyester cast had a significant effect on the total BMD and total area at the 4% site. This may be explained by reduced movement artefact at the 4% site resulting in higher precision of measurements, and therefore despite the percentage change being quite small, a statistically significant difference is more easily produced. There was no significant difference seen for the remainder of pQCT derived bone measurements. Our findings for the polyester cast at the 4% bone region can be compared with the HR-pQCT data by van Kooten which also found

that there was no significant effect of the polyester cast on the vBMD measurement and determination of mechanical properties [6]. As expected, the presence of a Plaster of Paris cast influenced a larger breadth of measurements at both the 4% and 66% sites. Despite this, all differences were less than 9% compared to no cast. Based on this polyester casts may be seen as preferable for use in conjunction with pQCT scans, however this study also provides estimates of expected change in measurements in the setting of either cast type.

The precision of pQCT measurements taken with polyester cast material *in situ* was excellent. The CV with four layers of polyester cast material *in situ* (approximate thickness of a cast used clinically) was 0.58%. Twelve layers of cast material produced a CV of 0.71%. This is comparable with previous estimates *in vitro*, which have shown the mean CV for short-term precision measurements to be less than 0.67% [12]. The relative precision error was high with Plaster of Paris cast material *in situ*, ranging from 1.11 - 2.37%. Despite being much higher than that of polyester, this value is in line with the *in vivo* precision error for bone measurements, which has previously been shown to be less than 2.25% [13, 14].

In a clinical setting the exact thickness of cast material at the fracture site is difficult to control, and therefore the measured BMD can be expected to be more variable compared to the QA phantom measurements. This is because the cast is applied to the limb as a whole, rather than just at the fracture site. This results in the overlap of cast material at different points around the fracture site, and minor variations in cast thickness within the pQCT slice. This was reflected in the *in vivo* study, which showed the standard deviation of trabecular BMD measurements to be 43.3 mg/cm³ and 41.2 mg/cm³ for polyester and Plaster of Paris respectively, compared to the largest standard deviation in the QA study of SD 0.89 mg/cm³. Additional movement artefact is also likely to contribute to this.

pQCT has a number of advantages over other absorptiometry imaging techniques. pQCT assessed vBMD has been shown to be more representative of actual bone material quantity and quality compared to areal bone mineral density (aBMD) obtained from DEXA measurements [15]. The effective dose from pQCT examination has been estimated as lower than 0.01 mSv [16], a figure comparable with a plain film radiograph of a distal limb (0.01 mSv) and peripheral DEXA (0.01 mSv)[17]. However, pQCT is currently infrequently utilised in the clinical setting due to limited reference data, minimization of movement artefacts and patient positioning being critical in producing accurate and reproducible scans, and the lack of availability of pQCT scanners. Despite this, pQCT offers many potential advances in the assessment of bone biomechanical properties.

d) Conclusion

We have shown that pQCT measurements are affected by the presence of both polyester and Plaster of Paris cast material. Cast thickness was associated with a reduction in BMD measurements, with Plaster of Paris casts having a higher attenuation compared to polyester casts. This reduction is proportionally much lower than the previously estimated density changes during fracture healing, and indeed this effect was not significant when using standard thickness casts *in vivo*. This demonstrates that pQCT is a feasible method for imaging in the presence of either a polyester or Plaster of Paris cast.

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Contributors Statement

Authors MB, CR and PP designed the study. Author MB performed the phantom study and the in vivo trial and prepared the first draft of the paper. He is guarantor. Authors RB, CR and PP contributed to the experimental work. All authors revised the paper critically for intellectual content and approved the final version. All authors agree to be accountable for the work and to ensure that any questions relating to the accuracy and integrity of the paper are investigated and properly resolved.

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