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Three-dimensional reconstructed MRI of an acrylic meniscal cartilage phantom: The effect of acquisition slice thickness upon accuracy of volume measurement

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ABSTRACT

The aim of this study was to determine the influence of slice thickness upon the accuracy of volume measurement taken from three-dimensional reconstructed magnetic resonance (MR) images.

A pair of scaled meniscal cartilage phantoms (medial and lateral) were created from a low viscosity acrylic casting resin. The two phantoms were imaged simultaneously using a modified proton density turbo spin-echo (PD TSE) MR sequence at slice thicknesses of 4.0, 3.0, 2.0, 1.5 and 1.0mm. At each slice thickness, a three-dimensional reconstructed image of each phantom was created, using a commercially available software package. Using the software's inbuilt analysis functions, a volume measurement was then made of each image.

The software generated volume measures were compared to a "gold standard" mass/density measure of the phantoms. Percentage measurement error (PME) measures were calculated, with mean values ranging from 19.42% (4.0 mm slice thickness) to 1.05% (1.0 mm). Paired *t* testing suggested no statistically significant difference ($P = 0.15$) between the means of the PME values for the two phantoms suggesting an acceptable degree of measurement consistency.

In conclusion, the results of this study suggest that the three-dimensional reconstructed technique can be used to achieve a highly accurate volume measurement (PME < 5%) of irregular (non-geometric) objects or image components (such as human meniscal cartilages) without the need to employ sub-millimetre acquisitions. Such slice thicknesses are within the capabilities of most commercial MR scanners, making the results reported here relevant to the majority of clinical imaging sites.

Key words:
Three-dimensional reconstruction; measurement error; acrylic phantom; MRI.

INTRODUCTION

Previous work has demonstrated the reliability of three-dimensional reconstructed techniques in obtaining volumetric information and in allowing highly accurate[1] and repeatable[2] measurement of simple objects, in a pre-clinical setting. Some authors have discussed the further progression of this capability from planar (linear) functions to interactive three-dimensional volumetric analysis.[3-5]

It has been suggested that volumetric measurements generated from three-dimensional reconstructive techniques represent a more reliable technique compared to conventional (sectional) imaging, the former being unaffected by the plane of data acquisition and minor variations in patient/object (re)positioning.[4,6-8] Some preliminary work has been attempted in this area previously but the reported findings show varying degrees of inconsistency and the fundamental effects of acquisition slice thickness and lesion size have not been definitively quantified. A previous undertaking by Marshall et al[3] proposed an acrylic phantom based model for testing the application of three-dimensional reconstructive medical software in a preclinical setting. Although broadly discussing the concept, quantifying the direct effect of slice thickness upon the accuracy of volumetric analysis was not a focus of this study.[3]

The current work builds on another earlier study[9] that explored the application of a volumetric analysis technique using simple acrylic phantoms of known geometric sizes. In that study, a series of cubic acrylic phantoms were imaged using a proton density, turbo spin-echo (PD TSE) sequence, at varying slice thicknesses, to determine the effect of slice thickness upon three-dimensional image volume measurement accuracy. The findings suggested that a high degree of volume measurement accuracy could be achieved using slice thicknesses routinely used in musculo-skeletal imaging (i.e. 1 - 4 mm).[9] This study was however restricted to geometric volume measurement and had limited applicability to the clinical setting. The aim of the current study was to quantify the relationship between slice thickness and

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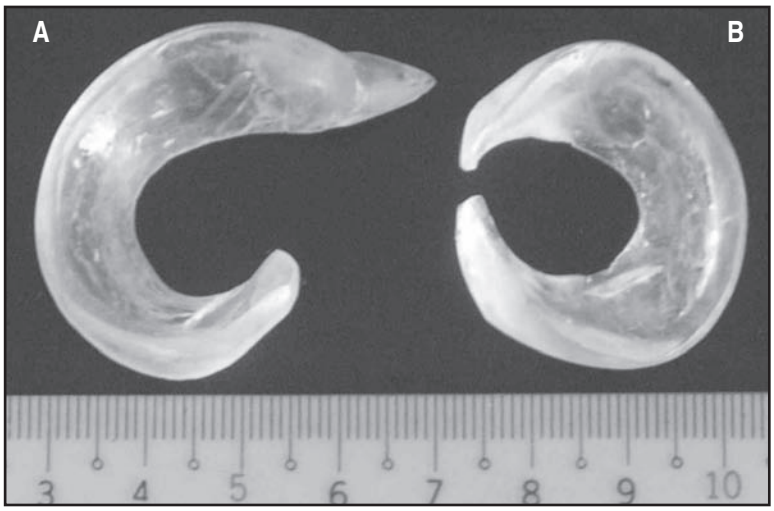
accuracy of volume measurement derived from three-dimensional reconstructions using an acrylic phantom to simulate the human meniscal cartilage.

METHOD

Phantom creation

Two solid acrylic phantoms were purpose manufactured to resemble human menisci. They were shaped using a negative cast, poured-resin approach, to reflect a scaled presentation of disarticulated medial (phantom A) and lateral (phantom B) meniscal cartilages of an adult human knee. A low viscosity acrylic casting resin (Megapoxy HX; RESIMAX, Adelaide, Australia) was used for phantom creation with the moulds left to set at ambient room temperature for 72 hours. The final phantoms, following hand and machine polishing, are shown together in Figure 1.

A mass/density technique was employed to determine the reference (precise) volume of each phantom. An A-200S digital balance (Sartorious Analytics, Gottigen, Germany) with a stated accuracy of 0.0001 grams was used to determine the weight of each phantom separately. To minimise random error, the weighing process was repeated in its entirety five times for each phantom. The mean weight for each phantom was then calculated and used for subsequent volume determinations. Given the manufacturer provided specific gravity of the set acrylic compound (1.07), the formula {volume = mass/density} was used to calculate the precise volume of each phantom.

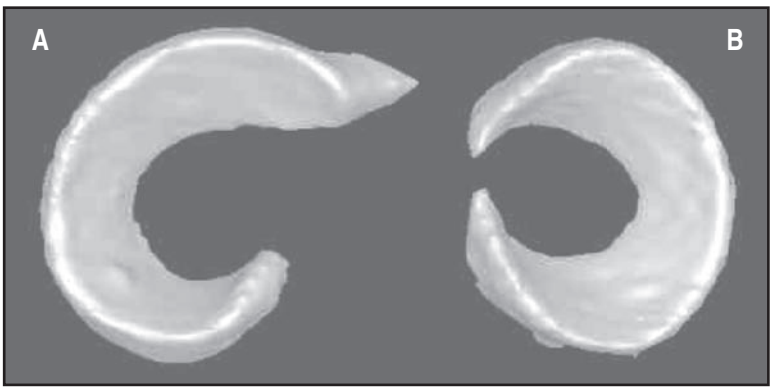


Above

Figure 1: The acrylic meniscal phantoms showing (A) medial and (B) lateral cartilages.

Below

Figure 2: Three-dimensional reconstructed computer display of the two acrylic meniscal phantoms showing (A) medial and (B) lateral cartilages.



MR scanning

Using a technique employed previously,[9] the phantoms were suspended using nylon thread in the centre of an air-tight water bath and were completely immersed in water. Careful attention was paid during water immersion to ensure the absence of surface adherent air bubbles. Based on earlier work,[9,10] water was used to surround the phantom in an attempt to provide a maximal degree of delineation of the fluid/phantom interface.

All scan data were acquired using a 1.5 Tesla Philips Intera Gyroscan MR device (Best, Netherlands) and a receive-only quadrature lower extremity coil (IGC Medical Advances Inc, Milwaukee, WI, USA). The two phantoms were imaged together using a two-dimensional (anisotropic), modified PD TSE sequence (repetition time [TR] 1500; echo time [TE] 20; flip angle [FA] 90º; echo train length [ETL] 5; inter-slice gap 10%; matrix 256 x 256; field of view [FOV] 140 mm), in a superoinferior plane, at slice thicknesses of 4.0, 3.0, 2.0, 1.5 and 1.0 mm. The MR imaging sequence was selected on the basis of an earlier study[9] which demonstrated that the PD TSE sequence provided optimal fluid-acrylic edge delineation in a submerged phantom model, when compared to a range of other routine and specialised sequence types.

Volume measurement

Once the phantoms had been imaged, the image data were transferred via CD-ROM media (TDK Corporation; Chuo-ku, Tokyo, Japan), in both DICOM and JPEG file formats, to a remote computer workstation (Silicon Graphics; Mountain View, CA, USA), for three-dimensional image generation and volumetric analysis using the Velocity 2 Pro reconstructive software package (Image3, LLC, Utah, USA).

Three-dimensional images were generated of the two phantoms, at each of the 5 acquisition slice thicknesses, using a semi-automated threshold-based technique. As previously described,[11-13] where it was deemed on image review that the software had misrepresented the acrylic-fluid interface, manual corrections were made to the images. Static examples of the three-dimensional image output displays are shown as Figure 2. For each image, volume generations were made and recorded using the softwares inbuilt object analysis tools.

Statistical analysis

The collected volumetric data were entered into a Statview (Abacus Concepts, USA) data sheet for subsequent analysis. A percentage measurement error (PME) was calculated for each image, directly comparing the software generated volume measure to the precise mass/density calculated measure. Paired *t* testing was performed to determine if there was a difference in the mean PME values between the two phantoms.

Table 1: Three-dimensional image determined phantom volumes.

Phantom reference volume (mm^3)	Volume as measured by the software (mm^3) Acquisition slice thickness †				
	4.0mm	3.0mm	2.0mm	1.5mm	1.0mm
(A) 2741.53	3293.98	3062.15	2959.60	2828.06	2702.52
	(552.45)	(320.62)	(218.07)	(86.53)	(39.01)
(B) 2803.68	3327.73	3078.04	2990.85	2883.26	2784.74
	(524.05)	(274.36)	(187.17)	(79.58)	(18.94)

† the absolute difference from the reference volume (mass/density method) is shown in parentheses.

Table 2: PME for the both phantoms separated by slice thickness.

Phantom	PME (%)* Acquisition slice thickness †				
	4.0mm	3.0mm	2.0mm	1.5mm	1.0mm
(A)	20.15	11.69	7.95	3.16	-1.42
(B)	18.69	9.79	6.68	2.84	-0.68
mean	**19.42**	**10.74**	**7.32**	**3.00**	**-1.05**

* PME calculation = (software volume - reference volume) / 100.

† note: - a positive (+) value indicates that the software over-estimated the phantom volume while a negative (-) value indicates that the software under-estimated the phantom volume.

RESULTS

Reference volumes for phantoms A and B, based on the mass/density technique described above, were 2741.53mm^3 and 2803.68 mm^3 respectively.

The software-generated volumes of each phantom and the difference from the reference (mass/density) measurements, at each of the five acquisition slice thicknesses, are shown in Table 1. Inspection of this data demonstrates a reduction in absolute error as acquisition slice thickness decreases.

The calculated PME values for each phantom measurement are shown in Table 2 as are the mean values for each acquisition slice thickness. These data also indicate a reduction in error as acquisition slice thickness decreases. The relationship between slice thickness and PME of three-dimensional volume measurement is also demonstrated graphically in Figure 3 with the PME of both phantoms plotted together against decreasing acquisition slice thickness.

Paired *t* testing suggested no significant difference ($P = 0.15$) between the means of the PME values when comparing the two phantoms.

DISCUSSION

The purpose of this study was to determine the effect of slice thickness of MR images upon accuracy of volume measurement using a three-dimensional reconstructed model of a pair of complex non-geometric shapes designed to simulate scaled meniscal cartilages of the adult human knee.

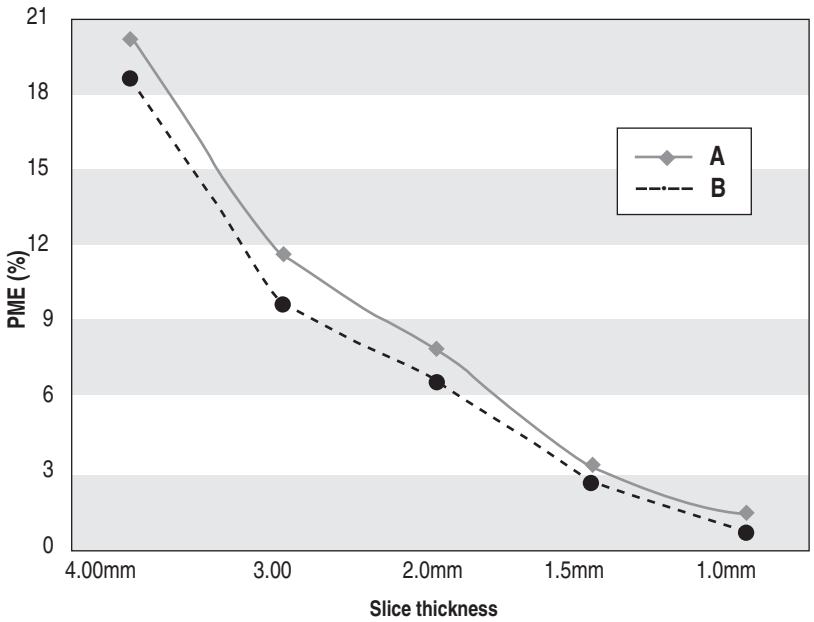
The major finding of this study was the demonstration of a near linear relationship between slice thickness of MR images and the accuracy of volume measurement derived from reconstructed 3D images. Within the slice thickness range investigated (1 - 4 mm), mean PME values of as low as 1.05 per cent were achieved. This suggests that, given careful MR imaging sequence selection and therefore appropriate contrast between structures being imaged (facilitating accurate image segmentation), the volume of similar sized irregular-shaped objects could also be accurately measured in the clinical setting.

This study represents a progressive step in a series of research endeavours aimed at the development and validation of a previously reported image reconstruction technique. Previous work has provided preliminary data regarding its ability to provide accurate and reproducible linear and geometric volume measurements under a range of optimal and varied imaging conditions. The use of acrylic phantom materials rather than sacrificed *(ex vivo)* tissue samples, allows consistent, reproducible and highly accurate gold standard comparison.

Measurement of the volume of non-geometric objects provides a challenging task when using reconstructed three-dimensional images. Highly accurate and complex between- and within-slice interpolation is required in order to reconstruct curved surfaces lying at inconsistent angles to the acquisition plane. Given that few anatomical features possess simple geometry, the ability to perform such functions and achieve accurate volume measurement under such conditions is critically important for any technique destined for clinical application.

The authors recognise several limitations to broader generalisation of the findings reported herein. Firstly, for consistency, the MR imaging parameters used in this study were kept

Figure 3: Graphical demonstration of the relationship between PME and acquisition slice thickness, showing phantoms A (solid line) and B (broken line).



constant for each phantom and slice thickness. During review of the images it was noted, as expected, that they became increasingly noisy (grainy) with decreasing slice thickness. This can be easily explained by the reduced signal-to-noise ratio present when finer slices are used. While the results reported here demonstrate a high degree of volume measurement accuracy, especially at the finer slice thicknesses, it could be rationalised that appropriate modification of the scan parameters to accompany the decrease in slice thickness would have improved image signal-to-noise ratio. This would improve the clarity of the acrylic-fluid interface and therefore increase the quality of the resultant three-dimensional images from which volume measurements were made.

Secondly, acrylic was used as the phantom material of choice based upon the homogeneity of its MR signal characteristics and the clear delineation of its interface with water under immersion. Clearly, *in vivo* meniscal cartilage is unlikely to demonstrate either such a uniform MR intra-substance response nor such an obvious distinction between itself and the immediately surrounding tissues. These two factors are likely to make software-based selective segmentation and semi-automated reconstruction more challenging. Just how significantly these elements influence volume measurement accuracy is intended to be the objective of future research.

In contrast to previous research which has explored MR volume measurement using ultra-fine (sub-millimetre) slice thicknesses,[14] the findings reported here have been achieved using an MR sequence in line with standard contemporary clinical imaging (i.e. 1-4 mm). The results are therefore considered likely to be reproducible at other clinical imaging sites using a comparable generation scanner and sequence type.

CONCLUSIONS

The findings of this study support earlier work suggesting a near-linear relationship between acquisition slice thickness and the accuracy of volume measurements derived from three-dimensional reconstructed MR imaging. Using irregular non-geometric acrylic phantoms, PME values of three per cent or less were achievable using MR imaging parameters available to most clinical imaging sites. These findings also highlight the potential usefulness of acrylic casting-resin as an MR phantom material in instances where a high degree of precision and known geometric size are considered desirable.

Based on this study it is recommended that a slice thickness of less than 2.0mm be employed when volume measurement from three-dimensional reconstructed images is being considered.

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