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FULL PAPER

Building an orthopaedic CT phantom for under £50

¹BERNHARD TINS, FRCR and ^{2,3}JAN HERMAN KUIPER, PhD

¹Department of Radiology, Robert Jones and Agnes Hunt Orthopaedic Hospital, Oswestry, UK

²Institute of Orthopaedics, Robert Jones and Agnes Hunt Orthopaedic Hospital, Oswestry, UK

³Institute for Science and Technology in Medicine, Keele University, Keele, UK

Address correspondence to: Dr Bernhard Tins

E-mail: Bernhard.Tins@rjah.nhs.uk

Objective: In procuring a CT scanner for orthopaedic imaging, the ability of the scanner to cope with metal artefacts for visualising bone and bone lesions around orthopaedic implants is an important feature. A durable and easily transportable CT phantom would help to compare this feature between CT scanners. The aims of this study were to develop a CT phantom that is easy to build, easily transportable, stable over time, cheap and challenging CT scanner performance.

Methods: A CT phantom resembling a femur and tibia with a total knee replacement was constructed from spare components of a knee replacement, wall filler and polystyrene. A number of plastic strips and cylinders were placed between metal implant and bone substitute during construction to act as “bone lesions”. The phantom was fixed in a watertight acrylic box with epoxy resin.

Results: The total manufacturing time was below 3 h staggered over several days and the total cost was below £50. When empty, the phantom is easily transportable. The box can be filled with water on site visits ensuring a

reproducible attenuation. This phantom is stable (*i.e.* not affected by decay of biological tissue).

Conclusion: The phantom was easy to construct and is well transportable and stable in time. The phantom can be used in a procurement process allowing direct comparison of different scanners regarding technical factors and software performance. It can further be used for quality assurance, scan parameter optimisation and research. We conclude that a simple and transportable CT phantom can be built using few resources that allows to compare CT scanners with respect to their ability to visualise bone lesions around metal implants.

Advances in knowledge: It is possible to build a CT knee replacement phantom in a few hours and for less than £50. Other than the total knee implant, this CT phantom can be built with material available from any DIY store and simple tools. This CT phantoms allows objective comparisons in CT procurement. This CT phantom allows objective assessment of imaging protocols for clinical practice.

INTRODUCTION

There are many uses for phantoms in radiology, such as quality assurance of CT scanners, assessment of imaging equipment or assessment of different imaging protocols. Commercially built CT phantoms are usually pricey and off the peg solutions do not always meet the individual needs of a user.

The authors of this article wanted to assess the performance of different CT scanners for orthopaedic imaging as part of a procurement process. An important aspect in this context is the ability of the scanner to image the bone around metallic joint replacements in order to assess if bone loss is present.^{1–3} Such bone loss can be localised, in the form of scalloping, or can be linear, more evenly distributed around the implant.⁴ Typically, the areas of bone loss are filled with soft tissue, rich in macrophages. The attenuation value of such tissue is much lower than bone, around

0–100 HU.⁵ Imaging such defects is prone to metal artefacts, and manufacturers of scanners have implemented various algorithms to reduce such artefacts. In particular, the advent of iterative reconstruction algorithms have led to an improved image quality and artefact reduction compared to filtered back projection.^{6,7} In order to make objective assessments of the scanner's and software's ability to image bone defects around implants, independent of manufacturer-provided imaging examples, ideally the same item should be scanned on all CT scanners to be assessed. Obviously, it would be unethical to scan a human volunteer.

The use of CT phantoms to assess the ability of CT scanners to image bone defects around implants has been described before.⁸ Some of these models used human cadavers^{5,9} and others were constructed using unfixed animal bone.⁸ Specialist surgical equipment and expertise are needed for both and in the UK, the use of human cadavers would be

very difficult due to legislative hurdles. Neither of these models was made durable and would have a limited shelf-life.

It was therefore decided to construct an artificial CT phantom. This should be easy to build, easily transportable, stable over time, cheap and should be able to challenge CT scanner performance. The aim of this article is to describe the construction of an artificial orthopaedic CT phantom in the shape of a mock total knee replacement (TKR).

METHODS AND MATERIALS

The knee replacement consisted of a cobalt chromium femoral component (Natural-Knee, Sulzer Orthopaedics Ltd, Baar, Switzerland), and a titanium tibial component (PFC Sigma, DePuy, Leeds, UK). These were chosen based on matching size, even though they are from different manufacturers. The combination of a cobalt chromium femoral component and a titanium tibial component represents typical clinical practice. In particular, the cobalt chromium implant was expected to create a significant amount of artefact. The titanium implant was expected to create limited artefact. The severity of artefact is related to the atomic numbers and material density.

“Bone defects”

Multiple polyoxymethylene (POM) cylinders of defined size were glued onto the deep aspect of the femoral component and on the distal aspect of the tibial component simulating bone defects at the implant bone interface. POM cylinders were chosen for their defined size, shape, attenuation and ease of use. A defined shape and size was advantageous as it would allow to assess distortion and trueness of depiction on the CT images. A range of sizes was chosen to assess which lesions would be visible on CT imaging. These were:

8 mm diameter, 5 mm height

11 mm diameter, height 5 mm, 10 mm and 13 mm

16 mm diameter, height 6 mm and 7 mm

A polypropylene plastic strip of 7 cm by 5 mm by 0.5 mm was glued to the shaft of the tibial component to simulate a linear (long and thin) defect.

Bone substitute

The “medullary bone” was formed by a commercial filler (Multi Purpose Filler Powder, Bartoline Ltd, Beverley, UK), obtained from a DIY shop, mixed with polystyrene pellets to simulate medullary bone with fatty marrow spaces. The relative proportion of filler and polystyrene pellets were chosen by visual assessment based on one of the authors experience as a musculoskeletal radiologist. The addition of polystyrene pellets was not absolutely necessary but added structure that can be comparatively assessed. Polystyrene was chosen for its low attenuation, bone marrow attenuation varies between 50 and -200 HU depending on fat and cellular content. The filler consists of calcium magnesium carbonate, calcium sulphate hemihydrate (plaster of Paris) and organic acids that act as setting time modifiers.^{10,11} The

Figure 1. Photograph of the finished TKR CT phantom. The phantom is set in epoxy resin in a Perspex box. TKR, total knee replacement.

mineral components are similar to the mineral component of natural bone.¹² The chosen filler dries without shrinkage thus avoiding cracks. The filler/polystyrene mixture was applied in layers several centimetres thick and allowed to dry between the application of subsequent layers. The femoral and tibial “bone” were produced separately. Minor reshaping was easily achieved with sanding which also allowed for a smooth finish. When finished, the modelled “medullary bone” was covered in air-drying modelling clay (DAS, Daler-Rowney, Bracknell, UK), the thickness of the layer was about 2–3 mm. The clay layer was added to simulate cortical bone.

The tibial component would normally be fitted with a high-density polyethylene bearing surface, but this was not added because it would not affect the image quality at the bone-implant interface.

Presentation

The finished phantom was placed in an acrylic display box (Amazon UK, Slough, Berkshire, UK) on a small stand to improve appearances. This box measured 15 × 15 × 30 cm, with a wall thickness of 3 mm. The length, width and height of the modelled femoral component were 10.5 × 7.5 × 5.7 cm, that of the tibial component was 8.5 × 9 × 6.3 cm. The phantom was then covered with thin layers of two-component epoxy resin (UKR, UK Epoxy Resin, Burscough, UK) to seal the surface and immobilise the phantom in the acrylic box (Figure 1). The phantom could now be covered with water and placed in a CT scanner. After scanning, the water could be drained and the phantom allowed to dry naturally. The dry weight of the finished phantom was 2.85 kg. Before CT scanning 3 l of water was added leaving a several cm gap at the top. If the box were completely filled with water, the table movement when scanning would cause sloshing and spilling.

RESULTS

Material costs, construction time and ease of use

The total material costs (excluding the prosthetic components) were under £50. The work was performed in a small workshop

Figure 2. CT images of the TKR phantom. Ap scout, (a). (b) Shows the TKR of a real patient for comparison. Axial image of the CT phantom just below the tibial tray showing “bone defects” at the “implant bone interface”, (c) Coronal reformat, (d) showing the “bone texture” created by a mix of filler with polystyrene pellets. Off-centre sagittal reformat showing the “lesion” next to the tibial tray, (d) lesions next to the femoral component can not be appreciated due to artefact. TKR, total knee replacement.

with basic tools and took in total less than 3 h although, especially for the external modelling of the filler and the setting in resin, multiple short visits were needed. The phantom was easily carried across the country, and proved easy to use for its purpose. One of the side-walls of the acrylic box cracked when travelling to a site visit, but despite the crack it could still be used.

CT appearances

The CT appearance of the TKR phantom resembled a real knee replacement (Figure 2a,b). The femoral and tibial component were encased by high attenuation material, and the clay provided a uniform cortex-like cover. The polystyrene added to the filler mix created multiple low attenuation pockets, adding structure to the “medullary bone” compartment.

The “bone lysis” lesions formed by the POM cylinders appeared visually similar to bone lesions on a clinical CT. They could be distinguished easily adjacent to the tibial component (Figure 2c). However, adjacent to the femoral component only larger lesions were visualised (Figure 2d). The image quality could be assessed at corresponding slices on images obtained on different scanners (Figure 3a/b vs c). Finally, the impact of

Figure 3. CT images of the phantom acquired with two different CT scanners. Equivalent locations are shown. The images of one CT scanner are without (a) and with (b) the application of a metal artefact reduction software algorithm. CT images acquired with another CT scanner (c) show significantly superior image quality. The CT phantom allows the comparison of CT scanner performance on multiple site visits.

metal artefact reduction software on the image quality could be assessed (Figure 3a vs b).

DISCUSSION

The authors set-out to construct a CT phantom that was easy to build, easily transportable, stable over time, cheap and would challenge CT scanner performance in the presence of metal implants, including reconstruction software algorithms. The knee replacement phantom described here fulfils all these criteria. The complex shape and high density of knee replacements typically causes significant artefact on CT and MRI and formed a suitable test for any scanner and scanner software.

There was a clear difference between the two implant components in the ability to visualise the “bone defects”. This was expected as the tibial component was titanium and had lower attenuation, causing minor artefact, while the femoral component was cobalt chromium and caused a major amount of artefact. There was also a visible difference between different CT scanners and reconstruction algorithms, which allowed us to objectively compare scanner performance with respect to metal artefact removal and bone defect detection.

During the phantom design it was considered setting the knee replacement in human bone. Human bone is obviously most realistic and human cadaver models for implant imaging are described in the literature.^{5,9,13} However in the UK, the human tissue act makes the use of human bone for this purpose difficult,

especially because the phantom would need to be transported to various places, including abroad.

An alternative would be to use animal bone^{8,14} though obviously the shape of animal bones varies from that of human bones. The shape of the femoral component of a knee replacement in particular is complex and ideally, the appropriate surgical jigs would be required to achieve a close fit between bone and implant. However, these jigs are unlikely to fit animal bones. Moreover, it would be challenging to machine bone lesions of a known size into a bone/implant construct, in particular around hard-to-reach areas such as a stem.

Constructing our own bone substrate, on the other hand, made it easy to incorporate lesions at the “bone”-implant interface. This approach also allowed creating “intramedullary” bone lesions if desired or required.

One could consider three-dimensional printing though this would add significant cost and complexity.

Implant loosening is either infected or not (so called aseptic loosening). Aseptic loosening is generally more common. Either way, typically there is bone loss at the implant–bone interface with attenuation values around 50 HU. The lesions are filled with granulation tissue. Aseptic loosening in particular can present as a thin line of radiolucency at the bone implant interface. Often loosening presents as cone, dome or cylindrical lesion. The CT phantom has aimed to simulate these lesions with cylindrical lesions extending into bone and thin liner lesions at the bone–implant interface. Choosing a number of different size allows to assess image quality assessment based on the ability to recognize these lesions.

When choosing the material simulating bone a few considerations were employed. The attenuation should be similar to that of bone. The chosen material should be readily available, cheap, safe to handle, stable over time, easy to manipulate and ideally, water resistant. There are many commercially available fillers familiar from DIY projects fulfilling these criteria. The filler consists of calcium magnesium carbonate (dolomite), calcium sulphate hemihydrate (plaster of Paris) and organic acids that act as setting time modifiers.¹⁰ The mineral contents have a radiodensity with values comparable to bone.^{12,15} Care must be taken to choose a non-shrinking filler as otherwise cracks will develop during the drying stage. Plaster of Paris could also be used for this, however, we found commercially available filler extremely easy to handle. Using such fillers, any unwanted irregularities could be easily rectified with simple tools such as screwdrivers or files. Sanding improved the surface appearance. Filler also bonds to most surfaces and can be filled in around the polymer “defects” on the deep surface of the implant. Although we added a layer of modelling clay, in retrospect this clay mantle was not necessary.

Adding polystyrene pellets added texture to the “bone” and allowed for better assessment of distortion and artefact near the implant on CT imaging. The clay mantle was chosen to simulate

cortical bone but in retrospect this was not necessary. Applying a thin mantle of filler only (without polystyrene) on the surface of the phantom achieved a smooth and homogenous finish. When dry, filler is water resistant and once covered with resin the phantom is sealed and immobilised in place.

The mix of filler and polystyrene pellets was denser than human medullary bone and as such lesions at the implant–“bone” interface should be easier to recognize than in real life due to higher attenuation differences.

Formal assessment of signal-to-noise ratio was not undertaken. The purpose of the phantom is to provide a stable scaffold in which to place the knee implant. The placement of lesions allows for comparison of visibility with different imaging protocols, reconstruction algorithms and between different CT scanners. The phantom has been used in a CT procurement process and qualitative differences in image quality between CT scanners were appreciable when assessed by six consultant radiologists, though this is not subject of this paper.

When pouring layers of resin, there are a few issues to consider. Resin does shrink when hardening. Thicker layers result in an increased risk of cracking. Sufficient time must be allowed for complete hardening and shrinkage of the resin before the next layer is applied. It would have been possible to completely set the phantom in resin, rather than using a box. However, the resulting phantom would have been quite heavy and with increasing volumes of epoxy resin the issue of cracks becomes more relevant. The cost would also be increased.

Mounting the phantom in a box allowed filling the box with water when scanning and also allowed for reproducible phantom positioning. The attenuation of water is universally 0 HU (by definition) and therefore constant wherever the phantom is taken. It is also possible to place additional objects next to the phantom when scanning. Because the 3 mm wall thickness acrylic box we used developed a crack, we will use a stronger box for future phantoms, either with thicker walls or a stronger non-metallic material.

Costs

The knee implant parts were remains from a research project and surplus to requirements and therefore free. However, it should be possible to obtain free implants from manufacturers, ex-demonstration implants, implants that are out-of-date or implants out of clinical use. The POM spacers were cut from off-cuts and free. One could use whatever polymer is to hand, such as nylon or polyethylene, ideally with attenuation close to bone defects. The filler cost less than £5 and was mixed with polystyrene left over from packing material. The resin was not bought specifically for the phantom, but since only a thin coating was required the required volume can be bought as 250 or 500 g kits below £20. The modelling clay outer shell was not necessary and can be omitted. The acrylic box was the single most expensive item costing around £25, but any watertight non-metallic box would do.

CONCLUSION

With a few hours time and minimal cost it is possible to build a CT total knee replacement phantom. This allows for objective

comparison of CT scanners in a procurement process and to evaluate imaging parameters in the clinical setting of implant imaging.

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