Very low-dose computed tomography for planning and outcome measurement in knee replacement

THE IMPERIAL KNEE PROTOCOL

Surgeons need to be able to measure angles and distances in three dimensions in the planning and assessment of knee replacement. Computed tomography (CT) offers the accuracy needed but involves greater radiation exposure to patients than traditional long-leg standing radiographs, which give very little information outside the plane of the image.

There is considerable variation in CT radiation doses between research centres, scanning protocols and individual scanners, and ethics committees are rightly demanding more consistency in this area.

By refining the CT scanning protocol we have reduced the effective radiation dose received by the patient down to the equivalent of one long-leg standing radiograph. Because of this, it will be more acceptable to obtain the three-dimensional data set produced by CT scanning. Surgeons will be able to document the impact of implant position on outcome with greater precision.

The ability to plan a knee replacement precisely and measure the outcome accurately in both conventional and computer-assisted orthopaedic surgery is crucial for detailed analysis of the efficacy of these systems.

In this study we sought the optimal computed tomography (CT) radiation dose for both planning and outcome measurement in computer-assisted and conventionally performed knee replacement. In this field, CT is fast becoming the imaging modality of choice. The perspective distortion, magnification errors and orientation uncertainties associated with standard radiographs make them an insufficiently sensitive tool for both accurate pre-operative planning and post-operative measurement of accuracy.

Radiation dose is generally represented as the weighted dose (mSv) received by the radiosensitive organs. A typical CT scan of the pelvis gives around 10 mSv, which is equivalent to about 4.5 years of background radiation (average United Kingdom background radiation is 2.2 mSv per year). The Perth protocol for lower limb CT scans gives a dose of 2.7 mSv, whereas in our previous trials we used a protocol that gave 2.2 mSv. In comparison, the traditional long-leg standing radiograph, used to define the mechanical axis, gives a dose of about 0.7 mSv. The National Radiological Protection Board estimates that CT is used in 5% of annual radiological investigations but has a disproportionately high annual collective dose burden of 40%. The current evidence suggests a linear relationship between effective radiation dose and malignancy, with exposure to 10 mSv giving a 1:2000 risk of radiation-induced malignancy.

Although there is no true safe dose of radiation, one can facilitate the reduction of effective doses by manipulating and reducing the dose parameters. This study looked at ways of minimising radiation dose while maintaining image quality for pre-operative orthopaedic planning and post-operative assessment in knee replacement.

Materials and Methods

The initial part of this study was performed using a standard radiological (tissue equivalent) phantom pelvis and proximal femora (cadaver human bones in a rubber envelope). Owing to the unavailability of commercial leg phantoms, a simulated phantom of both legs was constructed using human cadaver femora, patellae, tibiae, fibulae and tarsal bones in a polythene envelope filled with water to represent the soft-tissue envelope of the legs.

The imaging was performed using the Siemens Sensation 4, four-slice multislice CT scanner (Siemens Medical Solutions, Erlangen, Germany). Both phantoms were placed in the supine position in the scanner to simulate the
pelvis and lower limbs of the human. A scout film (Fig. 1a) was taken between the iliac crest and the feet; this was used to specify the regions to be imaged (Fig. 1b). The whole phantom was initially scanned to reproduce a conventional scan. Subsequent scans were performed, reducing the volume areas imaged to include only the femoral head, 10 cm above and below the joint line of the knee and 2 cm to 3 cm on either side of the tibiotalar joint.

Following minimisation of the volume imaged, the milliampere-seconds (mAs) and collimation width were varied for each of the three regions (hip, knee and ankle). The kilovoltage (kV) was incrementally reduced from 140 to 100 for each of the three regions, and the mAs varied between 120 and 75 at the pelvis and 100 and 30 for both the knee and the ankle. Collimation width was increased from 4 mm x 1 mm sliced sequentially. For the three regions the x, y and z axes were kept fixed for the duration of the scan to maintain the relative position of the three regions with respect to each other.

Image quality and resolution at these different parameters were evaluated by two of the authors (RR, SH).

The effective dose in mSv was calculated from actual scans using two commercially-available software packages (CT DOSE; National Board of Health, Herlev, Denmark, and CT-EXPO; Medizinische Hochschule Hannover, Hannover, Germany) for the different parameters used.

Following optimisation of the scanning protocol (Table I), human subjects were initially scanned using the Sensation 4 (Siemens Medical Solutions) CT scanners, and when the 16 and 64 (Siemens Medical Solutions) multislice scanners became available this protocol was adapted for their use and the effective radiation doses recalculated (Table II). A conventional lower limb trauma splint was applied to stabilise the leg while in the scanner and thus reduce the risk of movement artefact, especially during movement of the table, in the regions not exposed to radiation. Following the scan the digital imaging and communications in medicine (DICOM) data were further checked for presence of such artefacts.

### Results

**Field reduction.** The phantom studies showed that we were able to restrict the region scanned to include only the whole

![Fig. 1a](image1a.png) ![Fig. 1b](image1b.png)

**Fig. 1a**

a) Scout film to demonstrate the Imperial knee protocol and b) the regions scanned.

<table>
<thead>
<tr>
<th>Area scanned</th>
<th>Kilovoltage</th>
<th>Milliampere-seconds</th>
<th>Scan length (cm)</th>
<th>Collimation (mm)</th>
<th>Calculation using CT DOSE program</th>
<th>Calculation using CT-EXPO program</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Male</td>
<td>Female</td>
</tr>
<tr>
<td>Hip</td>
<td>120</td>
<td>80</td>
<td>5</td>
<td>4 x 2.5</td>
<td>0.010</td>
<td>0.010</td>
</tr>
<tr>
<td>Knee</td>
<td>120</td>
<td>100</td>
<td>20</td>
<td>4 x 1</td>
<td>0.120</td>
<td>0.120</td>
</tr>
<tr>
<td>Ankle</td>
<td>120</td>
<td>45</td>
<td>5</td>
<td>4 x 2.5</td>
<td>0.0046</td>
<td></td>
</tr>
<tr>
<td>Scout film/scanogram</td>
<td>80</td>
<td>35</td>
<td>102.4</td>
<td>4 x 1</td>
<td>0.016</td>
<td>0.016</td>
</tr>
</tbody>
</table>

**Table I. Calculated doses for the Imperial knee protocol (Sensation four-slice scanner; Siemens Medical Solutions, Erlangen, Germany)**

* National Board of Health, Herlev, Denmark
† Medizinische Hochschule Hannover, Hannover, Germany

**Total effective dose (mSv)**

<table>
<thead>
<tr>
<th></th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total effective dose (mSv)</td>
<td>0.751</td>
<td>0.641</td>
</tr>
</tbody>
</table>
femoral head, 20 cm at the knee (10 cm on either side of the joint line) and 5 cm at the ankle (distal tibia and the talus), and this protocol was subsequently used for our patient studies (Fig. 2).

**Milliamperage reduction.** On viewing images of the hip, with sequential reduction of the milliamperage we found that at an intensity of < 80 mAs neither of the observers felt able to identify the centre of the hip with confidence. At the knee, an mAs of 80 was sufficient pre-operatively, with 100 mAs needed post-operatively (higher mA needed to reduce image artefact from the metal components). At the ankle an mAs of 45 was necessary to define the centre of the talus reliably.

The collimation width needed depended on the scanner used. In a four-slice scanner the width could be increased to 2.5 mm at both the hips and ankles while still providing adequate image quality, whereas at the knee 1.0 mm collimation was retained for image definition. In 16- and 64-slice scanners the collimation widths are narrower, but with the increased number of detectors in these new scanners the effective doses are further reduced (Table II).

With the reduction in mAs and scanned volume and optimisation of collimation width the effective dose was 0.841 mSv in females and 0.641 mSv in males, and 0.74 mSv in females and 0.54 mSv in males for the new 64-slice scanners, while maintaining a sufficient image resolution for our purposes. This contributed to an average effective dose to the hip of 0.7 mSv in females and 0.5 mSv in males, to the knee 0.1 mSv and the ankle 0.005 mSv in both genders (Table I). This procedure is available via the Imperial College orthopaedic website.\(^{14}\)

**Discussion**

In this study we looked at the effects of minimising the volume of a patient’s body that is scanned and the dose of radiation delivered. For the purposes of measuring limb alignment we chose to use the mechanical axis. This requires that only the centre of the femoral head be clearly identified proximally. Finding this point by limited low-dose scanning is simple and reproducible. By reducing the volume scanned in this particularly radiosensitive region, this protocol almost spares the ovaries in the female and normally avoids the testes in the male (while recognising

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**Table II.** Calculated doses for the imperial knee protocol for the different scanners

<table>
<thead>
<tr>
<th>Imperial protocol for each scanner</th>
<th>Collimation (mm)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Area</strong></td>
<td><strong>Kilovoltage</strong></td>
</tr>
<tr>
<td>Hip</td>
<td>120</td>
</tr>
<tr>
<td>Knee</td>
<td>120</td>
</tr>
<tr>
<td>Ankle</td>
<td>120</td>
</tr>
<tr>
<td>Scout film/scanogram</td>
<td>80</td>
</tr>
<tr>
<td>Total radiation dose (mSv)</td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>0.84</td>
</tr>
<tr>
<td>Male</td>
<td>0.64</td>
</tr>
</tbody>
</table>

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\(^{14}\) Images of the knee showing the scanned regions.
Fig. 3
Computer-assisted images showing the planned component positioning.

Fig. 4a
Figure 4a - 3D images of the plan (left) and post-operative scan (right). Figure 4b – The implant position relative to mechanical axes.
the wide normal anatomical variation in the relative position of these organs).

The reduction in the volume imaged in the region of the femoral head taken together with the minimisation of mAs in this extremely dose-sensitive region had a substantial impact in reducing the effective dose (Table I).

Further down the lower limb we found that scanning 10 cm either side of the joint line at the knee and 5 cm at the ankle, including the talus, was sufficient to identify the necessary landmarks (knee and ankle centres). The volumes between the hip, knee and ankle were not exposed to direct radiation. Although the reduction in effective dose achieved by this modification may be modest, any reduction in dose is worthwhile. By reducing the size of the data set, manipulation of the models was made faster, producing an unintended benefit from this protocol.

The low mAs used here leads to no significant degradation or reduction in quality of the bone image. The great variation in patient shape and size posed no challenge in this respect, as although this may reduce the quality of the soft-tissue image, the resolution of the interface between bone and soft tissue remains very clearly defined. Therefore, for the purpose of pre-operative planning and post-operative assessment in knee replacement only bony windows need be reconstructed.

For pre-operative planning the DICOM files are exported to the planner and segmentation of the bones is performed. This is followed by detailed planning of the implant position, with the precise location and orientation of each implant optimised in three dimensions (Fig. 3). The surgeon can then choose where to put each component and track back and forth between images to ensure that the choice of size and position is correct.

In computer-assisted surgery the plans made from the CT data are co-registered with points taken in the knee in the operating theatre. When a satisfactory match is achieved, the operation can be performed, using active or passive surgical navigation systems.

Following surgery, detailed and accurate comparisons between the planned and achieved component positions can be made using both 2D and 3D methods, if a pre-operative plan has been made (Fig. 4a). Co-registration of the precisely planned models with surface models from the post-operative scan gives real measurements of implant position, enabling the measurement of the accuracy of joint replacement in all six degrees of freedom, giving both translation and rotation errors in all three planes. Even without a pre-operative CT-based plan this protocol allows measurement of implant position relative to the mechanical axis (Fig. 4b).

The aim of this exercise was to find a compromise between radiation exposure and the acquisition of images which are good enough to enable the surgeon to generate a reliable 3D data set for planning and assessing knee replacement procedures.

The dose burden per CT scan is now down, reduced to between 0.53 mSv and 0.84 mSv and compares favourably with traditional long-leg measurement films at 0.7 mSv (Fig. 5).\(^{15-18}\) By providing an entire 3D data set of the large joints of the lower limb, it offers significant advantages over long-leg films for the accurate determination of the position of implants in three dimensions and provides a permanent model of the patient’s anatomy for future reference.

The time needed to position and scan the patient is another source of concern with both imaging modalities. There are anecdotal reports of problems with patient-positioning when long-leg films are taken and the need for film to be repeated. With CT there is a greatly reduced risk of re-imaging, as the scanning time is now measured in seconds not minutes. The time spent in processing the pre-operative data in this study is still measured in minutes, not seconds. We expect that as the software is improved the time and skill needed will be substantially reduced.\(^1\)

Post-operative analysis is still time consuming and experimental; it being used as a research tool. As the software develops, it is envisaged that appropriately-trained staff will perform these analyses routinely. Such analysis will provide valuable information in poorly functioning or painful joints and allow detailed assessment to be undertaken before embarking on any further intervention.

Compared with the Perth Protocol\(^6\) we have shown a fourfold reduction in effective radiation dose with no compromise in data quality. Like the Perth protocol these images are non weight-bearing, but because the bones may be measured separately the combined mechanical axes can be calculated with complete correction for any rotary malalignment. Although this study does not compare the
accuracy of traditional long-leg radiographs with CT scans, this area will be addressed in future work.

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

References


