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TECHNICAL REPORT

CT arthrography: in vitro evaluation of single and dual energy for optimization of technique

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Abstract The purpose of this study was to optimize CT arthrography technique and determine if dual energy CT (DECT) can provide any benefit over single energy CT (SECT). Iodinated contrast attenuation at different concentrations was measured using DECT and SECT at different beam energies (140, 120, and 80 kVp). Dose and noise were measured on phantoms at different tube currents. Three bovine femoral condyles with artificially created cartilage defects were scanned with dose-equivalent protocols. Contrast-to-noise ratio (CNR) between cartilage and iodine was measured, and the appearance of cartilage defects was graded by two readers. DECT scans were post-processed for iodine quantification. The beam energy 80 kVp had the highest iodine signal, 50% greater than DECT, 75% greater than 120 kVp, and 100% greater than 140 kVp. Noise was nearly identical for all techniques when dose was matched. The 80 kVp level had the highest CNR, 25% higher than 120 kVp and DECT, and 33% greater than 140 kVp. The 80 kVp technique was also preferred by both readers. DECT iodine quantification was significantly limited by the post-processing application, noise, and beam hardening. In this in-vitro study, the SECT 80 kVp CT arthrography technique was superior to currently performed 120 and 140 kVP SECT techniques and DECT.

Keywords Knee · CT arthrography · Single · Dual energy · Technique

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Introduction

Computed tomography (CT) arthrography has been routinely used in musculoskeletal imaging for evaluation of suspected intra-articular pathology since the advent of CT scanners. The scanning techniques have evolved over time to take advantage of improvements in technology with the most significant advances related to the development of helical and multidetector-row CT (MDCT) scanners. A more recent advance in CT scanner technology has been the introduction of dual source CT systems. These systems have two separate x-ray tubes that can be operated at the same energy, referred to as dual source scanning, to improve the temporal resolution (primarily used in cardiac imaging) or to provide more photons to reduce noise (primarily used in imaging obese patients) or that can be operated at different tube energies, referred to as dual energy scanning [1]. Dual energy scanning allows tissues to be separated by their composition rather than simply by their attenuation as is done with single energy CT scanning. Dual energy CT (DECT) uses the fact that the change in attenuation of each material such as fat, soft tissue, or iodine is different between the two energies, allowing them to be separated. This change in attenuation is greatest for materials with a high atomic number, i.e., Z number, such as iodine and is low for materials with a lower Z number such as soft tissue [2]. DECT has been shown to be useful in various applications such as virtual noncontrast imaging, differentiating calcium and uric acid renal stones, or performing automatic bone removal for CT angiography [3–6]. The applications of DECT in musculoskeletal imaging have been limited thus far to specific applications such as gout and tendons/ligaments [7, 8].

The purpose of this study was to optimize CT arthrography technique and determine if DECT provides any benefit over the currently performed single energy CT (SECT). With the growth of dual source CT, more options for scanning techniques for arthrography are available. We wished to determine if these factors can improve the quality of studies. Additionally, DECT arthrography holds the potential to identify and quantify iodine absorbed into cartilage, allowing it to be used to track ionic contrast agents in a manner similar to delayed gadolinium-enhanced MR imaging of cartilage (dGEMRIC) for evaluation of early cartilage degeneration. The specific goals of the project were to determine the following: (1) Is iodine more apparent in dual energy CT (DECT) than single energy CT (SECT)? (2) How do DECT and SECT compare with respect to dose and noise? (3) Does DECT have a qualitative or quantitative advantage over SECT in an in-vitro animal model for assessment of articular cartilage? (4) Can DECT be used to identify and quantify iodine in cartilage?

Materials and methods

All scanning was performed on a dual source CT scanner (Definition, Siemens Healthcare, Forchheim, Germany). The scanning parameters were kept constant except for the x-ray beam energy and tube current (collimation 64× 0.6 mm, 1 s rotation time, pitch 0.9, B60 reconstruction kernel, reconstructed slice thickness 2 mm, and slice increment 1 mm). The evaluated DECT images were obtained using a linear mixture of 70% of the 140 kVp images and 30% of the 80 kVp images.

Iodinated contrast measurements

Syringes (20 cc) filled with concentration of iodinated contrast agent (Ultravist 300, Bayer HealthCare Pharmaceuticals, Wayne, NJ) ranging from 5 to 100% dilution with saline were placed in a water bath (one syringe at a time). The amount of water was adjusted to approximate the noise in a clinical CT knee arthrogram. The average noise from 15 CT arthrograms of the knee previously performed at our institution was obtained by placing a region of interest (ROI) in the extra-articular soft tissues to measure the standard deviation of the mean Hounsfield units (HU). The syringes were scanned with SECT at 80, 120, and 140 kVp and with DECT. The iodine attenuation was obtained by placing an ROI in the center of the syringe and measuring the mean HU.

Dose and noise measurements

The radiation dose of the different techniques was measured using a 32 in. CT Dose Index (CTDI) phantom and a calibrated dosimeter (Victoreen 660, Fluke Biomedical, Cleveland, OH) with a 100 mm pencil ionization chamber. For each energy (80, 120, and 140 kVp and DE 140/ 80 kVp), the center and peripheral exposure values were measured in the axial mode at different tube currents ranging from 100 to 500 mAs. In DECT, the ratio between the currents of the two x-ray tubes was kept constant at the clinical ratio of 4.25:1 between 80 and 140 kVp and the mAs of the 80 kVp tube was varied from 100 to 500 mAs . The volume CTDI was then calculated using standard formulas [9].

The CTDI value displayed on the scanner console was also recorded for each scan. The noise was measured by scanning a 20-cm water phantom at the same tube voltages and currents that were used for the dose measurements and measuring the standard deviation of the HU in an ROI at the center of the phantom. The effective tube currents (effective mAs = mAs/pitch) at 80 and 140 kVp and DE at 140/80 kVp were adjusted to deliver approximately the same dose as the current protocol using 120 kVp and 125 effective mAs.

In-vitro animal experiment

Three fresh frozen cow femoral condyles were thawed and scanned using the current clinical technique of 120 kVp, 125 eff mAs and dose equivalent techniques using 80 kVp, 500 eff mAs and 140 kVp, 85 eff mAs, and dual energy 140 kVp, 45 eff mAs and 80 kVp, 192 eff mAs. Prior to scanning, several types of cartilage defects including slits, grooves, and rounded defects were created in each condyle. With 80 kVp and DECT, the condyles were scanned in a 30% iodinated contrast bath (Ultravist 300). This concentration was chosen based on the experiment above to maximize the attenuation in the contrast without detector saturation (3,071 HU). With 120 and 140 kVp, the condyles were scanned in a 45% iodinated contrast bath (Ultravist 300) to approximate the attenuation achieved during clinical scans. The average attenuation of contrast in clinical scanning was calculated by placing an ROI within the contrast in the joint in 15 previously performed CT arthrograms of the knee after the injection of full strength iodinated contrast (Ultravist 300). Between the two scans, the condyles were cleared of contrast agent with saline for 24 h. The order of scanning was performed randomly.

The difference in the attenuation between cartilage and contrast was calculated as the contrast-to-noise ratio (CNR). An ROI was placed in the cartilage and in the contrast, and the mean and standard deviation of the HU were recorded. The CNR was then calculated as follows

$$CNR = \frac{meanHU_{contrast} - meanHU_{cartilage}}{sdHU_{cartilage}}$$

The locations and sizes of the ROIs were all kept constant between the different techniques.

The images were reviewed independently by two musculoskeletal radiologists, blinded to the technique, on a multimodality workstation (MWP, Siemens Healthcare, Forchheim, Germany) on a single monitor in a 4 on 1 format. For each condyle, each of the four techniques was randomly assigned to one of the four windows with text removed. The readers were allowed to scroll through all the images and adjust the window settings to simulate the setting of clinical reading. Each observer was asked to rank the techniques from best to worst for the visualization of the articular cartilage and cartilage defects for each of the condyles.

To test the effect of edge enhancement on defect detection, one of the samples was reconstructed using B20 and B30 kernels, and the images were compared qualitatively to the B60 images by both readers.

Dual energy post-processing

One of the femoral condyles was placed in 30% iodinated contrast bath (Ultravist 300) overnight to allow for equilibration of contrast into the cartilage and then scanned with the dual energy technique. The images were post-processed on a separate multimodality workstation using commercially available dual-energy software (Syngo DE, Siemens Healthcare, Forchheim, Germany). As no dedicated post-processing application for arthrograms was available, the liver virtual-non-contrast (VNC) application was used. The post-processed images were then visually graded by both readers.

Cadaver imaging

Both knees of a human cadaver were imaged after the intra-articular injection of 15 cc of a 20% iodinated contrast solution (Ultravist 300) using 80 kVp, 500 eff mAs. Images were graded by two readers, blinded to the CT technique, as to whether they were of diagnostic quality.

Results

Iodinated contrast measurements

Attenuation varied linearly with iodine concentration with all four CT techniques (Fig. 1). The attenuation was higher with lower tube voltage (kVp). The highest sensitivity, i.e., the change in attenuation per percent change in contrast concentration, was shown by the 80 kVp technique (97 HU/% concentration), approximately 75% higher than 120 kVp (55 HU/% concentration) and 50% higher than DECT (63 HU/% contrast concentration). The 140 kVp technique had the lowest sensitivity (46 HU/% contrast concentration), less than half of the 80 kVp technique. Saturation of the CT numbers (3,071 HU) at 80 kVp , however, occurred at an iodinated contrast concentration of 31%, significantly lower than at 120 kVp where the saturation occurred at iodine concentration of 54%. The saturation of the CT numbers at 140 kVp occurred at 64% iodine concentration. As for the DE technique, which uses both 80 and 140 kVp, the saturation is limited by the lower 80 kVp saturation point.

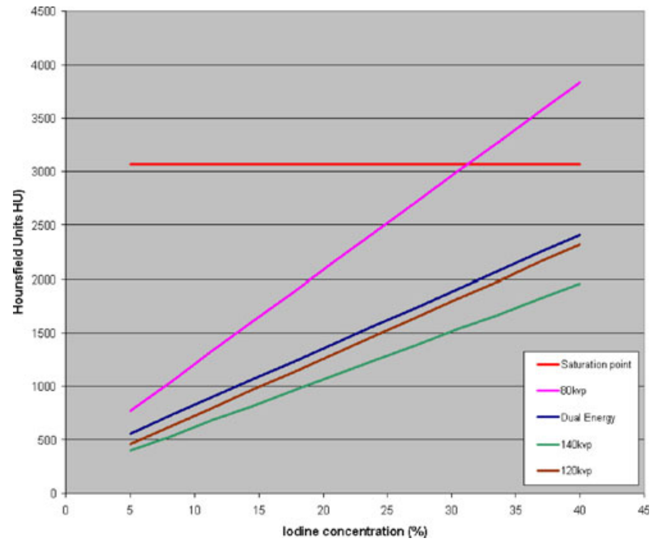

Fig. 1 Iodinated contrast concentration vs. attenuation at different x-ray beam energies. This chart demonstrates a direct linear relationship between iodinated contrast concentration and Hounsfield units for all beam energies. The slope of the lines (i.e., the change in attenuation per unit increase in iodine concentration) increases as the x-ray beam energy decreases

Dose and noise measurements

Dose varied inversely with noise by −1/2 power (Fig. 2) and was directly and linearly proportional with tube current for all the techniques (Fig. 3). For the attenuation provided by a 20-cm water phantom, the dose vs. noise curves were very similar regardless of the x-ray beam energy (Fig. 2). For a given dose, the noise was approximately the same regardless of the tube voltage, and for a given tube voltage, the tube current could be adjusted to achieve a specific dose (Fig. 3).

The measured dose values were in very good agreement with the CTDI values provided by the scanner. Using the CTDI values, the tube current (eff mAs) was adjusted to achieve scans using 80 and 140 kVp and DE that were nearly dose equivalent and therefore noise equivalent to our standard technique of 120 kVp, 125 eff mAs (Table 1).

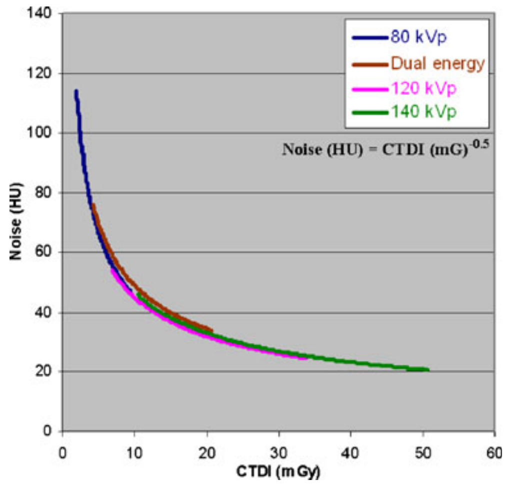

Fig. 2 Dose vs. noise at different x-ray beam energies. Relationship between noise and dose demonstrates an inverse relationship varying by −1/2 power. The curves are nearly identical for all the x-ray beam energies indicating that for a given dose, the same noise results regardless of the x-ray beam energy

In-vitro animal experiment

The CNR between the cartilage and contrast was highest for 80 kVp, followed by 120 kVp and DECT, and lowest for 140 kVp (Table 1). For the same dose, the 80 kVp technique had approximately 25% higher CNR than the current 120 kVp technique and DECT and 33% higher CNR than the 140 kVp technique.

Both readers ranked the 80 kVp images as the best for visualization of the cartilage and cartilage defects followed by 120 kVp and DECT, and lastly the 140 kVp images for all three condyles (Fig. 4). Both readers preferred the medium sharp B60 kernel to the smoother B20 and B30 kernels.

The post-processed DE iodine-only images using the liver VNC application were able to identify iodine within the cartilage as well as in the contrast bath (Fig. 5). The images, however, also incorrectly interpreted areas of bone as iodine. Identification of the margins of the cartilage layers, both superficially adjacent to the iodine bath and adjacent to the subchondral bone, were limited by noise.

Cadaver imaging

Both readers graded the cadaver images (Fig. 6) obtained using the 80 kVp dose equivalent technique as diagnostic in quality.

Discussion

Although CT arthrography has been widely used in clinical practice since nearly the advent of CT, to our knowledge, there has been no detailed study optimizing the technique. The reported scan parameters differ by institution and radiologist with most using a technique with 120 or 140 kVp tube energy and tube currents ranging from 125 to 200 mAs [10–17]. At our institution, we have used a 120 kVp and 125 eff mAs technique for CT arthrography of the knee. The purpose of this study was to optimize the technique for single energy CT arthrography and determine if DECT provides any additional benefit, specifically, to identify and quantify iodine in cartilage.

We found that iodine sensitivity (i.e., change in attenuation per unit change in iodinated contrast concentration) increases as the tube voltage decreases, with 80 kVp having the highest sensitivity. The 80 kVp level was ~75% more sensitive to iodine than 120 kVp, ~50% more sensitive than linearly mixed DECT, and ~100% more sensitive than 140 kVp (Fig. 1).

Radiologists often avoid using lower kVp believing that there will be more scatter and, therefore, more noise. This is true if the tube current is kept constant, however, if tube current is increased, noise can be reduced. Similarly, while an increase in tube current can lead to an increase in dose when tube voltage is kept constant, dose can be reduced by decreasing the tube voltage. In other words, it is possible to deliver the same dose using different tube voltages by appropriately varying the tube currents. Our dosimetry studies showed that for dose-matched SECT techniques using different tube voltages and a dose-matched DECT technique, noise is nearly identical (Fig. 2). This allows us then to select the technique that is optimal for the tissues being imaged, which is often cartilage in the case of CT arthrography. As expected, we also confirmed that the CTDI values measured and calculated using a dosimeter

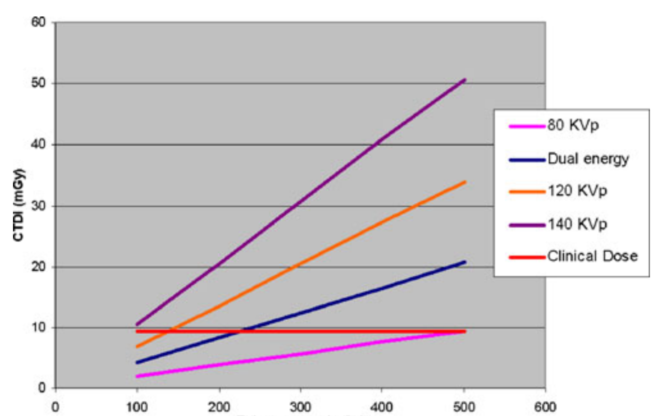

Fig. 3 Dose vs. tube current at different x-ray beam energies. Relationship between dose and tube current is directly and linearly proportional for all the x-ray beam energies. Therefore, the dose delivered using our current clinical technique at 120 kVp (*red line*) can be achieved at the other x-ray beam energies by appropriately varying the tube current

Table 1 Noise, CNR, and dose in cow condyles using dose-equivalent CT techniques

Energy (kVp)	Current (mAs)	Attenuation contrast (HU)[a]	Attenuation cartilage (HU)[a]	Noise (HU)[a]	CNR[a]	CTDI (mGy)
80	500	3,034	472	45	57	9.45
120	125	2,405	450	44	45	9.05
DE (140/80)	DE (45/192)	1,956	313	38	43	8.99
140	85	2,005	403	37	43	9.39

DE Dual energy CT, *CNR* contrast-to-noise ratio

[a] Average of three condyles

matched very closely to the CTDI values that are displayed on the scanner. Therefore, in clinical practice, the CTDI values provided by the scanner can be used as a quick and easy method of comparing dose between techniques without the need to conduct dosimetry.

Our animal experiments using dose equivalent techniques found that the 80 kVp technique had the highest CNR between cartilage and iodinated contrast, 25% greater than our current technique of 120 kVp, and 33% greater than a linearly mixed DECT or 140 kVp techniques, even when using full-strength iodinated contrast (Table 1). The CNR advantage for the 80 kVp technique would be even greater if less than full-strength iodinated contrast is used as is often the case in clinical practice. We also found that the 80 kVp technique was preferred qualitatively for the evaluation of the articular cartilage by both radiologists over the other techniques because of visually sharper margins and better edge definition.

Another potential advantage gained by using an 80 kVp technique is the ability to reduce the amount of iodinated contrast that needs to be injected when compared to the current higher energy techniques. Since many currently used non-ionic contrasts for arthrography are still hyper-osmolar to serum, using a smaller amount of contrast material in a given injected volume should result in less distention from influx of fluid and potentially decrease post-procedure discomfort [18]. Instead of the current technique of using full-strength contrast when using 120 or 140 kVp, the contrast can be diluted when using 80 kVp because of the higher iodine signal of 80 kVp. In our experiments, the optimal contrast agent dilution in vitro was 30% for 80 kVp. The higher iodine signal at 80 kVp may

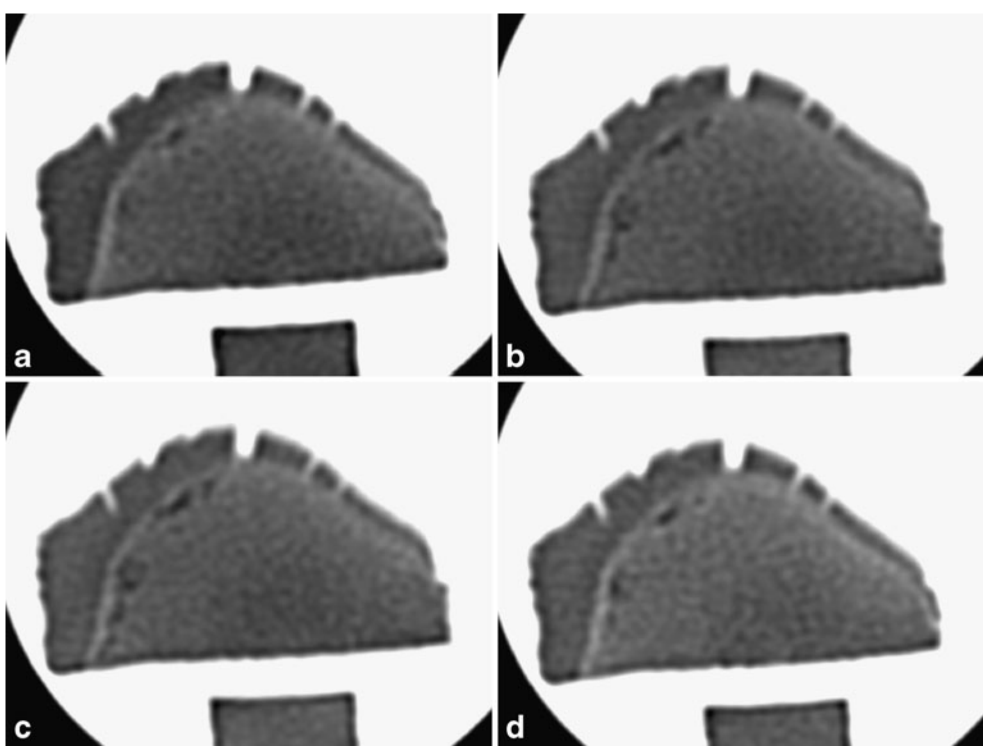

Fig. 4 CT scans of cow femoral condyles using dose-equivalent techniques. **a** 80 kvp, **b** 120 kvp, **c** 140 kvp, **d** dual energy. Cow femoral condyles in iodinated contrast bath imaged with the 80 kVp technique demonstrate sharper margins and better edge definition of the chondral defects when compared to other techniques

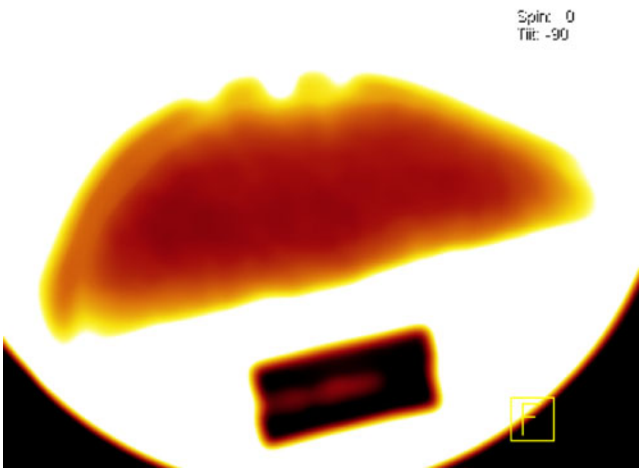

Fig. 5 Post-processed dual energy CT image of a cow femoral condyle. An iodine-only image of a cow femoral condyle in iodine bath generated by using the liver VNC (virtual noncontrast) post-processing application demonstrates the ability to identify iodine absorbed into the articular cartilage. The image is, however, limited by noise resulting in blurry margins and erroneous mapping of bone as iodine

also prove useful when there has been a long delay between injection and CT scanning.

In terms of DECT arthrography, the linearly mixed DECT technique was no better than our current 120 kVp technique with regard to iodine sensitivity (Fig. 1), CNR (Table 1), or visual appearance of the cartilage. These data suggest that it is unlikely that linearly mixed DECT would show any advantage for clinical CT arthrography. Post-processing techniques to identify and quantify iodine in cartilage using DECT had significant limitations. Currently, there is no commercially available dual energy post-processing application for CT arthrography. We used the only three-material decomposition post-processing application currently available on our scanner, liver VNC, which although not optimized for arthrography, still demonstrated the ability of DECT to detect iodine absorbed into cartilage. Quantification was not feasible because of the noise and the difficulty in separating the cartilage layer from the adjacent cortical bone, which was also incorrectly identified as iodine. Through this process, however, we were able to identify several challenges with DECT arthrography that we are currently working to address including the presence of four materials (bone, soft tissue, joint fluid, and iodine) in the field of interest requiring additional post-processing in order to apply a three-material decomposition technique; the inherent noise when evaluating the small width of the human cartilage layer; and beam hardening artifacts related to the proximity of the cartilage to adjacent dense cortical bone.

The primary limitations of this study include the in vitro technique and the small sample size. The quality of the lower kVp technique has not been investigated in patients. However, we were able to demonstrate diagnostic quality images with scanning of both knees of a single cadaver using the 80 kVp technique, which shows promise that this technique may be applicable to patients. Furthermore, we only considered CT arthrography of the knee, and this technique needs to be tested for other joints. Given the success with cadaver knees, we anticipate that similar diagnostic quality images should be possible with other peripheral joints such as the wrists, elbows, and ankles, where soft tissue attenuation would be similar to or less than the knee. Noise has, however, been shown to increase with decreasing kVp even when the dose is kept constant when scanning objects with large amounts of attenuation [19]. Therefore, while as yet untested, use of lower kVp techniques may prove more challenging for the hips and shoulders due to the higher degree of soft tissue attenuation that will likely result in noisier images. Further studies of the hips and shoulder are necessary, and it may be that the higher kVp techniques prove superior.

Despite these limitations, a dose equivalent CT arthrogram performed at lower single energy technique, such as 80 kVp, appears to have superior CNR and higher iodine signal than scans performed at the more standard higher tube energies such as 120 or 140 kVp for joints of knee size and smaller. Further studies including studies of different joints need to be performed to validate these findings in the clinical setting. Currently, DECT shows no advantage over SECT for arthrography. However, with development of appropriate post-processing methods, quantitative evaluation of iodine concentration in cartilage may become feasible.

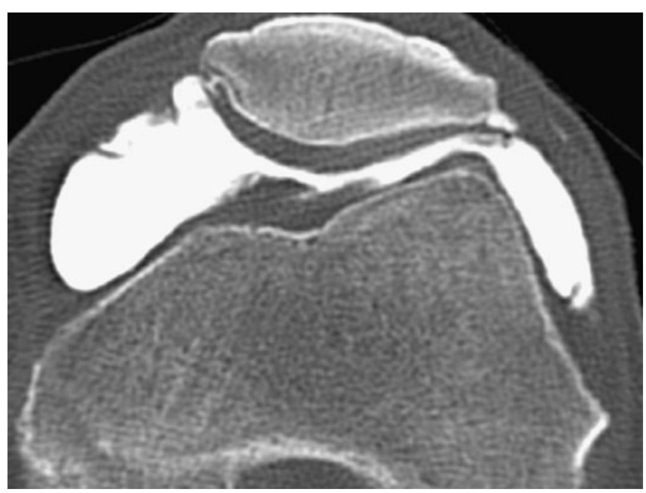

Fig. 6 An 80 kVp CT scan of a cadaver knee. Cadaver knee scanned using a dose equivalent 80 kvp technique demonstrates a diagnostic quality image

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