Renal Cyst Pseudoenhancement: Beam-hardening Effects on CT Numbers

PURPOSE: To determine if simple renal cysts may be accurately characterized with helical computed tomography (CT) during peak levels of renal enhancement.

MATERIALS AND METHODS: Water-filled “cysts” were suspended in varying concentrations of iodine solution, meant to simulate varying levels of renal enhancement, within an abdominal phantom. Volume-averaging effects were minimized by scanning cylindric 5–30-mm cysts with a helical technique (collimation, 5 mm; pitch, 1:1). Axial and helical techniques were then compared, and volume-averaging effects were evaluated by scanning 10- and 20-mm round cysts with 3-, 5-, and 7-mm collimation at background attenuation levels of 100 and 200 HU.

RESULTS: Cylindric cyst attenuation increased consistently with increasing background attenuation. As background attenuation increased by 90 HU, attenuation increased by 11–17 HU in small (5- or 10-mm) cysts, and by 7–9 HU in large (15–30-mm) cysts. As background attenuation increased by 180 HU, attenuation increased by 18–28 HU in small cysts and by 10–15 HU in large cysts. Spherical cyst attenuation differences were maximized when smaller cysts were imaged with larger collimation, which is when volume-averaging effects became apparent. Axial and helical CT numbers did not differ substantially. Computer simulation studies showed that the observed effect could not be explained by beam hardening alone.

CONCLUSION: Pseudoenhancement of renal cysts may occur if helical CT is performed during peak renal enhancement. CT algorithm modification may be necessary to correct for this effect, which is likely related to an inadequate algorithmic correction for beam hardening.

The emergence of helical computed tomographic (CT) technology has revolutionized abdominal CT imaging by enabling examinations tailored to specific organ systems. This is particularly true for the kidneys, where the accurate detection and characterization of small intrarenal masses with conventional CT may be difficult because of respiratory misregistration and volume-averaging effects (1,2). Advances in helical CT technology have largely overcome these limitations, as current helical scanning techniques enable volumetric data acquisition within a single breath hold, rapid imaging during peak levels of contrast material enhancement, elimination of respiratory misregistration artifacts, minimization of other motion artifacts, and production of overlapping reconstructed images without additional radiation exposure of the patient (3). As a result, helical CT has supplanted conventional CT as the preferred means of imaging the kidneys.

Dedicated helical CT of the kidneys is typically performed during peak levels of renal enhancement, when renal attenuation may measure 100–225 HU (4). This may facilitate the detection of renal lesions by maximizing conspicuity differences between normal enhancing parenchyma and hypoattenuating, hypovascular lesions. In theory, lesion
characterization should also be optimized, because scanning at this time should permit demonstration of subtle tumor enhancement indicative of lesion neovascularity, the most critical factor in diagnosing a renal tumor (2).

In our experience, however, a substantial lesion “pseudoenhancement” effect may also be encountered at this time. The pseudo-enhancement effect may result in mischaracterization of a simple renal cyst as an enhancing renal neoplasm. Such an effect appears to be most problematic in the evaluation of small (<15-mm) intrarenal parenchymal cysts, where cyst pseudoenhancement exceeding 10–15 HU may occur (Fig 1).

The goal of this study was to determine if simple renal cysts may be accurately characterized with helical CT during peak levels of renal enhancement. To accomplish this goal, we imaged a phantom designed for evaluation of the pseudoenhancement effect on simple cysts within a variably enhancing kidney.

MATERIALS AND METHODS

An abdominal phantom was constructed from polyethylene, a synthetic compound with a mass attenuation coefficient very similar to that of soft tissue. The phantom was built in the shape of an abdomen, measuring 20 × 30 × 40 cm (Fig 2). The abdominal phantom contained a central hollow cylinder 7 cm in diameter, which roughly approximated the diameter of a typical kidney. The central cylinder was filled with varying concentrations of iodine solution meant to simulate varying levels of renal enhancement. Iodine solutions were created by dilution of ionic contrast medium (iothalamate meglumine [Conray 60; Mallinckrodt, St Louis, Mo]) with water. Solution mixtures were titrated empirically by scanning (HiSpeed Advantage; GE Medical Systems, Milwaukee, Wis) serial dilutions until the desired solution CT numbers of 40, 90, 130, 180, and 220 HU were achieved. These solutions were meant to represent a spectrum of renal attenuation from that of a nonenhanced kidney (40 HU) to that of a kidney scanned helically at peak renal enhancement (220 HU). Solutions were instilled into the central cavity of the phantom through end valves, and residual air was flushed from the system.

Both cylindric and spherical “cysts” were constructed and studied in an attempt to first avoid and then include volume-averaging effects. Water-filled cylindric cysts 5–30 mm in diameter were placed within the solution-filled cylinder (enhancing kidney) and were suspended from both ends by hooks and sutures (Fig 3). Small cylindric cysts were constructed from 5- and 10-mm-diameter drinking straws filled with water and sealed at both ends. Large cylindric cysts consisted of elongated, water-filled latex balloons measuring 15, 20, 25, or 30 mm in diameter. Spherical cysts measuring 10 and 20 mm in diameter and constructed from round, water-filled latex balloons were suspended from the end hooks of the cylinder in a fashion similar to that of the cylindric cysts shown in Figure 3.

Prior to the study, a brief experiment was performed to ensure that the cysts were impermeable to iodine. In this experiment, cysts were soaked in 200 mL of undiluted 60% iothalamate meglumine solution for 3 days and scanned alongside control cysts that were soaked in only water. The lack of increase in CT numbers proved the absence of iodine diffusion through our phantom cysts.

The abdominal phantom was imaged with a helical CT scanner after being centered on the CT table to simulate normal anatomic positioning. In the first part of the experiment, helical scans were obtained through the centers of the cylindric cysts (section collimation, 5 mm; helical pitch, 1:1; reconstruction interval, 1 mm; field of view, 34 cm; 120 kVp; 220 mAs; and scanning time, 1 second).
In the second part of the experiment, spherical cysts, suspended in 100- and 200-HU background attenuation solutions, were imaged with both axial and helical techniques to investigate potential differences between these CT scanning methods (section collimation, 3, 5, and 7 mm; 120 kVp; 220 mAs; field of view, 34 cm; and scanning time, 1 second). Helical scans were acquired with a helical pitch of 1:1 and contiguous image reconstruction (3-, 5-, and 7-mm intervals).

For each combination of cyst size and background attenuation, five circular regions of interest (ROIs) were drawn completely within the cyst lumen (ROI size, 6–274 mm²), and the mean and SD of these five attenuation values were calculated. In addition, five circular ROIs were drawn completely within the cyst lumen (ROI size, 6–274 mm²), and the mean and SD of these five attenuation values were calculated.

To help explain the observed effects, we performed mathematical simulations of the CT scanning process with the SNARK93 computer system (SNARK93 user’s guide, Medical Image Processing Group, Philadelphia, Pa, 1993), which allows the user to specify the scanner parameters, mathematically describe images, and calculate CT projections. This system simulates single-section axial scanning, with a reconstruction algorithm very similar to that used in many commercial scanners. Most important, however, the simulation does not apply a beam-hardening correction, so that CT number changes secondarily to uncorrected beam hardening can be evaluated.

The simulated cyst cross-sectional diameters were 10, 15, 20, 25, and 30 mm. The background attenuation values were set at 40, 90, 130, 220, and 500 HU. The simulated scanner geometry matched that of a model 7800 scanner (GE Medical Systems). The beam-intensity spectrum consisted of 10% at 40 keV, 30% at 50 keV, 30% at 60 keV, 20% at 80 keV, and 10% at 100 keV. We used 360 views with 255 rays per view and the divergent beam-filtered back-projection algorithm with the Shepp-Logan filter (5) (cutoff at 1.0).

To ensure that inaccuracies in the reconstructions were due purely to beam hardening, we did not incorporate into our simulations other physical problems associated with CT data collection, such as noise due to photon statistics (5). The values for the mass attenuation coefficients were obtained from published tables (6). The pixel size used was 1.5 mm, and no beam-hardening correction algorithm was used. For each combination of cyst size and background attenuation values, a mathematically described image and its simulated CT reconstruction were produced and ROI (3 × 3) measurements were made to obtain the CT numbers of the water-filled cysts.

RESULTS

Cylindric cyst attenuation increased consistently with increasing background attenuation, as shown graphically in Figure 4 and in the raw data in Table 1. For example, the attenuation of the 5-mm cyst measured 5.2 HU ± 2.0 when background renal attenuation measured approximately 40 HU, which is roughly the attenuation of a nonenhanced kidney. The cyst attenuation increased to 16.1 HU ± 2.0 as background renal attenuation increased to 130 HU and to 23.4 HU ± 5.1 as background renal attenuation increased to 220 HU, which corresponds to renal attenuation values commonly achieved when helical CT is performed during peak renal enhancement (4).

The pseudoenhancement effect was most pronounced in smaller cysts. For example, an increase of 90 HU in background renal attenuation resulted in an 11–17-HU increase in 5- or 10-mm cysts, as compared with an increase of 7–9 HU in 15–30-mm cysts. Similarly, a larger increase of 180 HU in background renal attenuation resulted in an increase of 18–28 HU in small cysts as compared with 10–15 HU in large cysts.

Spherical cyst attenuation increased with increasing background renal attenuation in a manner very similar to that seen in the cylindric cysts (Table 2). For example, attenuation of the 10-mm cyst measured 7.9 HU when background attenuation measured 100 HU and increased to 15.1 HU as background renal attenuation increased to 200 HU. As one might anticipate, spherical cyst pseudoenhancement was maximized when 10-mm cysts were scanned with 7-mm collimation, which is when volume averaging became apparent (Table 2). For example, the 10-mm cyst showed 7.2 HU of pseudoenhancement as background attenuation increased from 100 to 200 HU when scanned helically with 3-mm collima-
Axial and helical CT numbers did not substantially differ (Table 2), aside from the effect observed in our phantom. For example, for the 20-mm cyst at a background attenuation of 180 HU, the calculated attenuation was 0.29 HU, while the observed value was 18.2 HU.

### DISCUSSION

Although renal lesion detection has improved substantially since the introduction of helical CT, in our experience, the characterization of small intrarenal masses remains problematic. Renal imaging at peak levels of enhancement may improve lesion conspicuity; however, pseudoenhancement effects may occur simultaneously. This may lead to potential mischaracterization of a simple cyst such as an enhancing renal neoplasm. In theory, this pseudoenhancement effect could also occur if conventional axial CT scanning is performed during peak renal enhancement. This phenomenon is less likely to be observed with conventional CT, however, as incremental-dynamic renal CT is usually performed over a longer temporal window than helical CT, during which renal enhancement is not as great.

We have demonstrated through the use of a phantom model that simple, nonenhancing cysts do indeed undergo pseudoenhancement as background attenuation increases. Specifically, we have shown that cyst attenuation increases in direct correlation with background renal attenuation. While this effect is substantial even when volume averaging is absent or at least minimized in the case of cylindrical cysts, the effect is most pronounced when small spherical cysts are imaged with larger collimation, which is when volume-averaging effects become apparent. The pseudoenhancement effect was observed with both the conventional and the helical CT techniques.

Artifactual changes in CT numbers are often referred to as beam-hardening effects. X-ray beam hardening is caused by an increase in the effective energy of a polyenergetic x-ray beam as it passes through a dense object secondary to preferential filtration of lower-energy x rays. While it is commonly known that beam hardening may lower CT numbers (7), it is less appreciated that an increase in CT numbers may occur.

Axial and helical CT numbers did not substantially differ (Table 2), aside from the instance of the 10-mm cyst studied at 7-mm collimation. At this solitary data point, the attenuation of the cyst at a background renal attenuation of 200 HU measured 19.5 HU when scanned helically and 31.2 HU when scanned axially. In the remainder of the cyst sizes and collimations studied, no substantial difference between axial and helical CT numbers was seen.

The results of the SNARK93 simulations are shown in Table 3 as a function of various cyst sizes and background attenuation values. The numbers in the body of the table are the mean attenuation values measured in the center of the cyst. Ideally, in the absence of any spectral effects, these should all equal 0 HU. For any cyst size, there was generally a gradual increase in reconstructed cyst attenuation as background attenuation increased. However, the size of this beam-hardening effect was too small to alone account for the effect observed in our phantom.
CT number of a central cylinder of water increased by 5–7 HU as surrounding background attenuation increased by 100 HU. They used a phantom model that would be less applicable to renal imaging and did not examine the effects of varying cyst sizes or varying background attenuations higher than 100 HU. Nevertheless, it lends credence to our results and demonstrates that pseudoenhancement secondary to beam hardening, or inappropriate correction for beam hardening, is a problem that has not been addressed over the past 2 decades.

Pseudoenhancement likely results from multiple factors, including beam hardening and volume averaging. We demonstrated that this effect does not appear to be caused simply by volume-averaging effects, which we minimized or completely eliminated through the use of cylindric cyst construction. We believe that the pseudoenhancement effect is likely due to an inadequate correction for beam hardening in the CT reconstruction algorithm. Our data suggest that the differences between our experimental and simulation results seem too large to be due to true beam hardening alone. Rather, it appears that the beam-hardening correction algorithm of the CT scanner may need to be refined for abdominal scanning with intravenous contrast agents. Since the algorithms were originally designed to suppress beam-hardening effects relating to bone and soft tissue on CT scans of the head, it seems plausible that they do not yield the requisite correction for iodine. As we are not privy to the exact mathematical manipulations and beam-hardening corrections used by the manufacturer, it is inappropriate to speculate on the exact algorithm problem that results in this phenomenon.

Because various CT scanners are not identical and may have different reconstruction algorithms, one should not conclude that the pseudoenhancement effects will be similar or even present in all scanners. Finally, the past practice of referring to all artifactual changes in CT numbers as “beam hardening” may be overly simplistic.

Our study had several limitations, most of which related to the oversimplification of our phantom model. It would have been ideal to use a model that included osseous structures, retroperitoneal fat, and other enhancing viscera, all constructed to anatomic scale. This was, unfortunately, beyond the means of this initial study.

In this study, we also did not evaluate the effects of beam hardening on different scanners or on scanning parameters (eg, milliampereseconds, reconstruction algorithm), all of which may have had some effect on the degree of pseudoenhancement observed. Further study is necessary to address these and other issues regarding beam hardening. Construction of more sophisticated phantom models may help to clarify the effect of beam hardening on CT numbers.

**Practical application:** In summary, results of this study confirm that pseudoenhancement may be observed in simple, small intrarenal cysts when studied at peak levels of renal enhancement. The pseudoenhancement is clearly attributable to some artifact other than volume averaging alone, likely an inadequate correction for beam hardening. Findings of prior studies have shown that beam-hardening artifacts may be corrected by scanning through an ROI twice with two different x-ray spectra (9); however, this would expose a patient to additional radiation and is not practical in a contrast-enhanced study.

Initial work by Joseph and Ruth (10) on phantoms scanned during electron-beam CT has shown promise in the search for an algorithm modification that will correct for beam hardening. Nevertheless, modification of a clinically applicable CT reconstruction algorithm is greatly needed to correct for this pseudoenhancement phenomenon. Until such modification is made, it may be necessary to modify current CT criteria used to characterize small intrarenal cysts. Specifically, an enhancement threshold of 15–20 HU may be more appropriate than the commonly used 10 HU (2). Alternatively, characterization of small intrarenal cysts may be better left to magnetic resonance imaging examination.

**References**