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FULL PAPER

Determination of optimal imaging settings for urolithiasis CT using filtered back projection (FBP), statistical iterative reconstruction (IR) and knowledge-based iterative model reconstruction (IMR): a physical human phantom study

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Objective: The purpose of this study was to compare CT image quality for evaluating urolithiasis using filtered back projection (FBP), statistical iterative reconstruction (IR) and knowledge-based iterative model reconstruction (IMR) according to various scan parameters and radiation doses.

Methods: A $5 \times 5 \times 5$ mm³ uric acid stone was placed in a physical human phantom at the level of the pelvis. 3 tube voltages (120, 100 and 80 kV) and 4 current-time products (100, 70, 30 and 15 mAs) were implemented in 12 scans. Each scan was reconstructed with FBP, statistical IR (Levels 5–7) and knowledge-based IMR (soft-tissue Levels 1–3). The radiation dose, objective image quality and signal-to-noise ratio (SNR) were evaluated, and subjective assessments were performed.

Results: The effective doses ranged from 0.095 to 2.621 mSv. Knowledge-based IMR showed better

objective image noise and SNR than did FBP and statistical IR. The subjective image noise of FBP was worse than that of statistical IR and knowledge-based IMR. The subjective assessment scores deteriorated after a break point of 100 kV and 30 mAs.

Conclusion: At the setting of 100 kV and 30 mAs, the radiation dose can be decreased by approximately 84% while keeping the subjective image assessment.

Advances in knowledge: Patients with urolithiasis can be evaluated with ultralow-dose non-enhanced CT using a knowledge-based IMR algorithm at a substantially reduced radiation dose with the imaging quality preserved, thereby minimizing the risks of radiation exposure while providing clinically relevant diagnostic benefits for patients.

INTRODUCTION

Up to 12% of the population will have urolithiasis in the USA, and half of the cases will suffer recurrence in the near future.¹ In addition, the prevalence and incidence of hospitalization for urinary stones has gradually increased.² Non-enhanced multidetector CT has been increasingly used to diagnose urolithiasis in patients who visit the emergency department. Intravenous pyelography or ultrasonography was widely used as the gold standard for diagnosis. However, non-enhanced CT has now become the diagnostic gold standard because of its high sensitivity and specificity.³ Recent studies have focused on reducing the radiation dose while maintaining image quality using new

iterative reconstruction (IR) algorithms compared with the standard filtered back projection (FBP).

A hybrid IR (iDose⁴; Philips Healthcare, Cleveland, OH) is one of the statistical IR methods that has been developed to decrease the radiation dose, noise and artefact for pulmonary, abdominal and brain CT.^{4–6} The iDose⁴ allows levels of 1–7, with higher levels resulting in greater noise reduction. The more recent knowledge-based IR [iterative model reconstruction (IMR); Philips Healthcare] was developed to use reconstruction steps back and forth to allow a greater dose reduction.⁷ This approach has three levels of noise reduction, similar to iDose⁴.

Lowering the effective dose (ED) decreases the quality of the image because of the excessive image noise, potentially causing a decrease in the diagnostic performance and confidence in the examination. Therefore, the as low as reasonably achievable principle is used as a reference to achieve the lowest radiation dose possible while maintaining an optimal image quality in multidetector CT examinations.⁸ Few clinical studies have been performed on the optimal CT imaging parameters because of ethical issues related to reimaging patients with various settings. Several clinical studies evaluated the usefulness of knowledge-based IMR algorithms for urolithiasis.^{7–12} The purpose of this study was to compare the image quality of three reconstruction algorithms (FBP, iDose⁴ and IMR) using a phantom and to find an optimal CT imaging setting that could preserve image quality but reduce radiation through systematic testing of various kV and mAs values.

METHODS AND MATERIALS

Phantom

The typical Korean male physical phantom (Radiation Health Research Institute of Korea Hydro and Nuclear Power, Seoul, Republic of Korea) was used for this study (Figure 1a). The phantom was modelled and constructed based on an average Korean healthy volunteer male with a height of 172 cm, weight of 68 kg and body mass index of 22.99 kg m^{-2} . The phantom's bone, lungs and soft tissues were composed of epoxy resin, urethane foam and polyurethane that had densities equivalent to the human tissue. The phantom was sliced with thickness of 2 cm. Its hole grids were 7 mm in diameter with an interval of 2 cm. A $5 \times 5 \times 5 \text{ -mm}^3$ uric acid stone was placed in a hole in the pelvis to represent a distal ureter stone. The phantom was fixed in a supine position in a frame to prevent shaking during scanning (Figure 1b).

CT protocol and image reconstruction

The phantom was scanned using a 256-multidetector CT scanner (Brilliance iCT; Philips Healthcare). The scan range was between the proximal aspect of the 12th thoracic vertebra and the distal aspect of the symphysis pubis of the phantom in the supine position to standardize non-enhanced CT for urolithiasis. Automated z-axis dose modulation calculated from the survey image (DoseRight; Philips Healthcare) was used for all scans. The scanning parameters were as follows: section thickness, 3 mm; increment, 2.7 mm; detector configuration, 128×0.625 ; pitch, 0.915; beam collimation, 80 mm; rotation time, 0.4 s; and helical acquisition. Three tube voltages (120, 100 and 80 kV) and four current–time products (100, 70, 30 and 15 mAs) were used.

The raw data were reconstructed with FBP, iDose⁴ (Levels 5–7) and IMR (soft tissue Levels 1–3) with a pre-released knowledge-based IR prototype system (Philips Healthcare) as recommended by the vendor. Thus, a total of 84 reconstructed imaging data sets were ultimately obtained.

Radiation dose and objective image quality

The dose–length product (DLP) and volume CT dose index (CTDI_{vol}) were noted by the manufacturer's CT scanner software. A constant region-specific normalized ED value was used ($0.015 \text{ mSv mGy}^{-1} \text{ cm}^{-1}$) to estimate ED from the DLP.¹³ The objective image noise was checked by an independent urologist who did not perform the subjective image assessment. Objective image noise was evaluated as the standard deviation of the Hounsfield unit (HU) in rectangular regions of interest (each with an area of 400 mm^2) placed in transverse homogeneous subcutaneous tissue of the phantom at the level of the stone (Figure 2). The signal-to-noise ratio (SNR) was defined as the CT number (HU) divided by the standard deviation and was calculated.

Figure 1. Outward appearance of the Korean physical phantom. (a) The phantom has 43 slices with the thickness of 2 cm; (b) the phantom was fixed in a supine position in a frame to prevent shaking during CT scanning.

Figure 2. CT image of the phantom at 100 kV and 30 mAs using three image reconstruction techniques. The arrows point to the uric acid stone with a 5-mm diameter. The objective image noise was evaluated as the standard deviation of the Hounsfield unit in rectangular regions of interest (each with an area of 400 mm²) placed in transverse homogeneous subcutaneous tissue of the phantom. The noise in the images produced by filtered back projection (a), iDose⁴ (b) and iterative model reconstruction (c) was 45.2, 21.7 and 8.0, respectively.

Subjective image assessment

The 84-image data set was independently and subjectively rated by one radiologist and one urologist, with at least 10 years' of experience, who were blinded to the scan parameters or reconstruction algorithms used. All images were transmitted to picture archiving and communication systems and displayed in a random fashion on a Barco monitor that was calibrated every

3 months, and its resolution was 1200 pixels in width and 1600 pixels in height. The basic window/level was 400/40, and it could be changed if necessary. The image quality around the target stone placed in a hole was graded on a five-point scale¹⁴ (1 = poor image quality, not diagnostically acceptable for interpretation; 2 = suboptimal image quality, worse than acceptable quality; 3 = acceptable image quality, diagnostic

Table 1. Scan parameters and dose reports

Voltage (kV)	Reference current–time product (mAs)	Effective current–time product (mAs)	CTDI _{vol} (mGy)	DLP (mGy)	ED (mSv)
120	100	84	3.82	174.7	2.621
120	70	44	2.7	123.4	1.851
120	30	19	1.11	50.9	0.764
120	15	10	0.54	24.8	0.372
100	100	61	2.25	102.9	1.544
100	70	43	1.56	71.3	1.070
100	30	18	0.63	28.7	0.431
100	15	10	0.28	13	0.195
80	100	58	1.03	46.9	0.704
80	70	41	0.72	33	0.495
80	30	18	0.3	13.8	0.207
80	15	10	0.14	6.3	0.095

CTDI_{vol}, volume CT dose index; DLP, dose-length product; ED, effective dose.

interpretation possible; 4 = good image quality; and 5 = excellent image quality). The confidence level for diagnosing urolithiasis was rated on a three-point scale¹⁴ (1 = no confidence; 2 = confidence with reservations; and 3 = highly confident). The noise in the whole image was subjectively evaluated on a three-point scale using the graininess of the image or pixel-to-pixel variation¹⁴ (1 = minimal; 2 = acceptable; and 3 = excessive, rendering diagnostic interpretation impossible).

Statistical analyses

The Mann–Whitney *U*-test and Kruskal–Wallis test were used to compare the objective image noise, SNR, subjective image quality, confidence level and image noise from FBP, iDose⁴ and IMR. Agreement between the subjective data from the radiologist and the urologist was verified using Cohen's *k* statistic. The *k*-values were interpreted as follows: slight (0–0.20), fair (0.21–0.40), moderate (0.41–0.60), substantial (0.61–0.80) and almost perfect (0.81–1.00).¹⁵ The recursive partitioning method was used to confirm the break point in the subjective image assessment. All statistical analyses were conducted using SPSS® v. 18.0 (IBM Corp., New York, NY; formerly SPSS Inc., Chicago,

IL) and R v. 3.0.2. Statistical significance was considered when *p*-value was <0.05.

RESULT

Radiation dose and objective image quality

CT scan parameters and dose reports are summarized in Table 1. Lower voltages and current–time products tended to display lower CTDI_{vol}, DLP and ED. The EDs were between 0.095 and 2.621 mSv. The objective image noise showed an inverse relationship with CTDI_{vol}, as shown in Figure 3. FBP, iDose⁴ and IMR had significantly ($p < 0.001$) different objective noise (53.5 ± 10.0 , 22.1 ± 39.2 and 9.2 ± 7.2 HU, respectively). IR (iDose⁴ and IMR) had significantly ($p < 0.001$) lower noise than FBP. The noise in IR was significantly ($p < 0.001$) lower for IMR than for iDose⁴ in all ranges of CTDI_{vol}. A similar trend as that in Figure 3a is shown in levels in Figure 3b. Among the levels of iDose⁴ and IMR, there was no statistically significant difference. IMR had significantly ($p < 0.001$) higher SNR than FBP and iDose⁴ (8.56 ± 4.5 , 1.56 ± 1.01 , and 3.14 ± 1.76 , respectively). Figure 3c shows a positive correlation between CTDI_{vol} and SNR in three reconstruction algorithms.

Figure 3. Relationship between objective image noise, signal-to-noise ratio (SNR) and volume CT dose index (CTDI_{vol}). (a) Iterative model reconstruction (IMR) produced significantly lower objective image noise than filtered back projection (FBP) and iDose⁴ (9.2 ± 7.2 , 53.5 ± 10.0 and 22.1 ± 39.2 HU, respectively; $p < 0.001$). (b) Regarding the levels of iDose⁴ and IMR, the higher the level, the less objective the image noise. However, there was no significant difference statistically. (c) IMR showed higher SNR than FBP and iDose⁴ (8.56 ± 4.50 , 1.56 ± 1.01 , and 3.14 ± 1.76 , respectively; $p < 0.001$).

Subjective image assessment

Among the reconstruction methods, the subjective image quality and diagnostic confidence were not significantly different ($p = 0.597$ and $p = 0.732$, respectively). The subjective image noise showed significantly ($p = 0.003$) different results. After applying Bonferroni's method, iDose⁴ and IMR were significantly superior with regard to subjective image noise compared with FBP ($p = 0.011$ and $p = 0.001$, respectively). The subjective image quality showed substantial interreader agreement ($k = 0.684$). Interreader agreements were almost perfect for diagnostic confidence and subjective image noise ($k = 0.829$ and $k = 0.858$, respectively). The subjective scores of two readers according to various settings are shown in Figure 4. The break point of the subjective image quality, confidence level and image noise were 0.4013, 0.2895 and 0.2010 mSv for the ED. All groups divided by the break point showed significant ($p < 0.001$) results. The 100 kV and 30 mAs showed the same qualities as the subjective assessments with 120 kV and 100 mAs in the IR algorithms.

DISCUSSION

IRs are becoming increasingly popular because they can provide lower image noise with a decreased radiation dose.¹⁶ Statistical IR algorithms such as iDose⁴ involve an initial FBP reconstruction followed by multiple iterative modelling of noise

statistics (both X-ray photon noise and electronic noise).^{17–19} Statistical IR algorithms have already been applied to urolithiasis.¹⁴ On the other hand, knowledge-based IMR algorithms are pure IR techniques that do not involve blending with FBP images. Knowledge-based IMR algorithms are mathematically more complex but more accurate than statistical IR algorithms.^{20,21} Furthermore, knowledge-based IMR showed the potential for decreasing the radiation dose by 74% at the abdomen⁷ and by 79% at the chest.²¹ Although our study was performed for urolithiasis, our recommendation for CT imaging is to reduce the radiation dose by approximately 84% based on the routine protocols of 120 kV and 100 mAs. Our results are as follows: (1) new IMR algorithms can show lower objective noise and higher SNR than FBP; (2) scans obtained at 100 kV and 30 mAs can have the same subjective qualities as those obtained using the regular or standard CT setting of 120 kV and 100 mAs although the objective noise and SNR had statistically significant differences. The radiation dose can be reduced by approximately one-sixth (0.431 mSv) in ED using this setting. Drake et al²² analysed low-dose CT studies between 2002 and 2008, and their ED values ranged from 0.5 to 2.8 mSv. Our results also showed a lower ED <1 mSv (possibly ultralow-dose CT).

The subjective image quality and diagnostic confidence in our study were not different among the three methods. By contrast,

Figure 4. Subjective image assessment by each CT parameter. The CT parameters are listed in the order of effective dose (ED). The arrow shows that break points of the subjective image quality, confidence level and image noise were 0.4013, 0.2895 and 0.2010 mSv in ED. All groups divided by the break points showed significant results ($p < 0.001$). (a) Image quality on a five-point scale (1 = poor image quality, not diagnostically acceptable for interpretation; 2 = suboptimal image quality, worse than acceptable quality; 3 = acceptable image quality, diagnostic interpretation possible; 4 = good image quality; and 5 = excellent image quality); (b) confidence level on a three-point scale (1 = no confidence; 2 = confidence with reservations; and 3 = highly confident); (c) subjective image noise on a three-point scale (1 = minimal; 2 = acceptable; and 3 = excessive, rendering diagnostic interpretation impossible). FBP, filtered back projection; IMR, iterative model reconstruction.

Botsikas et al¹⁰ found that model-based IR (GE Veo™; GE Healthcare, Milwaukee, MI) improved the subjective analysis compared with statistical IR [Adaptive Statistical Iterative Reconstruction (ASIR); GE Healthcare] in a clinical study with 53 patients. In addition, Kulkarni et al¹⁴ showed that statistical IR (ASIR) was superior to FBP in a study with 25 patients. This discrepancy may be caused by the difference between the use of a phantom and human subjects with urolithiasis. In a phantom serial study, it was possible to detect the radio-opaque lesion despite the poor image quality, which might cause upward levelling of subjective assessment. Our results are consistent with results reported in other phantom study.²³

There have been several reports on model-based IR and urolithiasis.^{7–12} Park et al¹² investigated 103 patients (the most recent among previous studies) by IMR of the mean ED at 0.68 mSv. An accuracy of 100% for ureter stones ≥ 3 mm in diameter was achieved with an approximately 91.82% reduction of the radiation dose. Other studies noted that model-based IR (Veo) offered better objective and subjective analysis than statistical IR (ASIR).^{7–10} Pooler et al⁸ investigated 48 patients by model-based IR (Veo) of the mean ED at 0.91 mSv. An accuracy of 98% for stones ≥ 4 mm in diameter was achieved with an approximately 78% reduction of the radiation dose. In our study, knowledge-based IMR displayed better objective and subjective image noise than FBP and statistical IR (iDose⁴). These studies show the potential of knowledge-based IMR for urolithiasis diagnosis using low radiation.

Although various radiation doses are used at different institutions for CT examination, Fahmy et al²⁴ reported on 108 patients with acute stone episodes exposed to mean 29 mSv in the first year. This was caused by diagnostic imaging and follow-up examinations after urolithiasis treatment. Patients with persistent symptoms had more risks of exposure to radiation. Abdomen and pelvis CT may have a 4-fold higher radiation dose than head, neck or chest CT, which could increase the risk of cancer to approximately 1 in 2000.²⁵ However, CT at our recommended setting values (100 kV and 30 mAs) may use approximately 0.5 mSv, which is less than half of that used for intravenous urography and is comparable to just one simple radiograph of the kidneys, ureters and bladder.

Knowledge-based IMR has several weaknesses. Most other reports have mentioned that model-based IR reduced the objective image noise. However, there have been disagreements of the subjective image assessment to determine the effects of model-based IR due to a plastic appearance.²⁶ Therefore, subjective image assessment should be investigated in further studies on knowledge-based IMR. Model-based IR requires considerable time to reconstruct. The speed of FBP, statistical

IR and model-based IR was 15, 10 and 0.09 frames s⁻¹, respectively.^{21,27} Model-based IR takes about 1 h per case. Therefore, in an emergency situation, this approach would be difficult. In our study, using a pre-released prototype IMR, the reconstruction time was approximately 30 min. Nevertheless, the new computer technique has reached an acceptable speed using knowledge-based IMR.^{28,29}

Our study has several limitations. First, the phantom has a simple constitution compared with a human body. In addition, a stone with a fixed size in the hole of a phantom could make diagnosis of urolithiasis rather simple. The hole grids that were used had a diameter of 7 mm, whereas the stone had a diameter of 5 mm. The stone was surrounded by air, which does not reflect *in vivo* conditions. The contrast is greater, and therefore, the contrast-to-noise ratio is better, resulting in a significant bias. Therefore, further clinical study is needed. Second, our recommendation of setting values at 100 kV and 30 mAs was identified in an ideal average phantom model. Patients who are suspected to have urolithiasis have various body mass index values, and some patients will not actually have a stone. Our recommendation could represent the minimal criterion that would be needed after the diagnosis or treatment of urolithiasis. In addition, we used a uric acid stone because the most common calcium oxalate stones can be visualized without difficulty because of their high HU. However, it may be not easy to find uric acid stones with low-dose CT.³⁰ Various stone compositions should be evaluated. Finally, although the reviewers were blinded, experienced reviewers, including radiologists, may be able to distinguish image sets obtained using various parameters (various kV and mAs) and image reconstructions (FBP, iDose⁴ and IMR), because of the difference in image texture. Thus, bias may be present in the subjective image assessment. In addition, the reviewers already knew that a stone was present, and they knew its location, resulting in a bias of the diagnostic confidence level. Despite the limitations, our study also has positive features. Because this was a phantom study, we could examine various parameters without ethical considerations. Eventually, we determined the optimal CT imaging settings while preserving image quality. Our results can serve as the basic point for clinical study.

In conclusion, knowledge-based IMR helps to reduce image noise and increase the SNR compared with FBP or statistical IR. At setting values of 100 kV and 30 mAs, the radiation dose can be decreased by approximately 84% while keeping subjective image assessment. Further clinical studies should be performed to overcome the limitations of this phantom study and confirm the potential of IMR.

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