Published in final edited form as:

AJR Am J Roentgenol. 2009 June ; 192(6): W271–W274. doi:10.2214/AJR.08.1502.

Detection of urinary stones at reduced radiation exposure: a phantom study comparing computed radiography and a low-dose digital radiography linear slit scanning system

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Abstract

Objective—In this experimental study we assessed the diagnostic performance of linear slit scanning radiography (LSSR) compared to conventional computed radiography (CR) in the detection of urinary calculi in an anthropomorphic phantom imitating patients weighing approximately 58 to 88 kg.

Conclusion—Compared to computed radiography, LSSR is superior in the detection of urinary stones and may be used for pretreatment localization and follow-up at a lower patient exposure.

Keywords

urinary calculi; radiography; radiation protection

Introduction

Patients with urinary stones usually receive numerous abdominal radiographs during their follow-up. Although exposure of a single radiograph is relatively low, the dose from those studies cumulates with a parallel increase of risk to develop a radiation induced cancer during the patient's life which is especially dangerous in young patients [1]. Linear slit scanning radiography (LSSR) obtains high-quality 2D radiographic images at a very good contrast-to-noise ratio and substantially lower patient exposure compared to conventional plain film or digital radiography [2-5]. The method is overwhelmingly used for the rapid assessment of the skeletal system after trauma. If LSSR would produce at least the same diagnostic accuracy and image quality as conventional plain radiography, one might choose LSSR to localize the stones before shockwave lithotripsy or for follow-up after treatment. In the present phantom study, we compared the detection rate of urinary calculi with different chemical compositions and sizes in LSSR and conventional computed radiography (CR) images.

Materials and Methods

Phantom

A hollow, anthropomorphic, plastic-encased phantom, representing the abdomen and pelvis of a patient weighing approximately 58 kg [6], was filled with water. The phantom contained cadaveric bones and measured 20 and 28 cm in the sagittal and coronal directions, respectively (small phantom). To imitate larger patients, gelatinous layer(s) were placed on its ventral and both lateral surfaces, resulting in AP diameters of 22 cm and 26 cm for an estimated patient weight of 71 kg (intermediate phantom) and 88 kg (large phantom).

Urinary stones

Twenty four stones of three sizes, i.e. 2.0, 5.0, and 7.0 ± 0.5 mm in the largest diameter, and eight chemical compositions were selected from human urinary stones harvested during surgery and endoscopy. The chemical compositions consisted of five types of pure stones (calcium oxalate monohydrate, calcium phosphate, magnesium ammonium phosphate, calcium hydrogen phosphate, and cystine) and three types of mixed stones. Our preliminary investigations showed that pure uric acid stones are not detectable on CR and LSSR images and therefore were not included in the analysis.

A 20×28 cm thin polyethylene sheet was divided into an 8×8 grid. The 24 stones were randomly positioned and affixed with tape in these fields. The stones were equally distributed between the upper and lower halves of the sheet. The sheet was placed on the ventral surface of the phantom with the upper half of the sheet above the iliac crest and the lower half on the bony pelvis (Figure 1). For each modality, a set of images was acquired in this configuration and a second set was acquired with the sheet rotated 180 degrees, so that stones formerly projecting onto soft tissues in the upper abdomen projected on the pelvic bones and vice versa.

Imaging

The Lodox Statscan™ Critical Imaging System (Lodox Systems, North America, LLC) was used to take LSSR scans of the phantom in the AP projection. The phantom size was selected manually on the user interface. All other technical parameters including tube energy and current were automatically selected by the Lodox unit using an algorithm designed by the manufacturer to keep patient exposure and image quality at optimum levels (Table 1). The CR images were acquired with a Philips Optimus x-ray system (Philips Medical Systems, Hamburg, Germany) using an anti-scatter grid. A Fuji FCR Profect CS (Fujifilm Medical, Tokyo, Japan) storage phosphor unit was used to read image information. Available tube energies best matching those on LSSR (i.e. 90, 102 and 117 kV) were chosen to image the small, medium and large phantoms, respectively. The small phantom was additionally imaged at 70 kV with the CR unit. Tube current was selected automatically by the unit at a reference dose of $3.5 \mu\text{Gy}$. The entrance surface dose, measured with a skin dosimeter (Unfors PSD4, Unfors, Ulm, Germany), in the small phantom at 90 kV was 5.12 mGy with CR and 0.191 mGy with LSSR.

Image evaluation

Three blinded radiologists with professional experience of 10 to 16 years interpreted the randomized images in a free response manner. They placed an acrylic transparency on the monitor and marked each perceived stone-like structure. Adjacent to each mark, a confidence level on a 3-point scale (1- possible stone; 2- probable stone; 3- definite stone) was recorded in addition to the overall image quality on a five point scale (1- poor; 2- sufficient; 3- intermediate; 4- good; 5- excellent). The radiologists were allowed to adjust the window and the level for optimal visualization of the images. The marks on the transparencies were compared with the true stone configurations on the polyethylene sheets. A mark was scored as

a true positive (TP) if the corresponding field contained a stone and otherwise it was scored as a false positive (FP).

Statistical analysis

The study design involved stone localization and multiple stones per image, which precluded the classical receiver operating characteristics analysis. Therefore, a new method for comparing the modalities was developed. This consisted of defining an appropriate figure of merit (FOM) that was defined as the probability that a stone was rated higher than a FP. The 95% confidence intervals for inter-modality differences of FOM (Δ FOM) were calculated using 1000 bootstrap samples from all possible TP and FP pairings.

Detection rates of readers were compared in a lesion-to-lesion manner and Cohen's kappa-statistics were calculated to assess the interobserver agreement.

Results

The figure of merit of LSSR was significantly higher than that of CR in 7 of 9 radiologist-phantom size pairings and, as a group, the radiologists performed significantly better using LSSR for all phantom sizes (Table 2). When comparing the FOMs for the small phantom imaged at 70 kV with CR to the 90 kV LSSR images, the combined 95% CI Δ FOM over all readers showed a significantly better performance for LSSR compared to CR.

The number of false positives was higher with CR compared to LSSR. The mean confidence level for TPs over all readers and phantom sizes was 2.713 with LSSR and 2.695 with CR. Averaging all readers and both modalities, 23% of all 2 mm stones were found. The corresponding rates were 71% and 74% for the 5 mm and 7 mm stones, respectively.

The mean interobserver agreement calculated in a lesion-to-lesion manner was good for CR ($\kappa=0.78$) and very good for LSSR ($\kappa=0.87$). The mean rank of image quality was 3.84 with LSSR and 3.10 for computed radiography.

Discussion

Possible reasons why LSSR was superior to CR are the different image postprocessing technique, the different scanning technology and detector system. Although we are not aware of any comparative study between CR and DR systems in the detection of urinary stones, DR systems using flat panel detectors have been reported to delineate anatomic structures in high attenuation areas of the chest better at a lower patient exposure compared to CR [7,8]. Beyond profiting from a detector with high detective quantum efficiency, the linear slot scanning technology used by the LSSR unit significantly reduces the number of scattered x-ray photons that reach the detector, which results in high contrast [4]. As our results show, these technical innovations may overcome the lower spatial resolution of LSSR compared to the CR system.

A potential limitation of our investigation is that patients weighing more than 90 kg were not simulated. Furthermore, we would have preferred conducting our study at tube voltages ranging from 70 to 85 kV, which are more suitable for the detection of calcified stones. Unfortunately, the lowest tube potential available for abdominal application was 90 kV for the LSSR scanner. Nonetheless, the overall performance was better with LSSR at 90kV than with CR at 70kV. We think that further improvement of stone detection with LSSR may be reached at lower tube energy. Therefore, pre-settings by the manufacturer should be optimized to this specific indication before any clinical implementation. A further limitation of our experimental setting was the lack of simulating bowel gas, which can hamper the detection of small urinary calculi in patients. However, our study setting took the overprojection of bones into account by using

two stone configurations, which were complementary in terms of containing each calculi projecting onto bones and soft tissues. The thorough analysis of detection rates classified by size and chemical composition of calculi was not our goal, since the number of stones in each group was too small for comparison. We also note that stones could not be embedded into the phantom. Instead, they were simply placed on its ventral surface which obviously does not correspond to the clinical situation. However, the superficial localization of stones had little effect on their detectability in projection radiographs as used in this investigation. Moreover, this setting was kept constant over the study so it did not influence the difference in performance with the imaging modalities.

We do not think that LSSR will replace CT as the method of choice for primary detection of urinary calculi, which has both a high sensitivity and specificity. However, LSSR has the potential to be used as a low-dose substitute in the pretreatment localization and follow-up of radiopaque stones with at least the same or even higher diagnostic performance as CR.

Acknowledgments

We are grateful to Dr. Robert M. Mini, Department of Radiooncology, Division of Medical Radiation Physics, University Hospital of Berne, to put the anthropomorphic phantom at our disposal. We also express our thanks to Dr. Roger Mueller, Department of Urology, University Hospital of Berne, for the human urinary stones investigated in this study.

D. P. Chakraborty was supported in part by grants from the Department of Health and Human Services, National Institutes of Health, R01-EB005243, R01-EB006388, and R01-EB008688.

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Fig. 1.

Anteroposterior radiograph of the small phantom using linear slit scanning technology at 90 kV showing urinary calculi projecting both on soft tissues and pelvic bones. Please note the 5 small lead pellets attached in the four corners and in the middle of the inferior margin of the plastic sheet as fiducial markers. Image quality was rated as excellent by all readers. The measured entrance skin dose of 0.191 mGy was about 5% of that with conventional computed radiography.

Table 1

Technical parameters used in the study for conventional computed radiography (CR) and low-dose digital radiography using linear slit scanning technology (LSSR). For LSSR, mAs values were calculated from the mA (given in parentheses), velocity of the C-arm (70 mm/s) and slit width (0.4 mm for small and medium phantom and 1 mm for large phantom). FFD = focus-film (detector) distance; lp/mm = line pairs per millimeter; and FOV = field of view

	Conventional CR				LSSR		
	small	small	medium	large	small	medium	large
Phantom size							
Tube potential (kV)	70	90	102	117	90	100	120
mAs (mA)	32.5	15.5	9.45	12.4	0.91 (160)	1.14 (200)	3.57 (250)
FFD (cm)			120			130	
Resolution (lp/mm)			10		4.2	4.2	2.1
FOV (cm ²)			35×43			46×52	
Pixel size (µm)			100		120	120	240

Table 2

Results of analysis for the detection of urinary calculi in three different phantom sizes with computed radiography (CR) and linear slit scanning radiography (LSSR) at 90, 100 and 120 kV. The table contains data of two complementary stone settings (i.e., 48 stones). TP = true positive, FP = false positive, FOM = figure of merit = the probability that a TP is rated higher than a FP, Δ_i = inter-modality difference in FOMs for the i^{th} reader and CI = 95% confidence interval. If a CI does not include zero then the difference is significant at the 5% level (marked with asterisk). Note that in 7/9 instances the readers individually performed significantly better with LSSR than with CR and that as a group they performed better with LSSR than with CR.

Modalities	Statistics	Phantom size								
		Small Readers (i)			Medium Readers (i)			Large Readers (i)		
		1	2	3	1	2	3	1	2	3
CR	# of TPs	29	27	31	27	26	30	25	20	28
	# of FPs	0	1	3	2	0	3	2	0	2
	FOM	0.802	0.651	0.619	0.712	0.771	0.694	0.651	0.708	0.640
LSSR	# of TPs	28	27	25	26	26	28	26	27	29
	# of FPs	0	0	0	1	0	0	1	0	0
	FOM	0.792	0.781	0.760	0.731	0.771	0.792	0.719	0.781	0.802
individual readers										
	Δ_i	-0.01	0.13	0.141	0.019	0	0.098	0.068	0.073	0.162
	CI(Δ_i)	(-0.026, 0.01)	(0.12, 0.141)*	(0.137, 0.145)*	(0.014, 0.024)*	(-0.016, 0.016)	(0.092, 0.105)*	(0.063, 0.075)*	(0.057, 0.089)*	(0.153, 0.168)*
average reader										
	Δ		0.087			0.039			0.101	
	CI(Δ)		(0.070, 0.102)*			(0.026, 0.052)*			(0.088, 0.115)*	