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Original paper

The synthetic localizer radiograph – A new CT scan planning method

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ABSTRACT

Objective: To investigate if the conventional localizer radiograph (LR) can be replaced by a synthetic LR (SLR), generated from a low-dose spiral CT scan, for CT scan planning with minimal changes to current clinical workflows.

Methods: A dosimetric comparison of SLRs and LRs was made using Monte Carlo methods. Water equivalent diameters (WEDs) of a centered and mis-centered phantom were estimated from low-dose spiral CT scans and LRs acquired at different angles. Body sizes, in the form of two lengths and two diameters obtained from SLRs and LRs, were compared for 10 patients (4 men and 6 women with a mean age of 74.8 and 76.2 years respectively) undergoing CT of thorax and abdomen. The image quality of SLRs for CT scan planning relative to LRs was rated using a 5-grade scale by four radiologists and two CT radiographers.

Results: An SLR can be obtained at a comparable effective dose to that of traditionally acquired LRs: 0.14 mSv. WEDs from LRs were more affected by mis-centering than WEDs calculated from low-dose spiral scans. One significant discrepancy of estimated body sizes was observed, the broadest part of the patient that on lateral localizers showed a mean deviation of 17.7 mm (range: 7.3–28.7 mm, $p < 0.001$). The anteroposterior/posteroanterior SLR image quality was assessed as better compared to an LR while the same could not be shown for lateral localizers.

Conclusions: SLRs based on low-dose spiral scans can replace LRs for CT planning.

1. Introduction

Recent developments in CT have resulted in the possibility of scanning patients with low radiation doses, taking advantage of techniques such as automatic tube current modulation (ATCM), iterative reconstructions and spectral shaping using tin filtration [1]. However, historically little has been done to optimize the radiation dose from the localizer radiograph (LR). The LR was introduced in 1978 as the "Scout View" [2]. By moving the patient through the X-ray beam while the X-ray tube and detector were stationary, a projection radiograph image of the patient could be obtained. Internal anatomical landmarks could then be localized prior to a CT scan. Today, LRs are routinely used for planning CT scans and they are essential in protocols associated with ATCM. Despite practical improvements, the basic concept of LRs (acquisition of a projection radiograph image) has remained unchanged since its introduction. Recent studies have shown that the LR can be acquired at low doses and that the LR should be optimized [3,4]. Further, attempts to improve the CT scan planning have been presented. Yin et al. [5] demonstrated that by adding a low-dose spiral CT scan prior to the diagnostic scan, a volumetric 3D dataset can be created for segmenting a patient's organs. Gomes et al. recently demonstrated that a low-dose spiral CT scan can be used to create a synthetic LR (SLR), by projecting through the reconstructed 3D patient volume [6].

The SLR has the potential to be introduced into clinical practice on already available scanners, while allowing greater flexibility (e.g. reconstruction at arbitrary angle at no additional radiation dose). Further, as an SLR is created from a reconstructed 3D volume of the patient, ambiguities due to magnification of anatomical features can be avoided. The concept of the low-dose spiral planning scan has great potential, beyond simply replacing the LR with a synthetic equivalent,

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as the patient geometry would be available prior the diagnostic scan. In theory, "automatic CT scanning" could be possible. The CT scanner could automatically locate, plan (including the ATCM) and perform the scan of a certain organ of interest, e.g. kidneys or liver. Prior to the diagnostic scan, more comprehensive and accurate estimations of the expected radiation dose and image quality could also be made.

As a first step towards this vision, the purpose of this study was to investigate if it is feasible to replace the LR as we know it with the SLR, generated from a low-dose spiral CT scan, with minimal changes to current clinical workflows.

2. Materials and methods

A dual source CT scanner (SOMATOM Definition Flash, Siemens Healthcare, Forchheim, Germany) was used. Hereafter an LR with the X-ray tube stationary at 12, 3 and 6 o'clock will be denoted LR-AP, LR-LAT and LR-PA, respectively, for a patient positioned supine.

2.1. Monte Carlo estimated patient doses

Patient doses for whole body low-dose spiral CT scans (from which SLRs were created) and for LR-AP, LR-LAT and LR-PA acquisitions were estimated using a commercial Monte Carlo dose estimation software package (ImpactMC, AB-CT Advanced Breast-CT GmbH, Erlangen, Germany). After modelling the CT scanner and defining scan parameters, the software accepts DICOM volumes as an input and delivers a 3D dose volume that can be segmented. The simulations were made using the ICRP 110 adult reference female computational phantom [7], including the patient table. The female phantom was selected, rather than the male phantom, as it has higher resolution due to thinner slices. The estimated effective dose was calculated from the organ doses. To keep the uncertainty of doses to the organs low, the numbers of histories used in the simulations were chosen so that the standard deviation of the noisiest region of interest in the phantom was lower than 2% [8]. The low-dose spiral CT scan doses were estimated with scan settings that gave lowest achievable dose in clinical practice and the LR doses were estimated using the default scan protocol setting at the CT scanner, according to vendor recommendations (Table 1).

2.2. Investigation of water equivalent diameters from LRs and SLRs

To investigate estimates of patient size with different scan techniques and patient centering, scans were acquired with an ATCM phantom (CT228 ATCM Phantom, The Phantom Laboratory, Salem, NY, USA), based on the work of Merzan et al. [9]. The phantom consists of three different sized sections: small, medium and large. The sections are homogenous in the Z-direction to let the ATCM function stabilize the tube current as it has previously been shown that some CT scanners need a short distance to do so [9]. LR-AP, LR-PA and LR-LAT images and spiral scans were acquired with the scan protocols simulated in the patient dose study (Table 1). Three scenarios were investigated with 10 repetitions: phantom centered, phantom lowered 3 cm and 6 cm. The phantom was lowered rather than raised to create mis-centering. The reason for this was that the patient table could not be elevated as much as it could be lowered due to mechanical restrictions. Also, mis-centering is more often too low than too high [10].

Table 2
The radiation doses to the most radiosensitive organs and the effective doses from the patient dose estimations. LR-AP, LR-LAT and LR-PA stands for LR acquired with the X-ray tube stationary at 12, 3 and 6o'clock respectively for a patient positioned supine.

Organ doses [mGy]	Weighting factor (ICRP103)	Spiral (SLR)	LR-AP	LR-LAT	LR-PA
Breast	0.12	0.13	0.13	0.07	0.02
Colon	0.12	0.15	0.15	0.07	0.08
Gonads	0.08	0.11	0.13	0.04	0.12
Lung	0.12	0.14	0.12	0.07	0.10
Red bone marrow	0.12	0.08	0.07	0.05	0.05
Stomach	0.12	0.15	0.14	0.03	0.05
Effective dose [mSv]		0.14	0.14	0.06	0.07

The water equivalent diameters (WEDs) from LR scans were acquired from the DICOM metadata [11]. The WEDs from the spiral scan volumes were calculated both with the patient table retained in the volume and with it removed [12]. Note that the WEDs for the low-dose spiral CT data were therefore calculated prior to the data-reduction to an SLR. WEDs were estimated for the three sections of the ATCM phantom, by averaging the WEDs over a length of 4 cm to minimize random errors.

2.3. Synthetic localizer radiograph creation

The reconstructed slices of the low-dose spiral CT scan were selected to be as thin as possible (0.5 mm, no overlap) and obtained using iterative reconstruction technique (SAFIRE level 5, Siemens Healthcare, Forchheim, Germany). An SLR was created from the 3D volume of the low-dose spiral CT scan using an in-house script (for MATLAB, Mathworks, Natick, MA, USA). The script removed the patient table from the 3D volume, after which an average intensity projection was made along the volume in the sagittal and coronal projections to generate LR-like 2D images. Note that summations were along columns or rows and therefore this projection scheme mimicked a non-divergent X-ray beam geometry (no magnification effects).

2.4. Prospective patient study

After approval from the local ethical committee, 10 patients older than 65 years scheduled for a routine CT of thorax and abdomen were recruited with informed consent between October and November 2017. The group consisted of 4 men (mean age 74.8 years and mean BMI 24 kg/m^2) and 6 women (mean age 76.2 years and mean BMI 24.4 kg/m^2). 2 of the patients had a hip prothesis. In addition to the scheduled routine examination, each patient underwent a low-dose spiral CT scan prior to the diagnostic scan. According to clinical routine, both an LR-PA and an LR-LAT were also acquired. Note that it is possible to use ATCM with a single LR, and that it is an active decision at our institution to use two LRs for CT examinations of thorax and abdomen. CT scan parameters for the low-dose spiral CT scan were the same as for the patient dose estimation (Table 1). SLRs were generated for the anteroposterior/posteroanterior (AP/PA) and the lateral (LAT) direction.

Table 1
The scan protocol settings that were used in the patient dose estimations and in the water equivalent diameter phantom study. The protocols include a low-dose spiral scan and localizer radiographs with the X-ray tube stationary at three different angles. The spiral scans were reconstructed with a slice thickness of 0.5 mm.

Scan type	Tube voltage [kVp]	Shaped filter	Tube current [mA]	Rotation time [s]	Pitch	Table speed [mm/s]	Collimation [mm]	X-ray tube angle [clock]	Recon filter	CTDIvol [mGy]
Spiral (SLR)	80	Standard + Narrow	20	0.5	1.5	115.2	38.4	–	I30f	0.14
Localizer radiograph	120	Standard	35	–	–	100	3.6	12, 3, 6	T20f	0.14

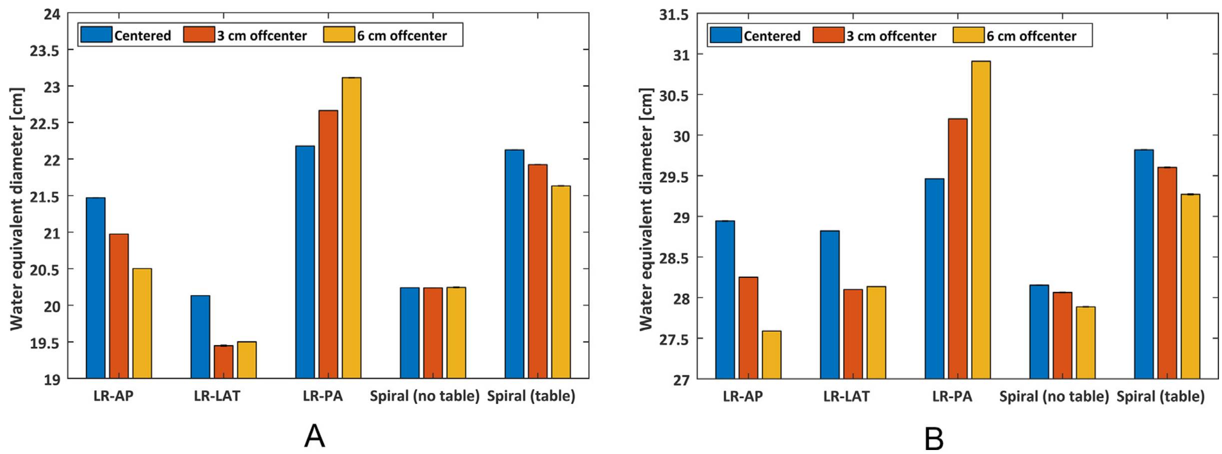

Fig. 1. Water equivalent diameters of the small (A) and large (B) section of the ATCM phantom (CT228 ATCM phantom, The Phantom Laboratory) estimated with 5 different methods and 10 repetitions. The standard deviation of the estimated water equivalent diameters from each method is shown with error bars. However, the standard deviations are small and barely distinguishable. LR-AP, LR-LAT and LR-PA stands for LR acquired with the X-ray tube stationary at 12, 3 and 6o'clock respectively for a patient positioned supine. The blue bars are water equivalent diameters for a centered phantom, while the red and yellow bars correspond to water equivalent diameters for a phantom off-centered 3 cm and 6 cm respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 2. A set of LR and SLR from a patient examination (female, 87 years old). A and C shows an LR-AP and an LR-LAT respectively. B and D shows SLR reconstructed from a low-dose spiral scan in the AP and LAT directions respectively. Note that when creating the SLR, further post-processing algorithm could be used to further enhance boundaries and organs.

The LR and SLR images were blinded and evaluated by 4 experienced radiologists (6, 19, 24 and 24 years of CT experience) and 2 experienced CT radiographers (16 and 32 years of CT experience). Window display settings were carefully selected to optimize the LRs and SLRs respectively. Measurements of four scan ranges were compared. The AP/PA images were evaluated by measuring the length of the lung (apex to its most caudal end), thoraco-abdominal length (lung apex to pubic symphysis) and the thinnest diameter of the patient. The LAT

Fig. 3. Axial image from the low-dose spiral scan showing the abdomen of a patient (same patient as in Fig. 2, female, 87 years old). Window center: −100, window width: 1600.

images were evaluated by measuring the broadest part of the patient. The deviations in measurements between the LR and the SLR were calculated. The review of the length determination was done at two occasions, at least 1 week apart using a cross-over design. A side-by-side relative visual grading analysis (RVGA) [13] of the image quality for planning a CT thorax-abdomen scan was made. A 5-scale grade was applied by setting a score of the SLR relative to the LR: 1 clearly superior, 2 somewhat superior, 3 equal, 4 somewhat inferior and 5 clearly inferior.

2.5. Statistical analysis

The differences between WEDs estimated from a centered phantom and a mis-centered phantom were evaluated by independent t-tests. No deviations from normality were indicated (Lilliefors corrected Kolmogorov-Smirnov test and visual inspection of histograms) with the exception for a single outlier observed for centered LR-AP WEDs. In this case, statistical conclusions with the t-test were not sensitive to the retention or exclusion of the outlier.

The measured body size lengths determined by the six observers were averaged for each patient and differences between SLR and LR evaluated by paired t-tests. Again, no deviations from normality were observed in the data.

The RVGA was analyzed by calculating a confidence interval (CI) for the mean using t-test statistics [14,15].

All statistical calculations were done using a commercial statistics application (SPSS 24, IBM Corporation) assuming a significance level of $\alpha = 0.05$.

3. Results

3.1. MC estimated patient doses

The doses to the most radiosensitive organs according to ICRP103 [16] and the effective doses from the Monte Carlo simulations are presented in Table 2. The effective dose was estimated to be 0.14 mSv for both the SLR and LR-AP. The effective dose from an LR-LAT or an LR-PA acquisition was around 50 % of the SLR dose (0.06 mSv and 0.07 mSv, respectively).

3.2. Phantom study investigating water equivalent diameter

The average estimated WED from scans of the small and the large section of the phantom are shown in Fig. 1a and b. The low-dose spiral scan WED estimates, calculated with the table removed as has been recommended [9], showed the least variation with mis-centering. In this case, no statistically significant variation was found for the small phantom section ($p = 0.87$) and while it was significant for the large section ($p < 0.001$), the variation was less than 0.3 cm. The largest WED differences from a centered and a 6 cm mis-centered phantom came from LR-AP and LR-PA (1–1.4 cm, $p < 0.001$), followed by LR-LAT (0.6–0.7 cm, $p < 0.001$).

The standard deviation of individual WED estimates (at single slice positions) was comparable for both SLRs and LRs and estimated as < 0.02 cm in all cases.

3.3. Prospective patient study

A set of LR and SLR images from the patient study is shown in Fig. 2 and a single axial image of the abdomen from a low-dose spiral CT scan is presented in Fig. 3, included to demonstrate a low-lose spiral scan image.

The differences in measured body sizes from LR and SLR images are presented in Table 3. No significant differences could be shown between LR and SLR measurements in the AP/PA direction for lung ($p = 0.84$), thorax-abdomen ($p = 0.06$), and the thinnest part of the patients ($p = 0.35$). A significant deviation between LR and SLR was observed in the LAT direction ($p < 0.001$), where the observers measured a mean difference of 17.7 mm between methods, when assessing the broadest part of the patient ($p < 0.001$).

The SLR method provided equal or better image quality with a mean score in the AP/PA direction of 2.5 (CI: 2.2–2.9), while significance could not be shown in the LAT direction (mean value: 3.3, CI: 2.7–3.9).

4. Discussion

The radiation doses for SLRs and LRs were similar to the dose for a chest X-ray examination (PA and LAT, 0.1 mSv) [17,18]. The patient doses for LR-PA were lower than for LR-AP, mainly because the patient table absorbs radiation prior to the patient and that there are more radiosensitive organs anterior. The patient doses for LR-LAT were also lower than for LR-AP, but in this case, it is due to the smaller area on the patient that the radiation hits. Note that generally, LR-AP is used in the CT vendors' default scan protocols. LRs can be acquired with

Table 3
Results from the measured length differences between the localizer radiograph (LR) and synthetic localizer radiograph (SLR) images of the patient study (10 patients). The lower and upper confidence interval (CI) and the p-values are calculated using a 95% CI.

Length (LR-SLR)	Direction	Mean [mm]	Std [mm]	Range [mm]	Lower CI [mm]	Upper CI [mm]	p-value
Lung	AP/PA	0.6	8.5	−14.9 to 12.3	−6.7	5.5	0.835
Thorax-Abdomen	AP/PA	−2.2	3.2	−7.4 to 1.3	−4.4	0.1	0.060
Thinnest part	AP/PA	5.8	18.4	−17.4 to 37	−7.4	19.0	0.347
Broadest part	LAT	17.7	7.7	7.3 to 28.7	12.2	23.2	< 0.001

radiation doses lower than vendor recommendations, however, as it has previously been shown that low LR doses can impact the ATCM negatively [9], caution should be employed. Observe that that SLRs at any rotation angle can be generated from the low-dose spiral CT scan data at no additional dose (e.g. AP/PA and LAT) and that additional information is therefore obtained, compared to a single conventional LR.

The standard deviation of WEDs from LRs and spiral scans have similar magnitudes. However, as can be seen in Fig. 1, the consistency of average WEDs with patient mis-centering is superior using a low-dose spiral compared to a conventional LR. The results for the LRs agree with the expectation that objects displaced towards the detector appear smaller in an LR and those displaced away from the detector appear larger. For the WEDs calculated from spiral scans including the patient table, the WEDs were reduced, as the table gradually moved out of the field of view. As expected, the WEDs of the small part of the phantom calculated from a spiral scan with the patient table removed did not change with patient mis-centering, however, the WEDs of the large part of the phantom did. The reason for this was that the CT numbers changed in the large phantom part (about 2 HU) due to the shaped filter. Note that a mis-centered patient would still have a negative effect because of the shaped filter, even with a correct WED estimation. Such mis-centering of patients results in both increased skin doses and degradation of image quality [10,19]. However, more consistent WEDs should still lead to a more consistent ATCM function. Further, the 3D volume data could be used to correct the patient position prior to the diagnostic scan, making it possible to fully benefit from available bowtie filters.

A statistically significant disagreement between SLR and LR estimates of the patient extent was only observed in the LAT direction ($p < 001$). For any beam orientation, a divergent X-ray beam will intersect the patient surface at positions displaced towards the X-ray tube, relative to iso-center, causing varying magnification. The effect is more pronounced for the LAT LR, as the displacement from isocenter is typically larger. This may explain for the increased discrepancies in spatial extent between LRs and SLRs observed in the LAT orientation. Such incorrect body size estimations should be minimized as they affect the CT scan planning negatively with less accurate field of view selection.

The results from the RVGA showed that the AP/PA SLR was slightly, but significantly, better than the LR (CI: 2.2–2.9, outside the score 3), while no significant difference could be determined for the LAT case (CI: 2.7–3.9). It is possible to conclude with high confidence, however, that the LAT SLR is no more than slightly worse than the LR (mean RGVA score < 4). The results suggest that it would be possible to replace LR with SLR in a CT scanner with little or no compromise in the image quality of the localizers for CT scan planning. It should be noted that when creating the SLR further post-processing algorithms could have been used, reducing noise and enhancing boundaries of significance. However, we chose to not include such an algorithm in this study. The image-quality presented here for the SLR can therefore undoubtedly be improved upon.

This study has some limitations; a single CT scanner was used and only 10 patients were included. The dosimetric effect of over-scanning of the low-dose spiral was not investigated as whole-body CT scans were simulated in the patient dose estimations. Although the LRs and SLRs were blinded and randomized, it is likely that the observers could distinguish between them due to different image characteristics. Perhaps the greatest limitation of this study is that the possibility to improve the ATCM was not investigated directly. It was not possible to feed the ATCM with our own WED curves to compare the ATCM response based on an LR and an SLR. However, we did show that WED differs between the techniques. This demonstrates, albeit indirectly, that the ATCM function will depend on how the localizer was acquired. It is worth noting that the observed changes in WED (> 1 cm) would change the ATCM appreciably, as a patient size increase of 3.6 cm requires the tube current to be doubled to keep the noise level constant [20]. Thus, the proposed technique of using SLR for ACTM has a great potential in reducing radiation doses and improving image quality.

The reconstruction time of the SLR could be a practical issue using today's CT scanners. The reconstruction of an LR is almost instant. That is currently not the case for an SLR, which requires a full patient volume to be reconstructed. The CT scanner used in this study reconstructs images (with iterative reconstruction technique) at a speed of approximately 20 images per second. A whole-body CT scan (thin slices) consists of around 1000 images, which therefore take around 50 s to reconstruct. However, computer processing speed is continuously improving, making this a short-term issue. Note that the process of creating an SLR from the 3D volume is fast, at around 5 s (using an in-house MATLAB program on a standard laptop computer).

There are advantages having a low-dose planning scan prior the diagnostic CT scan. During CT scan planning, viewing axial images could assist optimization of the start- and end-point of a scan volume: risk of over- or under-sampling the volume would be reduced. Handling of metal artifacts could be improved, as the geometry of the metal part is available prior the diagnostic CT scan and therefore an optimal metal artifact reconstruction technique could be chosen. On many models of CT scanners, a low-dose spiral is faster to acquire than a conventionally acquired LR, resulting in a reduced examination time. There would also be no time delay for the scanner to accelerate the rotation of the gantry after the planning scan has been collected, further improving scanning efficiency. These innovations leveraging the full power of the low-dose spiral planning scan would require changes in software and hardware.

In this study, we have shown that the low-dose spiral planning scan can be used in today's CT scanners with the SLR technique as a first step, providing some advantages over conventional LRs.

5. Conclusion

Based on dose, spatial fidelity and image-quality for CT scan planning, our results indicate that it would be feasible to replace the LR with an SLR in clinical practice, in today's CT scanners with small changes to current workflows. CT scan planning could in the future be made on 3D models of the patients (generated from spiral scan data) with SLRs created at no additional radiation dose.

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