



## Research article

## Feasibility of sub-milliSievert CT of the cervical spine: Initial results in fresh human cadavers



Julius Matthias Weinrich<sup>a,\*</sup>, Marc Regier<sup>a</sup>, Lennart Well<sup>a</sup>, Peter Bannas<sup>a</sup>, Oleh Nykolyn<sup>a</sup>, Axel Heinemann<sup>b</sup>, Susanne Sehner<sup>c</sup>, Cyrus Behzadi<sup>a</sup>, Klaus Püschel<sup>b</sup>, Gerhard Adam<sup>a</sup>, Azien Laqmani<sup>a</sup>

<sup>a</sup> Department of Diagnostic and Interventional Radiology and Nuclear Medicine, University Medical Centre Hamburg-Eppendorf, Martinistrasse 52, D 20246, Hamburg, Germany

<sup>b</sup> Department of Legal Medicine, University Medical Centre Hamburg-Eppendorf, Martinistrasse 52, D 20246, Hamburg, Germany

<sup>c</sup> Department of Medical Biometry and Epidemiology, University Medical Centre Hamburg-Eppendorf, Martinistrasse 52, D 20246, Hamburg, Germany

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## ABSTRACT

**Purpose:** To investigate the feasibility of sub-milliSievert CT of the cervical spine in fresh human cadavers using a standard-dose (SD) and four different reduced-dose (RD) protocols reconstructed with filtered back projection (FBP) and iterative reconstruction (IR).

**Methods:** The cervical spine of 29 cadavers was examined using different RDCT protocols with decreasing reference tube currents (RDCT-1:70 mAs; RDCT-2:50 mAs; RDCT-3:30 mAs; RDCT-4:10 mAs) at 140 kV. A clinical SDCT (160 mAs, 120 kV) served as reference. Raw data were reconstructed using FBP and two increasing levels of IR (IRL4&6). Images of the upper (C1–4) and lower (C5–7) cervical spine were evaluated for image quality, diagnostic acceptability and visibility of anatomical structures according to a 5-point-scale.

**Results:** Image quality of the upper cervical spine was diagnostically acceptable for all protocols using FBP and IR except for RDCT-4 with FBP. Image quality of the lower cervical spine was rated as non-diagnostic in RDCT-3 with FBP and RDCT-4 with FBP and IR. RDCT-3 with IR was the most reduced dose CT protocol allowing diagnostically acceptable image quality for both upper and lower cervical spine in all cadavers. RDCT protocols achieved significantly reduced effective radiation doses (SDCT:  $1.5 \pm 0.7$  mSv; RDCT-1:  $1 \pm 0.6$  mSv; RDCT-2:  $0.7 \pm 0.4$  mSv; RDCT-3:  $0.4 \pm 0.2$  mSv; RDCT-4:  $0.2 \pm 0.1$  mSv;  $p < 0.001$ ).

**Conclusion:** Diagnostically acceptable sub-milliSievert CT of the cervical spine is feasible with a low reference tube current at 140 kV using iterative reconstruction and could be suitable for isolated cervical trauma in co-operative patients.

### 1. Introduction

Injuries of the spinal column are common after traumatic injuries [1]. Due to fast volumetric acquisition with thin collimation and multiplanar reformations [2] resulting in high sensitivity and specificity for the detection of fractures [3,4] multidetector CT (MDCT) has become the first-line imaging modality for the initial assessment of suspected cervical spine injuries.

Unfortunately, MDCT of the cervical spine leads to a relatively high ionizing radiation exposure with alternating values of 1.1–2.38 mSv when iterative reconstruction is employed [5], but with levels as high as 26 mSv without it [6].

This is especially relevant for imaging of the cervical spine since radiation exposure to the thyroid gland is a recognized risk factor for development of thyroid cancer [7].

In order to comply to the as low as reasonably achievable (ALARA) principles, reduction of ionizing radiation of CT protocols without sacrificing image quality is needed [8]. However, dose reduction is associated with increased image noise which might impair image quality. Consequently, iterative reconstruction algorithms (IR) compensating for image noise have become widely popular [9].

There are only a few retrospective studies addressing dose reduction in cervical spine CT [5,10–12] and only one study, which performed a stepwise dose reduction in four formalin-treated cadaver specimens

\* Corresponding author at: Department of Diagnostic and Interventional Radiology and Nuclear Medicine, University Medical Centre Hamburg-Eppendorf, Martinistraße 52, Hamburg, 20251, Germany.

E-mail address: [j.weinrich@uke.de](mailto:j.weinrich@uke.de) (J.M. Weinrich).

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[13]. All of these studies were performed with a tube voltage of 120 kV, even though it has been suggested to be more susceptible to variations in body mass index [13,14]. A recent study has suggested that even a low tube voltage allows to reduce the radiation dose in a CT unenhanced study, a higher tube voltage (140 kV) combined with significant reduction of tube current might allow for additional dose reduction [13].

For ethical reasons, intraindividual comparison of multiple reduced dose CT protocols and feasibility of extremely reduced dose settings cannot be performed in patients. However, performing multiple CT scans in human cadavers can help to overcome this immanent limitation of clinical reduced dose CT studies.

Therefore, the aim of this study was to investigate the feasibility of sub-millisievert CT of the cervical spine in fresh human cadavers using a standard-dose and four different reduced-dose protocols reconstructed with filtered back projection and iterative reconstruction.

## 2. Materials and methods

Informed consent was obtained from relatives of the deceased and the local ethics committee approved this prospective study due to the anonymous utilization of data.

### 2.1. Imaging protocols

All examinations were performed on a 256-slice CT scanner (Brilliance iCT, Philips, Best, the Netherlands) using the following parameters: detector collimation: 128 × 0.625 mm; pitch: 0.586; tube rotation time: 0.5 s. The automatic exposure control system (automatic current selection) combined with z-axis dose-modulation (Z-DOM) was used.

Standard dose CT (SDCT) was performed at a tube voltage of 120 kV and a reference tube current of 160 mAs. Reduced dose CT (RDCT) was performed at a tube voltage of 140 kV and decreasing reference tube currents of 70 (RDCT-1), 50 (RDCT-2), 30 (RDCT-3) and 10 mAs (RDCT-4). Details are given in Table 1.

Subjects were placed in supine position with the head first on the CT table and arms next to the body for all protocols. Anteroposterior topogram served as orientation for the scan range from the foramen magnum to the top of the first thoracic vertebral corpus.

### 2.2. Reconstruction techniques

All CT data sets were reconstructed using filtered back projection (FBP) and two levels (IRL4 and 6) of an established IR algorithm (iDose<sup>4TM</sup>, Philips Healthcare) [15]. Within iDose<sup>4TM</sup>, increasing levels represent increasing strength of noise reduction. The technical details of IR have been described elsewhere [16].

**Table 1**  
CT protocol.

Protocol	SDCT	RDCT			
		1	2	3	4
Reference tube current (mAs)	160	70	50	30	10
Tube voltage (kV)	120	140			
Collimation (mm)	128 × 0.625				
Rotation time (s)	0.5				
Pitch	0.586				
Automatic tube current modulation	Z-DOM				
Level of Iteration	FBP and iDose Level 4&6				
Kernel	Bone (D)				
Section thickness (mm)	3				
Reformations	Axial, coronal, sagittal				

Note: Tube current-time product (mAs) values are given as the reference tube current values.

After reconstruction of the 29 SDCT and the 116 RDCT (four different protocols) with FBP and the two IR levels, 435 CT data sets of the cervical spine were available.

All datasets were reconstructed in a bone kernel in axial, coronal and sagittal planes with a 3 mm slice-thickness.

### 2.3. Radiation dose

CT dose index (CTDI<sub>vol</sub>) and dose-length product (DLP) were derived from the automatically generated dose protocol of each examination. Effective dose (ED) was estimated by multiplying the DLP (mGy\*cm) by a conversion factor of 0.051 mSv\*mGy<sup>-1</sup>\*cm<sup>-1</sup> for tube voltage of 120 kV and 0.052 mSv\*mGy<sup>-1</sup>\*cm<sup>-1</sup> for tube voltage of 140 kV [17].

Size-specific dose estimates were calculated for each subject. To calculate specific dose estimates, we measured the effective diameter from the anteroposterior (AP) and lateral (LAT) dimensions at the fourth cervical vertebra [18].

$$\text{Effective Diameter (cm)} = \sqrt{\overline{AP} \times \overline{LAT}}$$

A conversion factor based on the Medicine Report No. 204 by the American Association of Physicists was selected for each subject [19]. Size-specific dose estimate (SSDE) was calculated as follows:

$$\text{SSDE (mGy)} = \text{CTDI}_{\text{vol}} \times \text{conversion factor}$$

Estimated dose savings in SSDE and effective dose was expressed as the calculated percentage of radiation reduced between the SDCT protocol and each RDCT protocol.

### 2.4. Quantitative image analysis

Quantitative image analysis was performed using a dedicated PACS workstation (PACS IW, GE Healthcare, Milwaukee, MI, USA) by one co-investigator who was not involved in the qualitative image analysis process.

CT numbers (CT-N), defined as the attenuation in Hounsfield units (HU), were measured in axial plane by placing circular regions of interest (ROIs) of 25 mm<sup>2</sup> in the most homogenous area of both sternocleidomastoid muscles of the neck at the level of third and seventh cervical vertebra in each subject for each protocol. To prevent bias resulting from a single ROI measurement, each region was measured at three slices. Results were then averaged for further analyses. The standard deviation (SD) of CT-N served as objective image noise (OIN).

Shoulder superimposition was measured in each subject on the anteroposterior topogram. Shoulder superimposition was defined as the superimposition (in centimetre) within the scan range of the cervical spine.

### 2.5. Qualitative image analysis

For qualitative image analysis, all 435 CT data sets were anonymized, randomized and reviewed in a blinded manner. The images were reviewed independently by two radiologists with 4 and 5 years of experience in musculoskeletal imaging. As the protocol was designed as a dedicated bone trauma scan, a bone window (window width, 2500 HU; window centre, 500 HU) was used for qualitative evaluation.

Overall subjective image quality and visibility of defined anatomical structures were separately analysed.

Overall image quality was assessed taking into consideration the three quality aspects subjective image quality, image noise and streak artefacts using a 5-point scale (1 indicating worst through to 5 indicating best). Thereby, subjective image quality ratings were based on the sharp and clear distinction of anatomical structures, image noise was subjectively rated based on the extent of irregular granular pattern and artefacts due to beam hardening and photon starvation were

**Table 2**  
Radiation dose.

Protocol	SDCT	RDCT			
		1	2	3	4
Tube current-time product (mAs)	201.5 ± 93.8	90.6 ± 47.6	64.3 ± 33.9	38.3 ± 20.1	13.8 ± 5.3
CTDI <sub>vol</sub> (mGy)	13 ± 6	8.6 ± 4.5	6.1 ± 3.2	3.6 ± 1.9	1.3 ± 0.5
DLP (mGy*cm)	287.7 ± 141.2	191.7 ± 107.2	136 ± 75.9	81.2 ± 45.1	28.9 ± 12.3
Effective Dose (mSv)	1.5 ± 0.7	1 ± 0.6	0.7 ± 0.4	0.4 ± 0.2	0.2 ± 0.1
Size specific dose estimates (mGy)	28.4 ± 12.2	18.7 ± 9	13.3 ± 8.4	8 ± 3.8	2.9 ± 1

Note: Tube current-time product (mAs) values are given as the modulated tube current values.

subjectively rated based on presence/extent and impairment of visibility of the underlying structures.

The applied 5-point scale scoring system is composed as follows:

- 1 poor image quality with poorly defined anatomical structures, major irregular granular pattern, major streak artefacts with total impairment of visibility of the underlying structures
- 2 reduced image quality with limited resolution of anatomical structures, extensive irregular granular pattern, substantial streak artefacts with substantial impairment of visibility of the underlying structures
- 3 acceptable image quality with well distinction of anatomical structures, moderate irregular granular pattern, moderate streak artefacts without substantial impairment of visibility of the underlying structures
- 4 good image quality with clear & sharp distinction of anatomical structures, minor irregular granular pattern, minor streak artefacts with no impairment of visibility of the underlying structures
- 5 excellent image quality with excellent distinction of anatomical structures, no perceived irregular granular pattern, no perceived streak artefacts

Scores of 3–5 were considered as diagnostically acceptable and 1 and 2 as non-diagnostically acceptable image quality.

Anatomical structures were rated at three anatomic levels based on the European Guidelines on Quality Criteria Computed Tomography [20]: 1. sharp reproduction of cortical and trabecular bone, 2. sharp reproduction of intervertebral foramina, pedicle and intervertebral joints and 3. sharp reproduction of spinous and transverse processes.

Upper (C1–C4) and lower (C5–C7) cervical spine were evaluated separately (within the same reading session). Diagnostic acceptability for a CT scan was defined by the lowest score for either upper or lower cervical spine.

## 2.6. Statistical analysis

Sample characteristics are given as absolute and relative frequencies or mean +/- standard deviation, whichever is appropriate.

The effect of reconstruction level on the quantitative parameters (CT-N and OIN) was estimated with a mixed effect model for repeated measures (MMRM) to account for the repeated measurement structure of the data. The repeated structure was defined by three adjacent image slices at two different locations on the left and right side per subject and reconstruction level; so, a random intercept for each subject was modelled.

The visibility of anatomical structures and overall subjective image quality rated by two independent readers was modelled analogously to the quantitative parameters using a MMRM. Additionally, a second random intercept term for reader was included to account for potential cluster effects.

To compare the reconstruction levels within protocol and location for quantitative and qualitative parameters all three factors and their three-way-interaction (as well as all consecutive interactions) were

included in the according model. In the case of an insignificant interaction term only the consecutive interactions or the main effects remained in the model. This decision was reached by using the likelihood ratio test for model comparison. As potential confounder of the relation between the three predictors and the outcome the variables age, sex, BMI, days post mortem, shoulder superimposition and scan length were entered into the models. Since the visibility was rated at three different anatomical structures an indicator for the anatomical structure was added in this model.

Results were reported as estimated marginal means, which are represented in graphs with their corresponding 95% confidence intervals (95% CIs).

Inter-rater reliability between the two readers was assessed by calculating intraclass correlation coefficient (ICC).

P-values < 0.05, two sided were considered significant. All analyses were computed using Stata 15.1 (STATA Corporation, College Station, Texas, USA).

## 3. Results

### 3.1. Study population

Between February and June 2017, we included a total of 29 fresh human cadavers (15 male and 14 female) with an average BMI of  $25.2 \pm 4.8 \text{ kg/m}^2$  in our study. CT scans were performed  $4.8 \pm 5.7$  days post mortem. Average age at death was  $69.9 \pm 15.8$  years.

### 3.2. Radiation dose

The mean exposure, CTDI<sub>vol</sub>, DLP, SSDE and effective dose in all RDCT were reduced (all  $p < 0.001$ ) when compared to SDCT (Table 2).

When compared to SDCT, effective radiation dose was reduced by 33% in the RDCT-1, by 53% in RDCT-2, by 73% for RDCT-3 and by 87% for RDCT-4.

### 3.3. Quantitative results

The CT-numbers in RDCT and SDCT studies did not differ between protocols or iterations ( $p > 0.05$ ).

Shoulder position, BMI and SSDE were confounders for OIN ( $p = 0.001$ ).

Shoulder girdle superimposition (50%; 95%-CI: 3%–9% for ten centimetres of superimposed shoulder girdle) and increased BMI (40%; 95%-CI: 3%–7% for ten kg<sup>2</sup>/m in BMI) led to an increase of OIN. An increase of one mGy in SSDE led to a 30% decrease of OIN (95%-CI: 44%–53%). OIN ( $\pm$  95%-CI) for both, upper and lower cervical spine, is graphically displayed in Fig. 1.

OIN increased with reduction of radiation dose and was higher in the lower cervical spine compared to the upper cervical spine. Application of IR significantly decreased the OIN. With application of IRL6, OIN in RDCT-3 did not significantly differ from SDCT with FBP (Fig. 1).

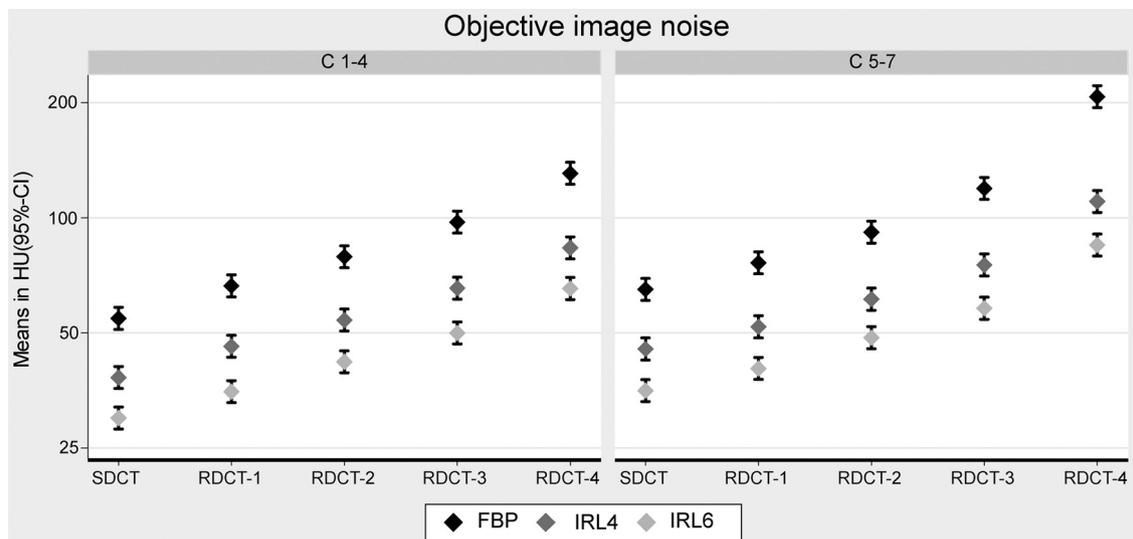


Fig. 1. Quantitative analyses of objective image noise for SDCT and different RDCT protocols for upper (C 1–4) and lower (C 5–7) cervical spine. Images were reconstructed with FBP, IRL4 and IRL6. Error bars represent the 95% CI. Note the overall higher image noise for the lower cervical spine. With application of IRL6, OIN in RDCT-3 did not significantly differ from SDCT with FBP.

### 3.4. Confounding factors for subjective quality and visibility of anatomical structures

Shoulder superimposition led to a decrease of image quality ( $p = 0.014$ ) as well as decreased visibility of anatomical structures ( $p = 0.022$ ).

### 3.5. Qualitative results

The image quality of the upper cervical spine was generally rated as high and except for RDCT-4 with FBP all protocols resulted in diagnostically acceptable image quality (Fig. 2). For the lower cervical spine image quality ratings were generally lower and RDCT-3 with FBP and RDCT-4 with FBP and IR were not diagnostically acceptable (Figs. 3 and 4).

The CT protocol with the lowest radiation dose, which allowed diagnostically acceptable image quality for both, the upper and the lower cervical spine, was RDCT-3 with both IRL4 and IRL6 (Fig. 5). There was no significant difference between the two applied IR levels ( $p < 0.05$ ).

### 3.6. Visibility of anatomical structures

Regardless of the protocol and applied reconstruction technique, cortical and trabecular bone was generally rated as less visible when compared to intervertebral foramina, pedicle, intervertebral joints as well as spinous and transverse processes ( $p < 0.001$ ).

Visibility of all anatomical structures was rated high for the upper cervical spine. The visibility of anatomical structures of the lower cervical spine was generally rated lower.

In accordance to the results of subjective image quality, RDCT-3 reconstructed with IRL4 and 6 was the protocol applying the lowest radiation dose which still resulted in a diagnostically acceptable image quality for visibility of anatomical structures in both the upper and lower cervical spine (Fig. 6). There was no significant difference between image quality for RDCT-3 with IRL4 and IRL6 ( $p < 0.05$ ).

### 3.7. Interobserver agreement

The readers showed an excellent agreement for evaluation of image quality (ICC = 0.90; 95%-CI: 0.89–0.92) and for evaluation of visibility of anatomical structures (ICC = 0.89; 95%-CI: 0.88–0.90).

## 4. Discussion

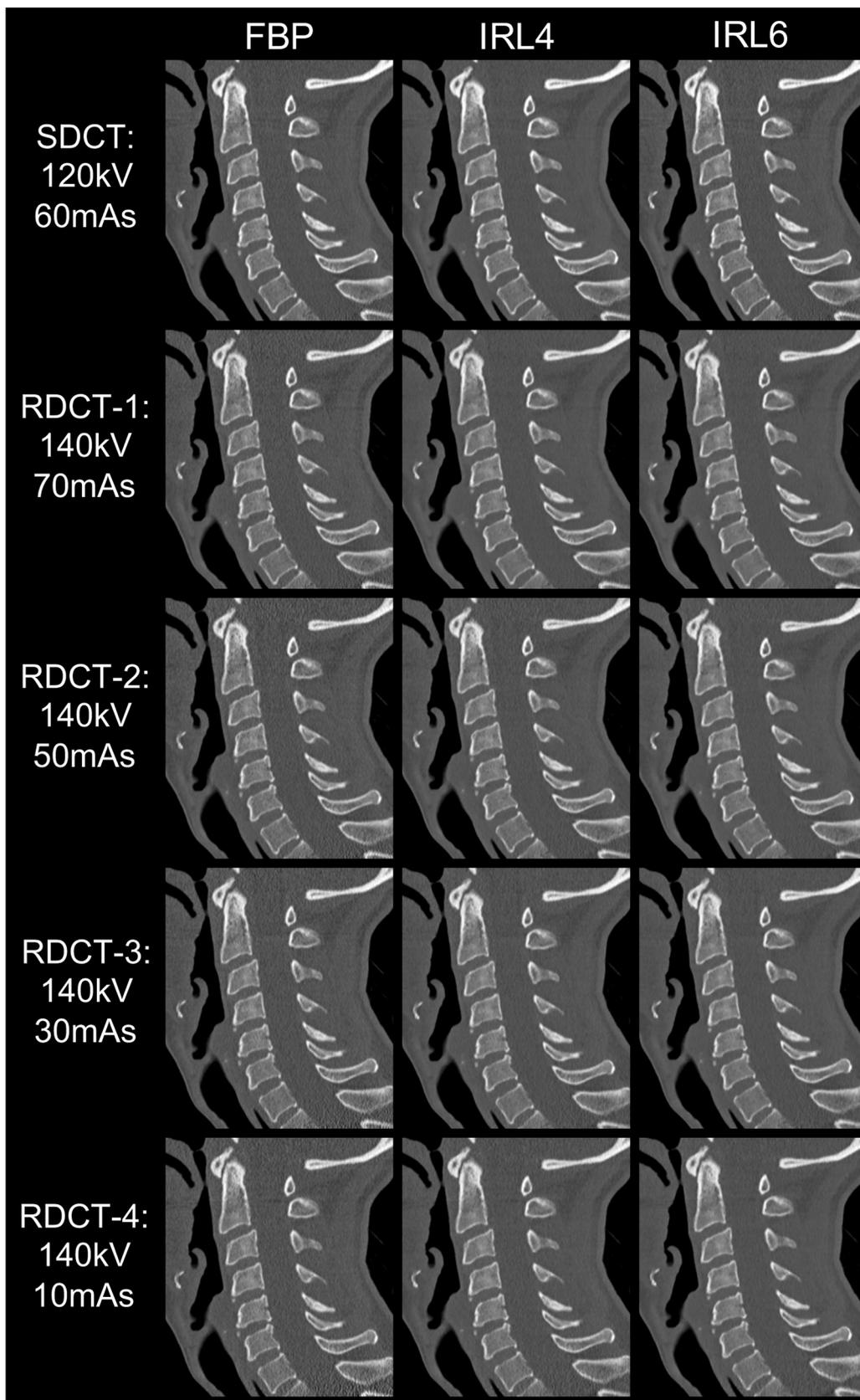
Our results show that a sub-milliSievert RDCT protocol with IR allows for a significant reduction of 73% of effective radiation dose while maintaining a high image quality of the cervical spine.

Diagnostic image acquisition of the upper cervical spine was possible for all cadavers using IR, even with a decrease in tube current to 10 mAs. The optimal combination of decrease in radiation dose and adequate diagnostic image quality of the cervical spine was achieved with a tube voltage of 140 kV, reference mAs of 30 reconstructed with IRL4 or IRL6.

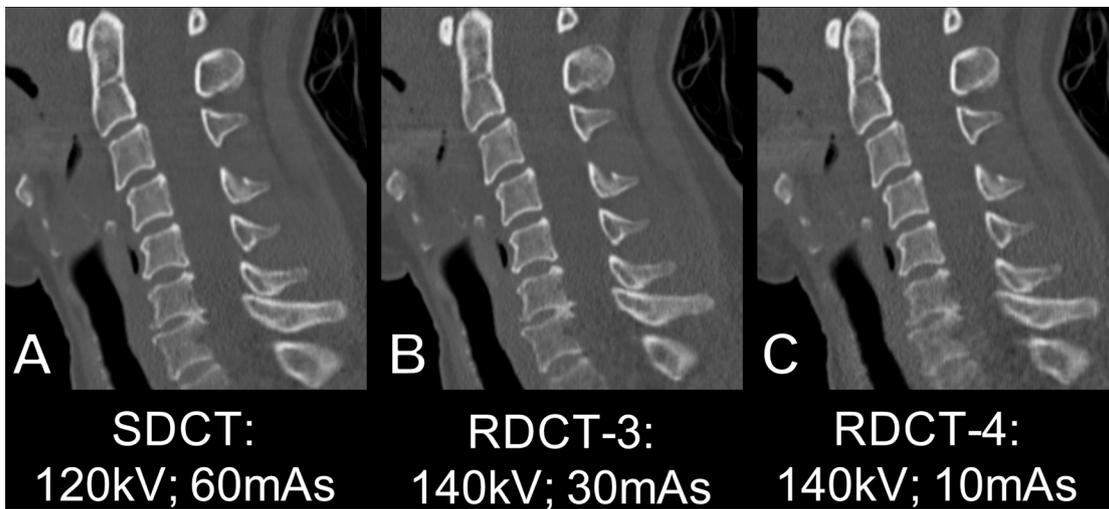
The non-diagnostic quality of the lower cervical spine in drastically reduced radiation dose protocols with 10 mAs is induced by streak artefacts due to the superimposed shoulder girdle, which is the limiting factor for further dose reduction. This is in accordance with previous studies stating the presence of more artefacts in the lower neck when compared to the upper neck [21]. However, with optimization of the shoulder girdle position, a 30% noise and artefact reduction can be achieved in lower cervical spine [22]. Since we examined cadavers in rigor mortis there was a natural incapability of active downward movement of the shoulder girdle. It is conceivable, that radiation dose as well as image quality could be further improved in stable and cooperative patients with suspected cervical spine disorder. It has to be considered though that patients with suspected cervical trauma often incorporate instrumentation that hinders their mobility and might increase both the artefacts and the applied radiation.

Regardless of the applied CT protocol and reconstruction, the sharp reproduction of cortical and trabecular bone was rated lower compared to the other evaluated anatomical structures. Improvement of visibility of anatomical structures for images reconstructed with IR was only evident in the most reduced dose RDCT protocols 3 and 4. These results are in accordance with Omouni et al. [12] who reported no improvement of visibility of cortical bone using IR in a clinical implemented protocol with higher radiation doses. However, Alshamari et al. reported significantly higher scores for sharp reproduction of all anatomical structures of the lumbar spine at an effective dose of about one mSv [23]. We believe that this contradictory finding by Omouni et al. and Alshamari et al. is reproduced in our experiments and IR only leads to significant improvement of visibility of anatomical structures for drastic reduced CT protocols.

A recent study has focused on the lowest possible radiation dose for CT of the cervical spine [13]. Tozakidou et al. examined four formalin-



**Fig. 2.** This figure shows all CT protocols and applied reconstructions in sagittal reformations in a cadaver specimen without superimposition of the shoulder girdle. Subjective image quality ratings were high in all CT protocols and reconstruction techniques for both upper and lower cervical spine leading to a diagnostically acceptable image quality.



**Fig. 3.** The figure shows the SDCT (A), RDCT-3 (B) and RDCT-4 (C) reconstructed with IRL4. In this specimen superimposition of the shoulder girdle is evident and impaired image quality of the lower cervical spine is visible in all scans. The superimposition of the shoulder girdle results in non-diagnostically image quality of the lower cervical spine for RDCT-4 (c).

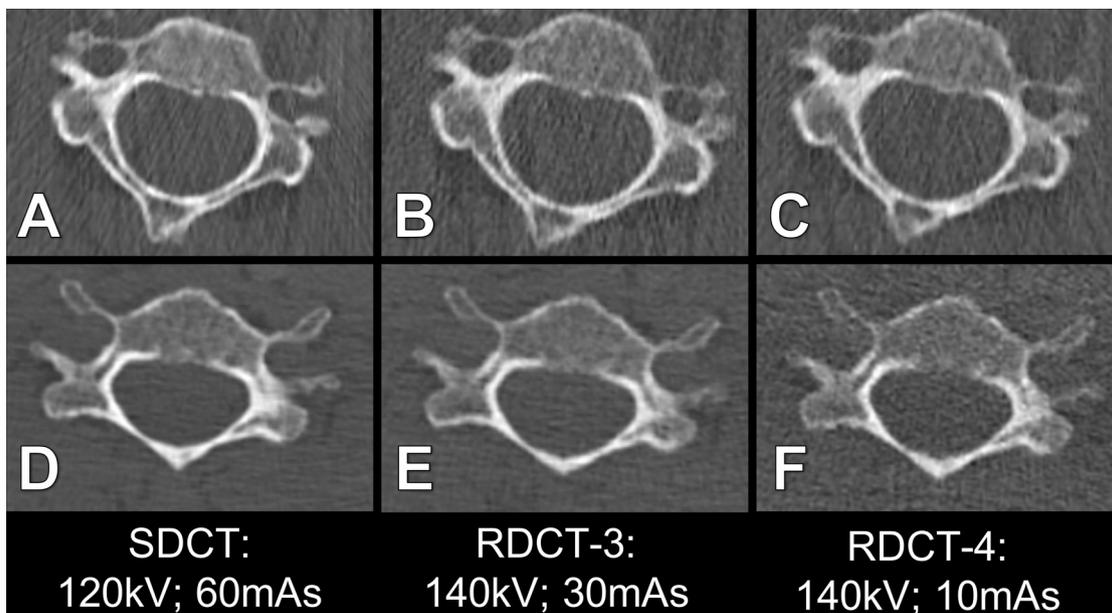
treated cadaveric specimens at a tube voltage of 120 kV and IR from another vendor. The authors state that a clinically acceptable image quality of the whole cervical spine can be achieved with a reference mAs of 105 resulting in an effective radiation dose of 0.8 mSv. The protocol used in our study with 140 kV and 30 mAs enabled an even higher dose reduction while maintaining diagnostically acceptable image quality with an effective dose of 0.4 mSv. However, it has to be considered that the radiation doses reported by Tozakidou et al. might be influenced by the surplus of volume due to formalin-treatment of 10–15 litres.

Even though a decrease in tube voltage might result in further dose reduction, previous studies addressing the issue of reducing radiation dose in whole spine MDCT for multiple myeloma patients proclaimed that a higher tube voltage and lower reference tube current are optimal parameters [14,24]. Gleeson et al. state that because of the intrinsic high contrast between bone and soft tissues, a higher tube voltage is less susceptible to variations in body mass and may reduce image noise

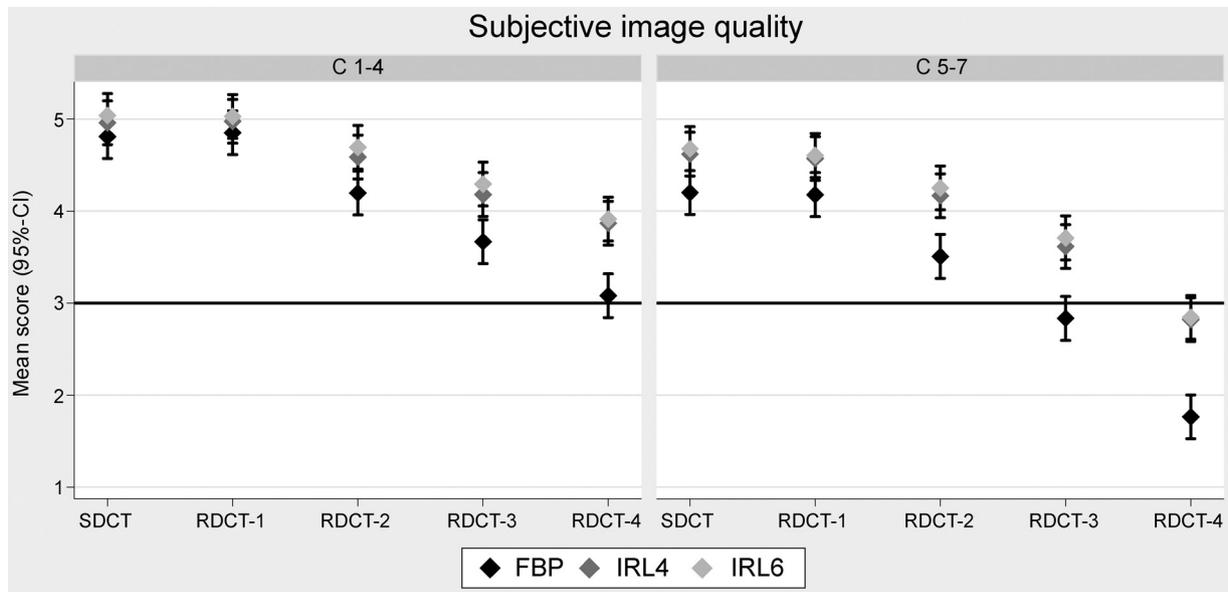
when depicting osseous structures [13,14].

In contrast, Hoang et al. showed that a reduction of tube voltage for contrast enhanced neck CT can result in greater than 50% reduction in the absorbed organ dose to the bone marrow of the cervical spine without impairment in subjective image quality [25]. The determination of tube voltage is dependent on the medical purpose, e.g. tube voltage reduction is suitable in contrast-enhanced CT e.g. in order to rule out cervical artery dissection.

European as well as American national diagnostic reference levels for  $CTDI_{vol}$  for cervical spine CT are reported to be between 3.5–39.7 mGy [26]. In contrast, our proposed imaging protocol with the use of IR results in a  $CTDI_{vol}$  of  $3.6 \pm 1.9$  mGy (effective dose:  $0.4 \pm 0.2$  mSv) for RDCT3, which is similar to a two-view radiograph with about 0.3 mSv [27]. Since CT of the cervical spine gives more anatomical and diagnostic information than conventional radiography, a RDCT with 0.4 mSv should be considered as a first line imaging method in clinical practice.



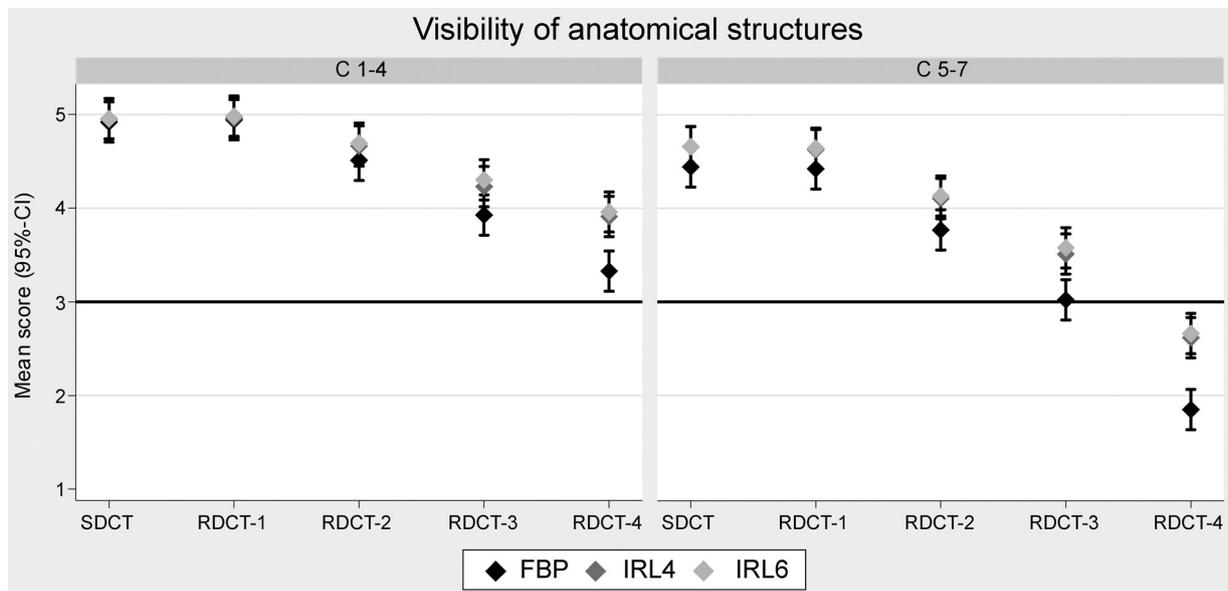
**Fig. 4.** The figure depicts axial reconstructions of the upper (A–C) and lower (D–F) cervical spine reconstructed with IRL4. A and D represent the SDCT, B and E RDCT-3 and C and F RDCT-4. While the image quality of RDCT-3 does not significantly differ from SDCT, the image quality the lower cervical spine being examined with RDCT-4 (F) is inferior to both, SDCT and RDCT-3.



**Fig. 5.** Analysis of overall subjective image quality for SDCT and different RDCT protocols for upper (C 1–4) and lower (C 5–7) cervical spine. Images were reconstructed with FBP, IRL4 and IRL6. Plots show mean scores of lower and upper cervical spine for subjective image quality. Error bars represent the 95% CI. Y-axis depicts the subjective five-point grading scale (1 indicating worst through 5 indicating best). Scores of 3–5 were considered as diagnostically acceptable image quality. The lowest radiation dose CT protocol allowing diagnostically acceptable image quality for both, the upper and the lower cervical spine, is RDCT-3 with both IRL4 and IRL6.

Our study has several limitations. The first and major limitation of this study is that we did not examine subjects with pathological findings such as subtle fractures. We tried to overcome that limitation by evaluating not just the overall image quality but also evaluated the distinction of small anatomical structures of the cervical spine in order to assess the visibility and diagnostic acceptability of the different reduced-dose protocols. Nevertheless, further studies are needed to assess the validity for detection of pathologies in the hereby presented submillisievert RDCT protocol. Second, the protocol was designed in order to evaluate the osseous cervical spine. Therefore, we did not assess its impact on soft tissue structures such as intervertebral discs or

ligaments. However, magnetic resonance imaging (MRI) is superior for evaluation of ligaments, intervertebral discs and spinal cord injuries when compared to MDCT. Therefore, MRI should always be performed when injuries to soft tissue, ligaments or spinal cord are suspected [28]. Also, our non-contrast enhanced protocol is not suitable to rule out cervical artery dissections. As cervical artery dissections are frequently seen in trauma patients [29], many trauma centres perform contrast-enhanced CT of the cervical spine in a polytrauma setting as part of the whole-body scan. Therefore, the proposed non-contrast enhanced RDCT protocol is mainly suitable for cooperative patients with isolated cervical trauma without suspicion of cervical artery dissection.



**Fig. 6.** Analysis of visibility analysis of anatomical structures for SDCT and different RDCT protocols for upper (C 1–4) and lower (C 5–7) cervical spine. Images were reconstructed with FBP, IRL4 and IRL6. The plots show the mean probability of visibility of all analysed anatomical structures. Error bars represent the 95% CI. Y-axis depicts the subjective five-point grading scale (1 indicating worst through 5 indicating best). Diagnostically acceptable visibility of anatomical structures was achieved for upper and lower cervical spine using SDCT, RDCT-1, -2 with IR and FBP and only RDCT-3 with IR.

Third, our scan range only covered the top of the first thoracic vertebra. 2.4–9 % [30,31] of all fractures in patients with cervical spine trauma are located in the cervicothoracic junction. Therefore, the cervicothoracic junction including the second thoracic vertebrae should at least be within the scan range [2] when obtaining a cervical spine CT. However, due to the consecutively increased superimposition of the shoulder girdle with expected higher levels of streak artefacts our proposed RDCT protocol might reach its performance limit. Further investigation is needed to evaluate the image quality of the cervicothoracic junction using a RDCT protocol.

Fourth, we only applied two different strengths of IR as well as FBP provided by only one vendor. This lack of variety might influence our result regarding the optimal strength level of IR. However, this choice was based on previous studies suggesting that higher strength levels of IR should be implemented for MDCT of the cervical spine [12]. Also, we believe that the basic idea of a higher tube voltage combined with a lower reference tube current while using IR can be translated into clinical routine for other CT scanners as well. As the field of iterative reconstruction algorithms is rapidly evolving, future studies also need to evaluate if more sophisticated reconstruction algorithms might overcome the limitation of impaired image quality of the lower cervical spine. Fifth, we evaluated reconstructions with a 3 mm slice thickness while other authors [2] recommend thinner slices in order to not miss non-displaced fractures. It is important to underline this limitation because image noise increases with thinner slices and can decrease image quality and the detection of pathological findings. However, Phal et al. [32] demonstrated that there is no significant difference between 1- and 3-mm axial images for the detection of clinically important cervical spine fractures when read in conjunction with multiplanar reformations. Even though the choice of slice thickness for osseous CT reconstructions varies between different centres, the chosen 3 mm slice thickness of our study is within the recommended range of the European Guidelines on Quality Criteria for Computed Tomography [20] and the American College of Radiology–ASNR–ASSR–SPR practice parameter for the performance of computed tomography (CT) of the spine for suspected cervical spine trauma [33]. Nevertheless, it has to be taken into account that our results are not generally applicable to smaller slice thicknesses as used by other centres.

Sixth, with an average time of 5 days between death and acquisition of CT data post mortal changes such as dehydration and general corpse decay may have changed tissue properties and therefore radiolucency of the studied corpses. However, we cannot conclude whether this might have contributed to more or less radiation dose and this topic should be studied in future studies in order to better understand the usefulness of corpses as study objects in reduced dose CT studies.

Lastly, the attempts to blind the evaluation process regarding different reconstruction algorithms and levels, unambiguous blinding might not have been achieved due to slightly altered image texture in different reconstructions. Additionally, the small sample size of 29 cadavers could have led to a memory bias.

In conclusion, diagnostically acceptable sub-milliSievert CT of the cervical spine is feasible with a low reference tube current at 140 kV using iterative reconstruction and could be suitable for isolated cervical trauma in cooperative patients.

#### Declaration of Competing Interest

None of the authors has a conflict of interest.

The local ethics committee approved this prospective study

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