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Individualized Scan Protocols in Abdominal Computed Tomography

Radiation Versus Contrast Media Dose Optimization

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Background: In contrast-enhanced abdominal computed tomography (CT), radiation and contrast media (CM) injection protocols are closely linked to each other, and therefore a combination is the basis for achieving optimal image quality. However, most studies focus on optimizing one or the other parameter separately.

Purpose: Reducing radiation dose may be most important for a young patient or a population in need of repetitive scanning, whereas CM reduction might be key in a population with insufficient renal function. The recently introduced technical solution, in the form of an automated tube voltage selection (ATVS) slider, might be helpful in this respect. The aim of the current study was to systematically evaluate feasibility of optimizing either radiation or CM dose in abdominal imaging compared with a combined approach.

Methods: Six Göttingen minipigs (mean weight, 38.9 ± 4.8 kg) were scanned on a third-generation dual-source CT. Automated tube voltage selection and automated tube current modulation techniques were used, with quality reference values of 120 kV_{ref} and 210 mAs_{ref}. Automated tube voltage selection was set at 90 kV semimode. Three different abdominal scan and CM protocols were compared intraindividually: (1) the standard "combined" protocol, with the ATVS slider position set at 7 and a body weight–adapted CM injection protocol of 350 mg I/kg body weight, iodine delivery rate (IDR) of 1.1 g I/s; (2) the CM dose-saving protocol, with the ATVS slider set at 3 and CM dose lowered to 294 mg I/kg, resulting in a lower IDR of 0.9 g I/s; (3) the radiation dose-saving protocol, with the ATVS slider position set at 11 and a CM dose of 441 mg I/kg and an IDR 1.3 g I/s, respectively. Scans were performed with each protocol in arterial, portal venous, and delayed phase. Objective image quality was evaluated by measuring the attenuation in Hounsfield units, signal-to-noise ratio, and contrast-to-noise ratio of the liver parenchyma. The overall image quality, contrast quality, noise, and lesion detection capability were rated on a 5-point Likert scale (1 = excellent, 5 = very poor). Protocols were compared for objective image quality parameters using 1-way analysis of variance and for subjective image quality parameters using Friedman test.

Results: The mean radiation doses were 5.2 ± 1.7 mGy for the standard protocol, 7.1 ± 2.0 mGy for the CM dose-saving protocol, and 3.8 ± 0.4 mGy for the radiation dose-saving protocol. The mean total iodine load in these groups was 13.7 ± 1.7, 11.4 ± 1.4, and 17.2 ± 2.1 g, respectively. No significant differences in subjective overall image or contrast quality were found. Signal-to-noise ratio and contrast-to-noise ratio were not significantly different between protocols in any scan phase. Significantly more noise was seen when using the radiation dose-saving protocol ($P < 0.01$). In portal venous and delayed phases, the mean attenuation of the liver parenchyma significantly differed between protocols ($P < 0.001$). Lesion detection was significantly better in portal venous phase using the CM dose-saving protocol compared with the radiation dose-saving protocol ($P = 0.037$).

Conclusions: In this experimental setup, optimizing either radiation (−26%) or CM dose (−16%) is feasible in abdominal CT imaging. Individualizing either radiation or CM dose leads to comparable objective and subjective image quality. Personalized abdominal CT examination protocols can thus be tailored to individual risk assessment and might offer additional degrees of freedom.

Key Words: computed tomography, abdomen, liver, contrast media, radiation dose, renal insufficiency, age, image quality, automated tube voltage selection

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Computed tomography (CT) of the abdomen is the workhorse of daily clinical practice and is used for the diagnosis of a wide variety of pathologies.[1] In recent years, contrast media (CM) injection protocols have been individualized based on different body size parameters (eg, total body weight, body surface area, and lean body weight).[2–10] Similarly, modern CT scanners automatically individualize both tube current (automated tube current modulation [ATCM]) and tube voltage (automated tube voltage selection [ATVS]) based on patient body habitus. The ATVS techniques are intended for contrast-enhanced CT scans, because they exploit the strong increase of iodine attenuation at lower tube voltage. Depending on patient body shape and imaging task, ATVS proposes the tube voltage that provides a desired contrast-to-noise ratio (CNR) at lowest radiation dose[11–13]—typically the lowest tube voltage with sufficient tube current reserves for the planned examination. The extent of radiation dose reduction at lower kV can be controlled by the user, for example, by applying different slider settings. In its vendor-recommended parametrization, ATVS focuses on radiation dose reduction and assumes the same CM protocol is used at all tube voltages. Contrast-to-noise ratio, however, is a combination of both radiation dose and iodine contrast. Therefore, by decreasing radiation dose beyond the proposed ATVS parameters (eg, by deviating from the vendor-recommended slider settings), and at the same time increasing CM dose (or vice versa), similar CNRs can be reached.[5] This offers perspective for further individualization of radiation and CM protocols. For example, in younger patients and/or in patients requiring repetitive scanning, a protocol favoring radiation dose reduction is preferred over a decrease in CM dose, so as to minimize the increase in lifetime attributable cancer risk due to ionizing radiation exposure.[14–16] On the other hand, in the elderly where reduced renal function is more common, a decrease in CM dose is preferred over radiation dose reduction.[17] Both radiation dose and CM injection protocols can be manually adapted, but the slider bar provided in ATVS to tailor the scan protocol offers a user-friendly alternative.

The current study aims to evaluate the feasibility of using standard ATVS slider positions combined with adapted CM injection protocols for

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reducing either radiation or CM dose, depending on individual risk assessment, compared with a standard combined protocol. This was done by structurally comparing objective and subjective image quality parameters in imaging of the abdomen within and between subjects.

MATERIALS AND METHODS

Animals

The study was performed on 6 healthy female Göttingen minipigs (Ellegaard, Dalmose, Denmark) with a mean body weight of 38.9 ± 4.8 kg. Three imaging protocols were compared intraindividually in all 6 animals with at least 1 week between examinations.

The animals were handled in compliance with the German Animal Welfare Legislation and with the approval of the State Animal Welfare Committee. All measurements were performed under general anesthesia, and animals were orally intubated and mechanically ventilated. Animals were placed in a prone position, and CT imaging was performed during end-expiratory ventilation stop.

Study Design

Computed tomography imaging was performed on a third-generation dual-source CT scanner (Somatom Force; Siemens Healthineers, Forchheim, Germany). Abdominal scans were done using slice collimation of 192 × 0.6 mm, rotation time of 0.5 seconds, and pitch of 0.85, resulting in a scan time of 4 seconds. Image reconstruction was done with a Br40 kernel, SAFIRE iterative reconstruction (level 3) at 0.75-mm slice thickness with 0.5-mm increment. The ATVS system (CAREkV; Siemens Healthineers) was operated with 90 kV semimode, ATCM, and fixed quality reference values (120 kV, 210 mAs). The ATVS slider position is determined by the scan indication. For parenchymal (eg, liver) studies, the vendor recommends position 7 to balance image noise increase and increased CM attenuation at lower tube voltage. The standard protocol in this study was performed with this configuration (slider position 7). At lower slider settings, less image noise increase is accepted at lower tube voltage, with the consequence of higher radiation dose. Level 3, originally intended for noncontrast scans, can therefore be used to perform CT scans with similar CNR compared with level 7 but reduced CM volume. This is the CM dose-saving protocol used in present study. At slider position 11, originally intended for CT angiographic examinations, more image noise is accepted at further reduced radiation dose. To maintain the expected CNR of slider level 7, the CM volume needs to be increased. This is the radiation dose-saving protocol. The protocol-specific CT scan configurations were combined with adapted CM injection protocols. Iopromide (Ultravist 300; Bayer AG, Berlin, Germany) was used, and CM administration was performed with the Medrad Centargo CT injection system (Bayer AG) into the ear vein of the animals. For the standard imaging protocol, 350 mg I/kg body weight was administered with a flow rate of 3.5 mL/s; the iodine delivery rate (IDR) was 1.1 g I/s. For the CM dose-saving protocol, the used standard dose (350 mg I/kg) was reduced by 16% to 294 mg I/kg and the flow rate was adapted to 2.9 mL/s (IDR, 0.9 g I/s), so as to maintain the same total injection time. A 26% higher CM dose (441 mg I/kg) than the used standard dose administered at 4.4 mL/s (IDR, 1.3 g I/s) was used for the low radiation dose protocol.[18] All CM injections were followed by a 20-mL saline chaser applied at the same flow rate. A summary of the combination of the scanner configuration and CM injections for each imaging protocol is given in Table 1.

Contrast timing was adjusted with bolus tracking in the descending aorta using a threshold of 100 Hounsfield units (HU). Arterial phase imaging started with a delay of 5 seconds followed by the portal venous and late phase using fixed delays of 60 seconds and 90 seconds.

The CTDI radiation doses were obtained from the dose reports of the CT scanner. The percentage change in relation to the standard imaging protocol was calculated.

Objective Image Quality

The data were evaluated on postprocessing software (SyngoVia, VB30; Siemens Healthineers, Erlangen, Germany). The HU and standard deviation (SD) were measured in the hepatic artery in arterial phase, by placing a region of interest (ROI) as large as possible in the vascular structures, taking into account the vasculature wall. In portal venous phase, 3 ROIs (area ≥ 2 cm^2) were drawn in 3 different liver segments, preferably in segments 2, 5, and 8, according to the Couinaud distribution, not containing vessels or biliary ducts.[19] Another as large as possible ROI was placed in the portal vein to measure the signal attenuation. The SD of the paraspinal muscle (ROI area ≥ 1 cm^2) was used to estimate image noise. The signal-to-noise ratio (SNR) was calculated by dividing the mean HU of the 3 liver segments by the noise. The attenuation of the left paraspinal muscle was used to calculate the CNR. The mean liver HU minus the HU of the paraspinal muscle,

TABLE 1. CM and Radiation Dose Parameters

		Protocol	
	Standard (n = 6)	**CM Dose Saving (n = 6)**	**Radiation Dose Saving (n = 6)**
Radiation dose parameters			
CAREkV	90 kV semimode	90 kV semimode	90 kV semimode
Reference, kV/mAs	120/210	120/210	120/210
Slider position	7	3	11
$\mathrm{CTDI}_{\mathrm{vol}}$, mGy	5.2 ± 1.7	7.1 ± 2.0	3.8 ± 0.4
CM injection parameters			
Concentration, mg I/mL	Iopromide 300	Iopromide 300	Iopromide 300
CM dose, mg I/kg	350	294	441
Mean CM volume, mL	45.5 ± 5.5	38 ± 4.8	57.3 ± 6.9
TIL, g	13.7 ± 1.7	11.4 ± 1.4	17.2 ± 2.1
Flow rate, mL/s	3.5	2.9	4.4
IDR, g I/s	1.1	0.9	1.3
Saline chaser, mL	20	20	20

CM, contrast media; $\mathrm{CTDI}_{\mathrm{vol}}$, CT dose index vol; TIL, total iodine load; IDR, iodine delivery rate.

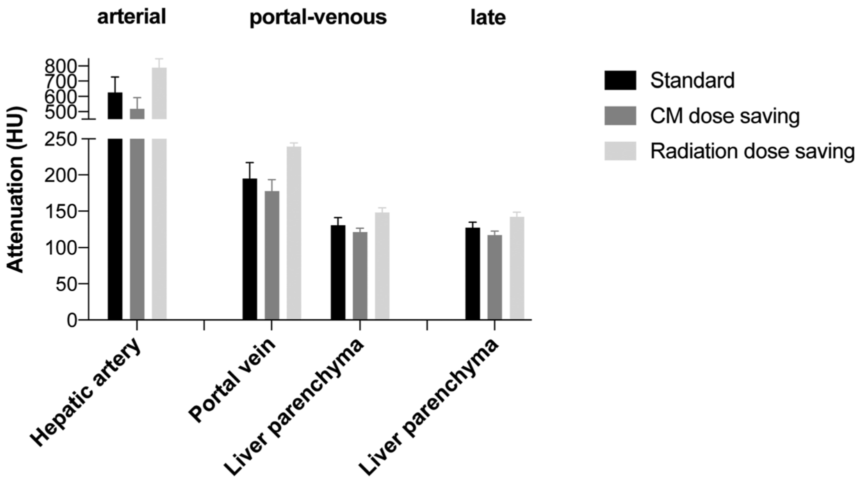

FIGURE 1. Effect of contrast media (CM) and radiation dose protocols on mean attenuation of the hepatic artery, portal vein, and liver parenchyma in 3 different scan phases. Error bars indicate the standard deviation. Abbreviations: HU, Hounsfield units.

divided by the SD of the paraspinal muscle resulted in the CNR. Similar calculations were performed for the delayed phase.

Subjective Image Quality

The scans were rated in consensus on diagnostic screens by 2 radiologists (C.M. and B.M.) with 10 and 5 years' experience in abdominal imaging. Adjusting the window level was allowed. The overall image quality, noise, and contrast quality were rated on a 5-point Likert scale (1 = excellent, 2 = good, 3 = moderate, 4 = poor, 5 = very poor).[7,20] Lesion detection was rated in portal venous and delayed phase using the same Likert scale. The arterial phase is not solely used for liver lesion detection at our center; therefore, this parameter was not considered relevant.

Statistics

All results are presented as mean ± SD or median with interquartile range (IQR) for subjective image quality. Heart rate, attenuation, SNR, and CNR were compared between the 3 imaging protocols using 1-way analysis of variance on ranks followed by the post hoc Tukey multiple comparisons test. Subjective image quality parameters were compared between protocols using the Friedman test followed by the Dunn test for multiple comparison. Two-sided P values <0.05 were regarded as statistically significant. Statistical analyses were performed using GraphPad Prism (GraphPad Software version 8, La Jolla, CA).

RESULTS

Injection Parameters and Radiation Dose

The mean heart rates did not significantly differ between protocols: 104 ± 20 beats per minute (standard), 105 ± 11 beats per minute (CM saving), and 102 ± 24 beats per minute (radiation saving). Table 1 shows an overview of radiation dose and CM injection parameters. As a result of the study design, CM volumes and radiation doses differed between groups. In the standard protocol, the CTDI_{vol}, mean CM volume, and total iodine load (TIL) were 5.2 ± 1.7 mGy, 45.5 ± 5.5 mL, and 13.7 ± 1.7 g, respectively. The mean radiation dose was higher in the CM dose-saving group and lower in the radiation dose-saving group, with values of 7.1 ± 2.0 and 3.8 ± 0.4 mGy, respectively. The TIL was lowest in the CM dose-saving group (11.4 ± 1.4 g) and highest for the radiation dose-saving group (17.2 ± 2.1 g).

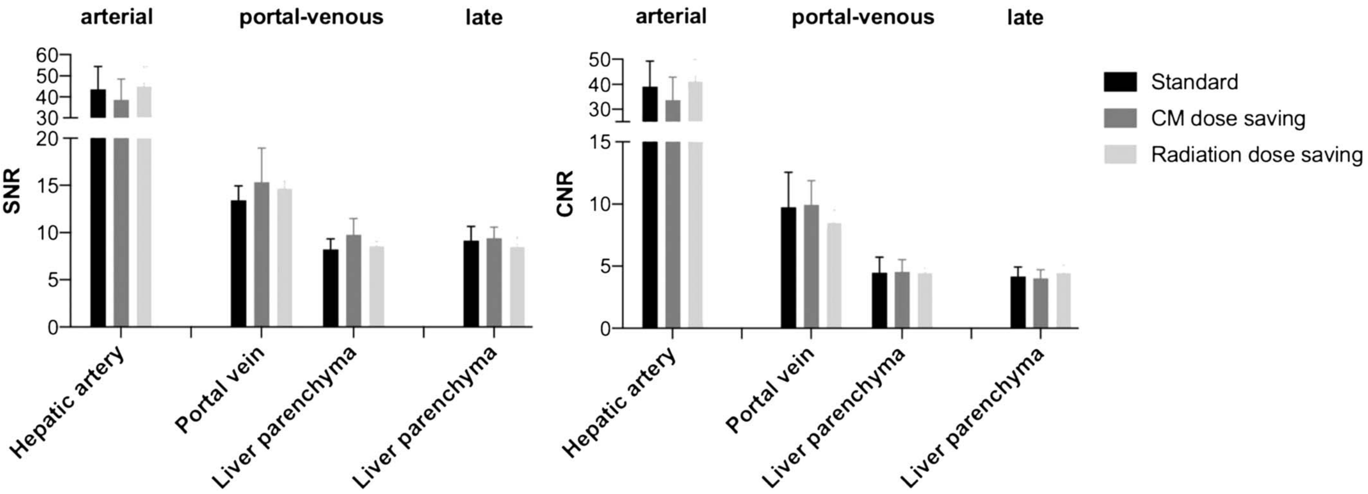

FIGURE 2. Effect of contrast media (CM) and radiation dose protocols on signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) of the hepatic artery, portal vein, and liver parenchyma in 3 different scan phases. Error bars indicate the standard deviation.

TABLE 2. Objective and Subjective Image Quality Parameters

	Protocol			
	Standard	**CM Dose Saving**	**Radiation Dose Saving**	***P***
Arterial phase				
Objective image quality				
Mean HU hepatic artery	627.5 ± 99.6	518.3 ± 75.2	788.5 ± 59.4	<0.001*
Mean HU liver parenchyma	81.4 ± 11.2	81.6 ± 15.0	97.5 ± 25.3	0.267
SNR liver	5.6 ± 1.0	6.0 ± 1.5	5.6 ± 1.8	0.838
CNR liver	1.1 ± 1.0	1.3 ± 1.1	1.8 ± 1.5	0.66
Subjective image quality, median (IQR)				
Overall	3 (2–3)	2.5 (2–3)	3 (3–3.3)	0.259
Noise	3 (2.8–3.3)	2.5 (2–3)	4 (3.8–4)	0.004†
Contrast	2 (1.8–2.3)	2 (1.8–2)	2 (1–2)	0.889
Portal venous phase				
Objective image quality				
Mean HU portal vein	195.3 ± 21.9	177.7 ± 15.8	239.3 ± 4.9	<0.001‡
Mean HU liver parenchyma	130.6 ± 10.5	121.3 ± 4.9	148.3 ± 6.3	<0.001§
SNR liver	8.2 ± 1.1	9.8 ± 1.7	8.6 ± 0.5	0.118
CNR liver	4.5 ± 1.3	4.5 ± 1.0	4.5 ± 0.4	0.990
Subjective image quality, median (IQR)				
Overall	2 (1.8–3)	1.5 (1–2)	2 (2–2.3)	0.049¶
Noise	2.5 (2–3)	2 (1–2)	3 (3–3.3)	0.001†
Contrast	2 (1.8–2)	1.5 (1–2)	2 (2–2)	0.222
Lesion detection	1.5 (1–2.3)	1 (1–1.3)	2 (2–2)	0.037†
Delayed phase				
Objective image quality				
Mean HU liver parenchyma	127.1 ± 7.7	117.1 ± 5.4	142.4 ± 6.3	<0.001‖
SNR liver	9.2 ± 1.5	9.4 ± 1.2	8.5 ± 1.0	0.504
CNR liver	4.2 ± 0.8	4.0 ± 0.7	4.5 ± 0.6	0.592
Subjective image quality, median (IQR)				
Overall	2.5 (2–3)	2 (1.8–2)	3 (2–3)	0.086
Noise	3 (2–3)	2 (2–2.3)	4 (3.8–4)	0.002†
Contrast	2 (2–2)	2 (1.8–2)	2 (2–2)	>0.99
Lesion detection	2 (2–3)	2 (1.8–2)	2 (2–3)	0.333

Mean HU, SNR, and CNR in different scan phases using different CM protocols and slider positions, as well as the subjective (overall) image quality.

*Post hoc comparison showed a significant difference between standard and radiation dose-saving ($P = 0.01$) and between CM dose-saving and radiation dose-saving ($P < 0.001$).

†Post hoc comparison showed a significant difference between CM dose-saving and radiation dose-saving.

‡Post hoc comparison showed a significant difference between standard and radiation dose-saving ($P = 0.002$) and between CM dose-saving and radiation dose-saving ($P < 0.001$).

§Post hoc comparison showed a significant difference between standard and radiation dose-saving ($P = 0.005$) and between CM dose-saving and radiation dose-saving ($P < 0.001$).

‖Post hoc comparison showed a significant difference between standard and CM dose-saving ($P = 0.05$), between standard and radiation dose-saving ($P = 0.005$), and between CM dose-saving and radiation dose-saving ($P < 0.001$).

¶Post hoc comparison showed no significant difference between groups.

CM, contrast media; HU, Hounsfield units; mean HU, mean attenuation; SNR, signal-to-noise ratio; CNR, contrast-to-noise ratio; IQR, interquartile range.

Objective Image Quality

Significant differences in attenuation (HU) of the hepatic artery in arterial phase and attenuation of the portal vein and liver in portal venous and the liver in delayed phase were found, with P values <0.001 in all cases (Fig. 1). The mean attenuation of the liver parenchyma in portal venous phase was 130.6 ± 10.5 HU for the standard protocol. Attenuation was lower using the CM dose-saving protocol (121.3 ± 4.9 HU) and higher using the radiation dose-saving protocol (148.3 ± 6.3 HU) ($P < 0.001$).

Signal-to-noise ratio and CNR did not significantly differ between groups in the arterial, portal venous, or delayed phases (Fig. 2). The mean SNR of the liver in portal venous phase was 8.2 ± 1.1 for the standard protocol, 9.8 ± 1.7 for the CM dose-saving protocol, and 8.6 ± 0.5 for radiation dose-saving protocol ($P = 0.188$). The mean CNR for the 3 protocols was 4.5 ± 1.3, 4.5 ± 1.0, and 4.5 ± 0.4, respectively ($P = 0.990$) (Table 2).

Subjective Image Quality

Overall subjective image quality and assessment of contrast did not significantly differ between protocols (Table 2). Lesion detection was significantly better in the CM dose-saving protocol compared with the radiation dose-saving protocol in portal venous phase ($P = 0.037$).

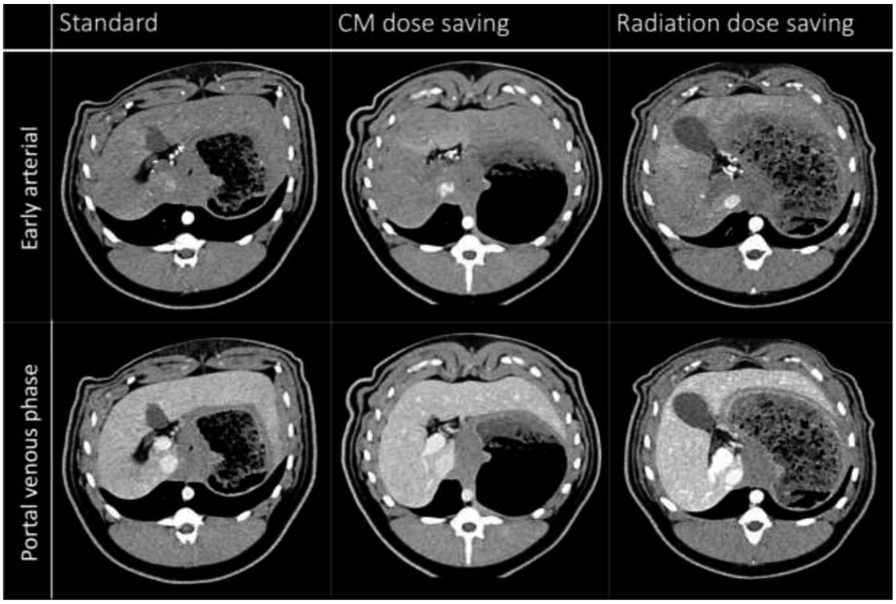

FIGURE 3. Example of acquired images of repeated scans in a single subject. Three different contrast media (CM) and radiation dose protocols were used. Standard protocol: 350 mg I/kg CM, iodine delivery rate (IDR) 1.1 g I/s, slider position 7; CM dose-saving protocol: 294 mg I/kg CM, IDR 0.9 g I/s, slider position 3; radiation dose-saving protocol: 441 mg I/kg CM, IDR 1.3 g I/s, slider position 11.

The IQR for lesion detection using the standard protocol varied between good and excellent (1–2.3). Using the CM dose-saving protocol, the IQR was excellent (1–1.3), and using the radiation dose-saving, the IQR was good (2–2). No significant differences in lesion detection were found in delayed phase (P = 0.333). Noise was rated lowest—corresponding with a better value on the Likert scale—for the CM dose-saving protocol and significantly higher for the radiation dose-saving protocol ($P < 0.01$) for all 3 phases. Figure 3 shows an example of images acquired from a single pig scanned several times in arterial and portal venous phases using the 3 protocols (standard, CM dose-saving, and radiation dose-saving).

DISCUSSION

The results of the current study show that optimizing either the radiation or the CM dose is feasible in abdominal CT imaging by combining scan and injection protocols. Based on an individual risk assessment, it seems possible to reduce either 1 of the parameters, without negatively influencing the objective and subjective image quality. Both SNR and CNR were comparable between groups in all scan phases (arterial, portal venous, and delayed phase). The attenuation of the liver parenchyma was significantly different between groups in portal venous and delayed phases, however expected based on the study design. The tube voltage was kept constant in each group (90 kV), whereas the CM injection protocol differed between groups. In the radiation dose, saving group TIL was highest and TIL was lowest in the CM dose-saving group. The overall and contrast image quality did not significantly differ between groups. Noise was rated significantly higher in the radiation dose-saving group, in all scan phases. Lesion detection was good to excellent in portal venous and delayed phase, with a significantly higher score for images acquired in portal venous phase using the CM dose-saving protocol. Overall subjective image quality was higher for images acquired using the CM dose-saving protocol, but post hoc comparison found no significant difference between groups.

The current study uses a more integrated approach, where previous studies on this topic have more disconnected set ups (eg, optimizing CM dose based on patient body composition or individualizing radiation dose based on ATCM and ATVS techniques).[2–6,21–24] The current results show that it is feasible to adapt either radiation or CM dose to individual risk assessment. As opposed to a more disconnected approach, using the ATVS slider offers an integrated concept.

By adjusting the slider settings in the semimode of the ATVS system on a third-generation dual-source CT scanner, Euler et al[13] showed that optimizing either radiation or CM dose led to comparable image quality in low kV CT angiography imaging, compared with a standard 120 kV examination. A 34.3% reduction in radiation dose or a 20.2% reduction in CM dose was feasible without significant difference in overall subjective image quality among protocols. In vascular imaging, in general more noise is accepted to be able to reliably assess vascular structures because surrounding organs are of less importance. In parenchymal studies, the balance between noise and attenuation of the organs is much more delicate. Both excessive noise and insufficient CM attenuation might result in diagnostic insufficiency, for example, an inability to detect liver lesions. Earlier studies focused on CM reduction in patients with reduced kidney function. By decreasing tube voltage, a substantial reduction in CM could be achieved without negatively influencing either objective or subjective image quality.[25,26] Reducing both parameters at the same time will decrease CNR and may lead to insufficient image quality.[13] However, in the current study, CNR was comparable between groups by adapting both radiation and CM dose, as intended in the study design.

Surprisingly, although not significant, the contrast was rated highest in images acquired using the CM saving protocol for both portal venous and delayed phases. Possible explanations are 2-fold. First, although intraindividual comparisons provide a unique opportunity for protocol evaluation, the small population of 6 means that each subjective image quality contributes to a sixth of the end result. Second, a combination of the factors scored in the current study (noise, contrast, and lesion detection) determines subjective image quality, and results may reflect the fact that it is difficult for readers to separate parameters.[27] For example, image quality of a low-noise, mediocre contrast enhancement CT image may still be evaluated "good," because the lack in CM enhancement is masked by low noise level. Unfortunately, to date, no objective parameter exists that is able to reliably quantify image quality in a way that incorporates both objective and subjective aspects.

Image quality depends on both scan parameters (radiation dose related) and CM injection protocol (CM dose related). Radiation and CM dose can be calculated for each individual patient, and the resulting data manually entered into scanner and injector devices. The ATVS techniques automatically individualize radiation dose, which can be very useful, but the aim is radiation dose reduction only. Information regarding the CM injection protocol (eg, CM volume) is not taken into account despite playing a role in ATVS methodology.[11–13] Automated tube current modulation and ATVS together optimize radiation dose by adjusting tube current and tube voltage based on the clinical question and patient characteristics. By incorporating the CM injection protocol into these algorithms, protocols can be further adapted to individual requirements, such as for patients with reduced kidney function or young age or to specific disease management regimes and active surveillance.

The current study has some limitations. First, it is a single-center animal study, and both generalization and translation to humans may be limited. However, Göttingen minipigs have been shown to be suitable as minipigs are anatomically comparable to humans.[28,29] Second, as the animals were healthy, no liver lesions could be evaluated, which makes the parameters "lesion detectability" slightly arbitrary. Another limitation is that the ATVS slider adjustment is a vendor specific technique, and results presented might therefore not directly be generalizable to other vendors.

In conclusion, in this experimental setup, optimizing either radiation (−26%) or CM dose (−16%) resulted in comparable objective and subjective diagnostic image quality in abdominal CT. This study demonstrates the feasibility of protocol individualization by adapting a combination of scan and CM injection parameters, which offers new opportunities for taking into account patient-related risk factors such as age and kidney function.

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