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Research article

Implementation of patient-tailored contrast volumes based on body surface area and heart rate harmonizes contrast enhancement and reduces contrast load in small patients in portal venous phase abdominal CT

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ABSTRACT

Purpose: The aim of this study was to evaluate the impact of a patient-tailored contrast volume protocol on portal venous phase abdominal CT-images compared to a fixed volume protocol in daily radiological practice.
Method: Data of 77 patients who underwent two contrast-enhanced CT-examinations were collected. The first examination was performed with a fixed contrast volume (95 ml), the follow-up examination was performed with a patient-tailored contrast volume based on patient's BSA and heart rate. The patient-tailored volume was calculated by a software application integrated in the interface of the injection pump. Two independent radiologists assessed subjective and objective image quality. Differences in enhancement and contrast volumes between both protocols were analysed.
Results: Despite a significant contrast volume reduction in women and in patients with low to normal BMI, enhancement was more consistent over different BMI-categories in the patient-tailored contrast volume protocol and there was no significant difference in subjective image quality between both injection protocols.
Conclusions: A patient-tailored contrast volume protocol based on BSA and heart rate can be considered in daily radiological practice to decrease contrast volumes in women and in low to normal BMI patients and to achieve more consistent contrast enhancement across different BMI-categories in venous phase abdominal CT.

1. Introduction

Continuous advances in computed tomography (CT) technology have led to improved CT-image quality in the last decades. To fully benefit from these latest advances, scanning circumstances and injection protocols should be constantly re-evaluated, optimized and standardized. Historically, fixed volumes of iodinated contrast have been used for different MDCT protocols. While recent studies have shown that adaptation of contrast volume to patient body habitus can improve image quality, currently there is no consensus on which body metrics should be used to personalize contrast volumes [1,2]. In daily clinical practice, fixed contrast volumes or simplified volume adaptations to body size are used because of practical considerations [1–5]. Iodine mass may be adjusted to body weight with 1:1 linear scales, for example by using simple look-up tables [1,6,7]. The aim of this study was to assess the impact of a combined BSA and heart rate based patient-tailored contrast volume protocol on portal venous phase abdominal CT images with respect to administered volumes and objective and subjective image quality.

Abbreviations: CT, computed tomography; MDCT, multidetector computed tomography; eGFR, estimated glomerular filtration rate; BSA, body surface area; keV, kilo-electronvolt; HU, Hounsfield unit; ROI, region of interest; BMI, body mass index; WHO, World Health Organisation; IQR, interquartile range; ICC, intraclass correlation; PACS, picture archiving and communication system; TBW, total body weight; LBW, lean body weight

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2. Material and methods

This retrospective study was approved by the local Institutional Ethical Review Board with a waiver of written informed consent. In January 2016 a software program (iCalc, Medicor Europe AG, Rotselaar, Belgium) was implemented by the radiology department to calculate patient-tailored contrast volumes based on body surface area and heart rate. The software program was implemented for all portal venous phase CT examinations covering the abdomen (i.e. chest-abdomen-pelvis or abdomen-pelvis). Information related to the scanning protocol and the injector report was sent to the dose monitoring system DoseWatch (GE Healthcare, Milwaukee, Wisconsin, USA) and the PACS (Agfa HealthCare NV, Mortsel, Antwerp, Belgium). This allowed registration of patient data, scan parameters and contrast related data.

2.1. Patient population

For 77 patients (42 men and 35 women) who required a portal venous phase CT examination on two different time points between July 2015 and September 2016, examination data were collected retrospectively, producing 154 examinations to analyse. Patients with reduced kidney function (eGFR < 60 ml/min) were excluded from this study.

2.2. Scanning protocol

All patients were scanned in the context of oncologic follow-up. All examinations were performed on the same 256 detector-row CT scanner (GE Revolution, GE Healthcare, Milwaukee, Wisconsin, USA) with a fixed tube voltage of 120 keV and automatic tube current modulation. A fixed scan-delay of 90 s was used in all examinations in order to obtain portal venous phase contrast enhancement. All patients were scanned in the supine position with the arms raised above the head.

2.3. Contrast injection protocol

The administered low osmolarity contrast medium was the same in all examinations (Xenetix 350, Iobitridol, iodine concentration 350 mg/ml, Guerbet, Roissy CDG Cedex, France). Contrast was administered with a dual mechanical power injector (Dual Shot Alpha 7, Nemoto Kyorindo, Tokyo, Japan) and was followed by a 30 ml saline flush. Contrast and saline were injected at a fixed injection rate of 1.2 ml/sec in both protocols. In the first examination a fixed contrast volume of 95 ml (33.25 g iodine) was injected, according to the departmental standard for portal venous abdominal CT scans. For the second examination the required contrast volume was calculated by a software application, integrated in the interface of the injector pump (iCalc, Medicor Europe AG, Rotselaar, Belgium). This application was developed to calculate patient-tailored contrast volumes based on BSA, heart rate, contrast medium concentration and the desired contrast dose per BSA using the following patented algorithm [8]:

+ (fixed volume depending on the heart rate and the contrast medium concentration) (BSA x target contrast dose per square meter)

The first part of the formula is rounded to the nearest integer. The fixed volumes in function of heart rate and contrast medium concentration are depicted in Table 1. BSA is calculated using the Mosteller formula [9]:

$((\text{Height} \times \text{Weight})/3600)^{1/2}$

(with W = weight in kilograms, H = height in centimetres).

The target contrast dose for this study was set to 45 ml/m^2 (15.75 g I/m^2).

Patient length and weight were asked prior to the scan while heart rate was measured using a portable finger pulse oximeter (Contec pulse Oximeter, Contec medical systems, Qinhuangdao, China). The CT-technologist manually entered this information in the iCalc calculator application. The calculated patient-tailored contrast volume was automatically injected, followed by a fixed volume of 30 ml saline flush. Attention was given that no patient received a higher amount than 150 ml, the safe limit used within the department for patients with normal renal function.

Table 1
Volume adjustments in function of heart rate and contrast concentration. The calculated patient-tailored contrast volume was adjusted depending on the patient's heart rate and the concentration of the contrast medium by adding or subtracting a fixed amount of contrast.

Adjusted volume	
Heart rate (bpm)	
< 55	− 10 ml
56 - 65	+ 0 ml
66 – 75	+ 10 ml
76 – 90	+ 20 ml
91 – 105	+ 25 ml
> 105	+ 30 ml
Contrast medium concentration	
320 mg I/ml	+ 8 ml
350 mg I/ml	+ 0 ml
370 mg I/ml	− 4 ml
400 mg I/ml	− 10 ml

2.4. Contrast volume analysis

Information of injected contrast and saline volumes and rate was sent to the dose monitoring system DoseWatch (GE Healthcare, Milwaukee, Wisconsin, USA) and the PACS (Agfa HealthCare NV, Mortsel, Antwerp, Belgium). These data were then exported in an Excel file to analyse. Patients were divided into four categories based on their BMI, according to World Health Organization (WHO) criteria: underweight BMI < 18.5, normal BMI 18.5–24.99, pre-obese BMI 25–30 and obese BMI > 30 [10]. Administered contrast volumes were analysed for all patients, with stratification by gender and by BMI category.

2.5. Objective image quality analysis

Two independent radiologists measured enhancement in the portal vein, the abdominal aorta, the splenic parenchyma, the liver parenchyma and in the psoas muscle, expressed in Hounsfield units (HU). The radiologists were blinded for the contrast protocol that was used. Measurements were performed on transverse CT-images with a reconstructed slice thickness of 2.5 mm. To measure enhancement, circular regions of interest (ROI) were used. The ROI areas ranged from 42.3 mm^2 – 107.9 mm^2 with a mean area of 63 mm^2, depending on the organ measured. Anatomical landmarks were used for slice selection in both examinations of the same patient, in order to obtain measurements at similar anatomical regions. Whenever possible, measurements in liver, spleen, portal vein and aorta were performed on one single slice, as shown in Fig. 1. Tissue enhancement was normalised to the density of air which was measured outside of the patient's body. Vessel/organ enhancement in HU was plotted against BMI-category for all patients and with stratification by gender, both for the fixed volume protocol and for the patient-tailored volume protocol. Pearson's correlation coefficient was calculated for each vessel/organ.

2.6. Subjective image quality analysis

Two independent radiologists subjectively analysed image quality according to quality criteria for computed tomography as published by the directorate-general for research and innovation of the European

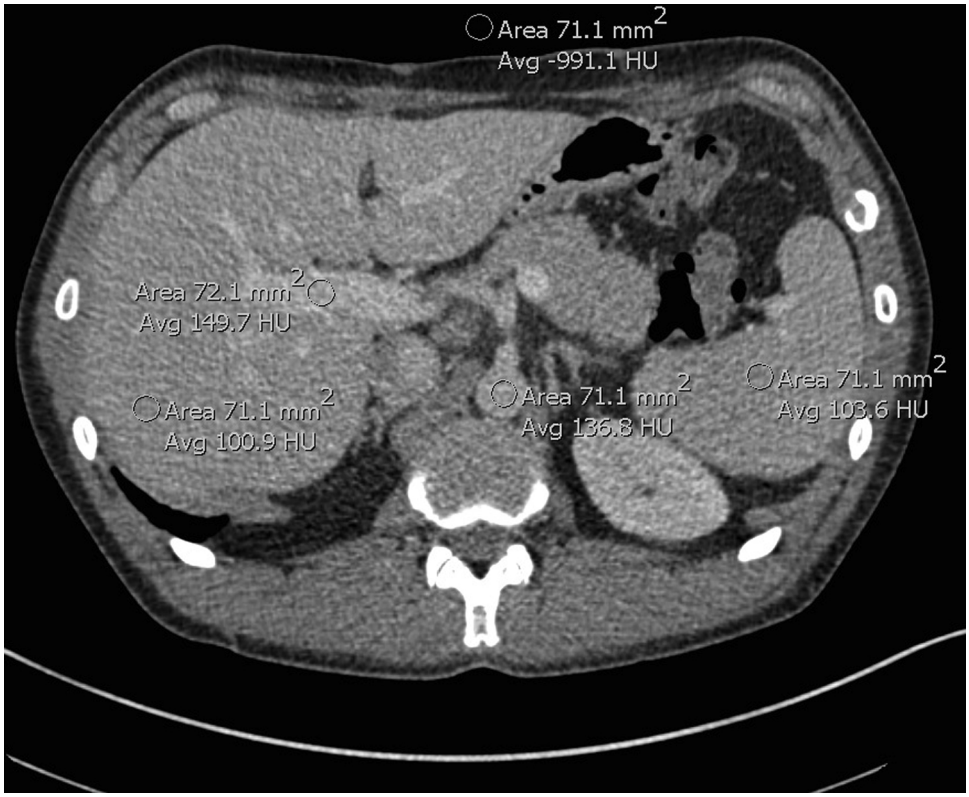

Fig. 1. Cross sectional venous phase CT image. ROIs for objective measurement of enhancement on one single slice.

Commission in 2000 [11]. Six criteria were scored on a scale from 1 to 5 as defined in Table 2. The radiologists were blinded for the contrast protocol that was used. Images were evaluated on the same diagnostic monitor (Barco Coronis 3 M P LED (MDCG-3221), Barco NV, Kortrijk, Belgium) with window width of 400 HU and level of 50 HU. As there were 77 cases in each protocol group and analysis was performed by two readers, there were a total of 154 individual analyses for each protocol group. The median result of the subjective score per criterium for each examination was calculated to determine interobserver agreement.

2.7. Statistical analysis

Data management was performed using Excel version 2010 (Microsoft Office 365, Microsoft Corporation, Redmond, Washington, USA) and statistical analysis was done with GraphPad Prism version 6 (GraphPad software Inc., La Jolla, California, USA) and SPSS version 13.0 (IBM, Armonk, New York, USA). To test for selection bias, patient data were stratified by gender and analysed for age, weight, length, BSA and BMI using a Mann-Whitney U test. A Wilcoxon matched-pairs signed rank test was used to test for absolute differences in BMI for the same patient between two examinations. To compare the contrast volumes between the patient-tailored protocol and the fixed volume protocol, a one sample *t*-test was used. To evaluate interobserver agreement and intraclass correlation (ICC) for objective and subjective image quality, a two-way random absolute agreement effect model for two readers was used. R-values below 0.4 were considered poor, between 0.4 and 0.59 fair, between 0.6 and 0.74 good and above 0.74 excellent. Correlation of data and trends of enhancement in both contrast protocols was assessed by calculation of Pearson's correlation coefficient. Correlation was considered positive when r-value > 0, correlation was considered negative when r-value ≤ 0. Mann-Whitney U test was used to evaluate if the correlation was statistically significant. Mann-Whitney U test was used to compare enhancement of each vessel/organ between both protocol groups. Outliers were detected using Tukey rules (outside 1.5x the Interquartile Range (IQR)). *P*-values below 0.05 were considered statistically significant. To compare subjective image quality between the two injection protocol groups a Wilcoxon matched-pairs signed rank test was used.

3. Results

3.1. Patient population

Patient characteristics are summarized in Table 3. There was no statistically significant difference in age and BMI comparing genders ($p > 0.05$). There was a statistically significant difference in weight, length and BSA ($p \leq 0.05$) with women having lower weight, length and BSA compared to men. The average time between two examinations was 175 day (SD 98, range 29–420 days). There was no statistically significant absolute difference in BMI for the same patient between the first and the second examination ($p = 0.6602$, mean absolute difference 0.9, SD 0.9, range 0–4.7).

3.2. Contrast volume analysis

Injected contrast volumes for the patient-tailored protocol were compared to the fixed volume of 95 ml. Results are shown in Fig. 2. Contrast volumes for the patient-tailored protocol ranged from 52 ml to 133 ml. 48 patients (62%) received less iodinated contrast and 29 patients (38%) received more contrast compared to the fixed contrast volume. Mean contrast volume for the patient-tailored protocol was 90.7 ml, which was not statistically different from the fixed volume ($p = 0.095$). After stratification by gender, there was a significant volume reduction of 12% in women for the patient-tailored protocol, with a mean contrast volume of 83.6 ml ($p = 0.002$). There was no statistically significant difference in mean contrast volume between both injection protocols in men, (97.6 ml versus 95 ml; $p = 0.34$). When

Table 2
Quality criteria for computed tomography as published by the directorate-general for research and innovation of the European Commission in 2000 [11].

Criterium	Subjective assessment				
	1	2	3	4	5
Visually sharp reproduction of the liver parenchyma and intrahepatic vessels	Severe blurring, edge definition very poor, intrahepatic vessels difficult to discern	Excessive blurring, edge definition poor, intrahepatic vessels can be discerned but are blurry	Moderate blurring, edge definition poor, intrahepatic vessels can be discerned	Minimal blurring, edge definition good, intrahepatic vessels easily discerned	No blurring, edges well defined, margins crisp, intrahepatic vessels easily discerned
Visually sharp reproduction of the aorta	Severe blurring, edge definition very poor, margins difficult to discern	Excessive blurring, edge definition poor, margins blurry	Moderate blurring, edge definition poor, margins can be discerned	Minimal blurring, edge definition good, margins easily discerned	No blurring, edges well defined, margins crisp
Visually sharp reproduction of the kidneys and proximal ureters	Severe blurring, edge definition very poor, proximal ureter difficult to discern	Excessive blurring, edge definition poor, proximal ureter blurry	Moderate blurring, edge definition poor, proximal ureter can be discerned	Minimal blurring, edge definition good, proximal ureter easily discerned	No blurring, edges well defined, margins crisp, proximal ureter easily discerned
Subjective image noise	Unacceptable image noise	More than average image noise	Average image noise	Less than average image noise	Minimal image noise
Subjective image contrast	Unacceptable image contrast	Less than average image contrast	Average image contrast	More than average image contrast	Good image contrast
Overall image quality acceptability	Not evaluable because of very high image noise and poor contrast, diagnostically unacceptable	Very poor because of high image noise and poor contrast, diagnostically unacceptable	Poor because of high image noise and moderate contrast, diagnostically acceptable only in limited conditions	Fair with increased image noise, willing to read in most clinical situations, probably acceptable	Good image quality comparable to routine clinical scanning, standard image noise, willing to read in all clinical situations, fully acceptable

Table 3
Patient characteristics. Number of patients, median and IQR of age (years), BMI, weight (kg), length (cm) and BSA (m^2) for men and women. *P*-value of Mann-Whitney U test for comparison between both genders.

Number of patients		Women 35	Men 42
Age (years)	Median	69	69
	IQR	59;75	62;76
	p-value*	0.7	
BMI	Median	25	26
	IQR	22;28	23;28
	p-value*	0.83	
Weight (kg)	Median	65.3	81.5
	IQR	59.6;76.25	69.5;85
	p-value*	0.001	
Length (cm)	Median	162	175
	IQR	158.4;168	170;178
	p-value*	< 0.0001	
BSA (m^2)	Median	1.71	1.96
	IQR	1.64;1.88	1.83;2.04
	p-value*	0.01	

* Mann-Whitney U test, IQR = interquartile range.

stratifying by BMI, a statistically significant lower mean contrast volume was found in underweight and normal BMI patients of 63.6 ml ($p = 0.0013$) and 80 ml ($p < 0.001$) respectively in the patient-tailored volume protocol, accounting for a reduction of 33% and 16% compared to the fixed volume protocol. There was a statistically significant higher mean injected volume of 110 ml ($p < 0.05$) in high BMI patients in the patient-tailored protocol, corresponding to a relative increase of 16% compared to the fixed contrast volume.

3.3. Objective image quality analysis

Interobserver correlation was excellent for splenic parenchyma, liver parenchyma, abdominal aorta and portal vein ($r > 0.9$) and was good for the enhancement of the psoas muscle ($r > 0.7$). Since correlation was good to excellent, enhancement values were averaged over the two readers. Results of vessel/organ enhancement plotted against BMI are shown in Fig. 3 and Table 4. Results are depicted for all patients (Fig. 3A-B) and after stratification by gender (Fig. 3C-F).

In the fixed volume protocol (Fig. 3A, C, E) there was a statistically significant negative correlation ($r \leq 0$ and $p \leq 0.05$) between enhancement and BMI for portal vein, aorta, spleen and liver in all patients together (Fig. 3A) and in women (Fig. 3C), i.e. when patient BMI increased, the enhancement decreased. There also was a statistically significant negative correlation between enhancement and BMI for spleen and liver in men (Fig. 3B). No significant correlation ($p > 0.05$) was found between enhancement and BMI for portal vein and aorta in men.

In the patient-tailored volume protocol (Fig. 3B, D, F) there was either a statistically significant positive correlation ($r > 0$ and $p \leq 0.05$) between enhancement and BMI, i.e. enhancement increased when patient BMI increased, or there was no significant correlation ($p > 0.05$) between enhancement and BMI i.e. the direct relationship between enhancement and BMI was lost.

For the psoas muscle there was never a significant correlation between enhancement and BMI.

Enhancement per vessel/organ was compared between both volume protocols for all patients and after stratification by gender. Results are shown in Fig. 4 and Table 5. Results are depicted for all patients (Fig. 4A) and after stratification by gender (Fig. 4B-C). A statistically significant lower enhancement of liver ($p < 0.05$), spleen ($p < 0.001$), abdominal aorta ($p < 0.05$) and portal vein ($p < 0.001$) was observed for the patient-tailored volume protocol compared to the fixed volume protocol considering all patients together. After stratification by gender, there was only a statistically significant lower

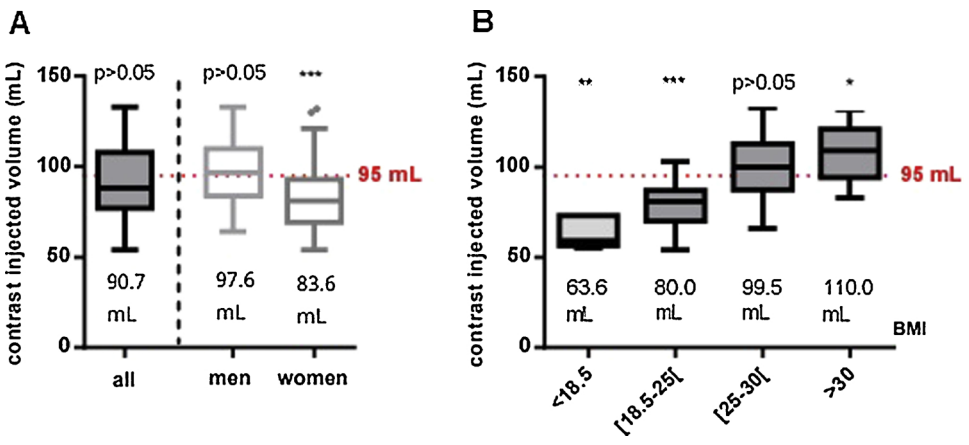

Fig. 2. Contrast volumes in the patient-tailored volume protocol compared to the fixed contrast volume protocol. Boxplot showing mean, SD and outliers of contrast volumes. Each boxplot is compared to the fixed volume protocol (95 ml, dotted line). A. Contrast volumes for all patients and after stratification by gender. B. Contrast volumes stratified by BMI-category. *P*-values of one-sample *t*-test; * = $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$.

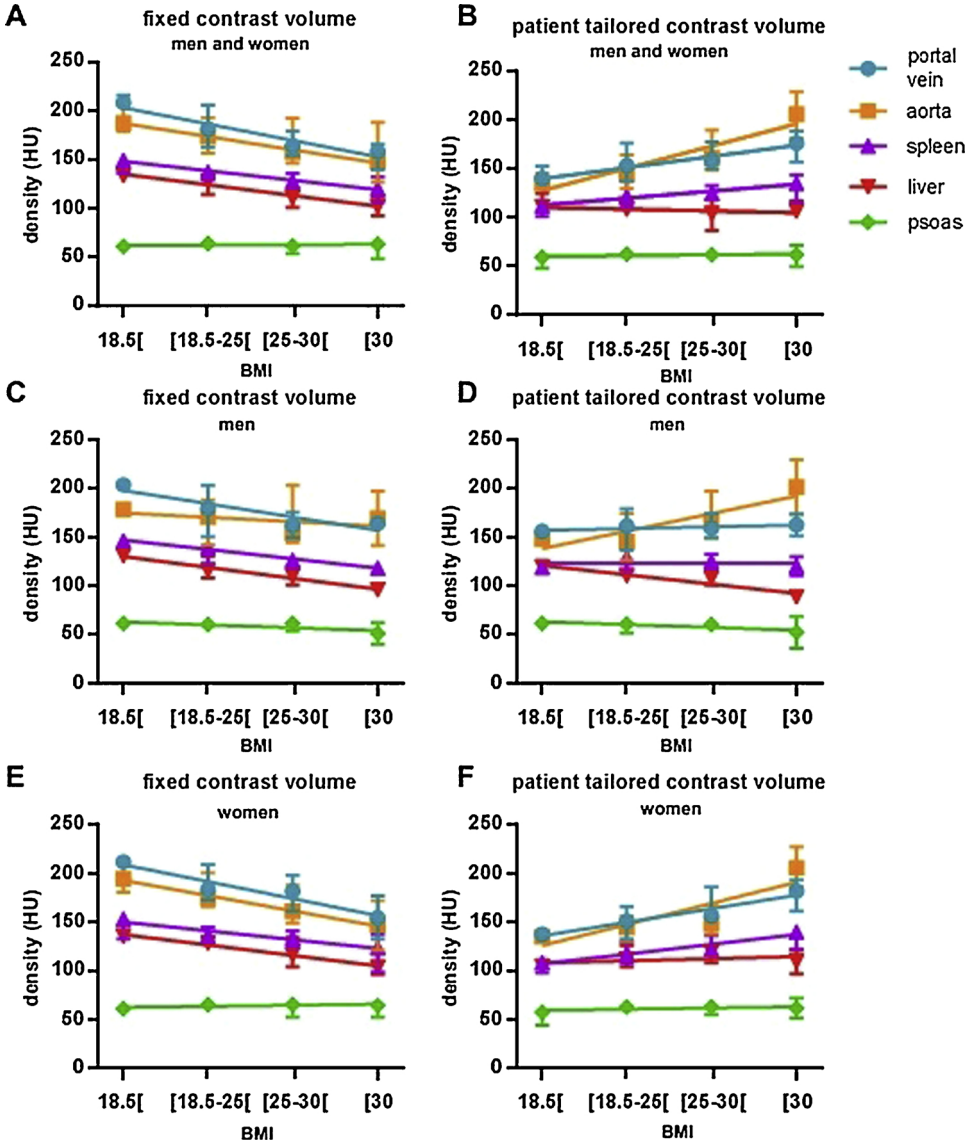

Fig. 3. Vessel and parenchymal tissue enhancement in Hounsfield units in function of patient BMI. Plots showing median and IQR of vessel/organ enhancement per BMI-category. (A–C–E). Enhancement of aorta, portal vein, spleen, liver and psoas muscle in the fixed volume protocol group (95 ml) for all patients (A), men (C) and women (E) respectively. (B–D–F) . Enhancement of aorta, portal vein, spleen, liver and psoas muscle in the patient-tailored volume protocol group for all patients (B), men (D) and women (F) respectively.

Table 4
Pearson's correlation coefficients of vessel/organ enhancement over different BMI-categories for all patients and after stratification by gender. Pearson's correlation coefficient (r ≤ 0: negative correlation, r > 0 = positive correlation) for enhancement of portal vein, abdominal aorta, spleen, liver and psoas muscle over different BMI-categories with the fixed and patient-tailored volume protocol, for all patients and for men and women separately. *P*-value of Mann Whitney U test to evaluate the statistically significance of Pearson correlation coefficient (p ≤ 0.05: significant correlation, p > 0.05: no significant correlation).

			Portal vein	Aorta	Spleen	Liver	Psoas muscle
Fixed volume protocol	Pearson's correlation coefficient	All	−0.960	−0.996	−0.992	−0.983	0.365
		Men	−0.919	−0.567	−0.992	−0.988	−0.769
		Women	−0.960	−0.995	−0.952	−0.992	0.652
	p-value*	All	**0.040**	**0.004**	**0.008**	**0.017**	0.635
		Men	0.081	0.433	**0.008**	**0.012**	0.231
		Women	**0.041**	**0.005**	**0.048**	**0.008**	0.348
Patient-tailored volume protocol	Pearson's correlation coefficient	All	0.981	0.940	0.979	−0.796	0.633
		Men	0.787	0.899	−0.003	−0.946	−0.843
		Women	0.963	0.871	0.969	0.452	0.579
	p-value*	All	**0.018**	0.060	**0.021**	0.204	0.367
		Men	0.213	0.101	0.997	0.054	0.157
		Women	**0.036**	0.129	**0.031**	0.548	0.421

*Mann Whitney U test, *p*-value ≤ 0.05 = significant linear correlation.

enhancement of liver, portal vein, spleen (p < 0.01) and abdominal aorta (p < 0.05) in women for the patient-tailored protocol. No significantly lower vessel/organ enhancement was noted in men comparing both volume protocols. There was no significant difference in enhancement of the psoas muscle comparing both volume protocols.

3.4. Subjective image quality analysis

Interobserver agreement was poor (r < 0.4) for fixed contrast volumes and fair (0.4 < r < 0.5) for patient-tailored contrast volumes. Since interobserver agreement was poor to fair, results of both readers were analysed separately for each protocol group. As there were 77 patients in each protocol group and there were two analyses per patient, there were a total of 154 individual analyses in each protocol group. There was no statistically significant difference in subjective image quality (p > 0.05) between both volume protocols comparing the results of each reader, as shown in Table 6.

4. Discussion

This study aimed to evaluate the effect of a BSA and heart ratebased patient-tailored volume protocol on portal venous phase abdominal CT images in terms contrast volumes and of objective and subjective image quality, compared to a fixed contrast volume of 95 ml.

Timing and magnitude of enhancement in helical MDCT depend on many factors. Arbitrarily, these factors can be divided into factors related to scanning technique (most importantly x-ray energy), factors related to contrast medium (e.g. contrast dose, injection rate, time course and duration of injection, injection shape, contrast osmolarity and viscosity, saline chaser) and patient-related factors (e.g. body habitus, cardiac output, gender, venous access site, comorbidities) [6]. The most important patient-related factor to take into account to optimize the magnitude of enhancement, is body size [6]. This can be easily understood since body size is directly related to blood volume [6]. Larger patients have larger blood volumes, leading to higher dilution of intravenously injected contrast [6]. Intravenously injected iodine contrast will redistribute from the vascular to the interstitial spaces of organs [6]. Well-perfused organs (e.g. kidney, spleen, liver) will show more intense enhancement due to their high capillary fluid volume compared to their extracellular fluid volume [6,12]. Tissues with a high extracellular fluid volume compared to the capillary volume (e.g. fat), contribute little to dispersion/dilution of the contrast medium in the blood [6,12]. Using a fixed contrast volume protocol, small patients will receive a relatively high amount of contrast while larger patients receive a relatively low amount of contrast. This causes highly variable interpatient enhancement, decreasing with increasing BMI, as demonstrated in our study (Fig. 3A, C, E). In order to correctly adjust iodine dose to patient size, it is important to take into account a person's metabolic mass [13]. Different body size indices have been proposed. Mostly because of practical considerations, many previous studies used total body weight (TBW) to adjust iodine dose to body size [1,2,4,5,14]. However, it has been shown that this strategy overestimates the amount of contrast medium needed in large patients. This is explained because a weight-based dosing doesn't take into account the larger increase in fat tissue with increasing weight compared to other tissues, while fat tissue only has a small impact on dispersion and dilution of the contrast medium [6]. Lean body weight (LBW) and BSA have been shown to be more accurate indices to correct iodine dose to patient size [6,12,13,15]. LBW is the total body weight minus the fat weight and can be measured using specialized scales or can be estimated using different formulas. BSA is an estimation of a person's body surface. It is a body size parameter that provides good adjustment of iodine dose across a wide range of body sizes and weights and was found to be more practical in use than LBW [6,12,13,15,16]. It is a parameter frequently used as an index for determination of drug dose and in physiologic measurement to correct for differences in body composition [13,15].

Next to patient size, cardiac output is a second patient-related factor that has an impact on contrast enhancement [6]. While cardiac output mainly affects timing of contrast enhancement – which is especially important in angiographic CT applications – it also has, to a lesser degree, an effect on magnitude of enhancement [6]. This can be understood because of the slower clearance of contrast with decreasing cardiac output, resulting in a higher and prolonged contrast enhancement profile [6]. Cardiac output is defined as the product of stroke volume and heart rate [17]. Since cardiac output currently cannot be measured non-invasively [17], heart rate was used as a substitute. The heart rate was measured using a portable finger pulse oximeter.

In order to minimize the influence of other patient-bound confounding covariates on enhancement, this study analysed examinations with a fixed contrast volume and a patient-tailored contrast volume in the same patient. Other confounding factors related to scanning technique and contrast medium that were kept constant for all examinations included CT-scanner, tube voltage, scan-delay, contrast medium type, injector pump, injection rate and saline chaser.

In this study, a software application (iCalc, Medicor Europe AG, Rotselaar, Belgium) implemented in the injector pump interface, was used to calculate patient-tailored contrast volumes. Using a software application allowed efficient implementation in a busy radiology department.

The current study found a reduction of contrast in 62% of patients in the patient-tailored volume protocol compared to the fixed volume

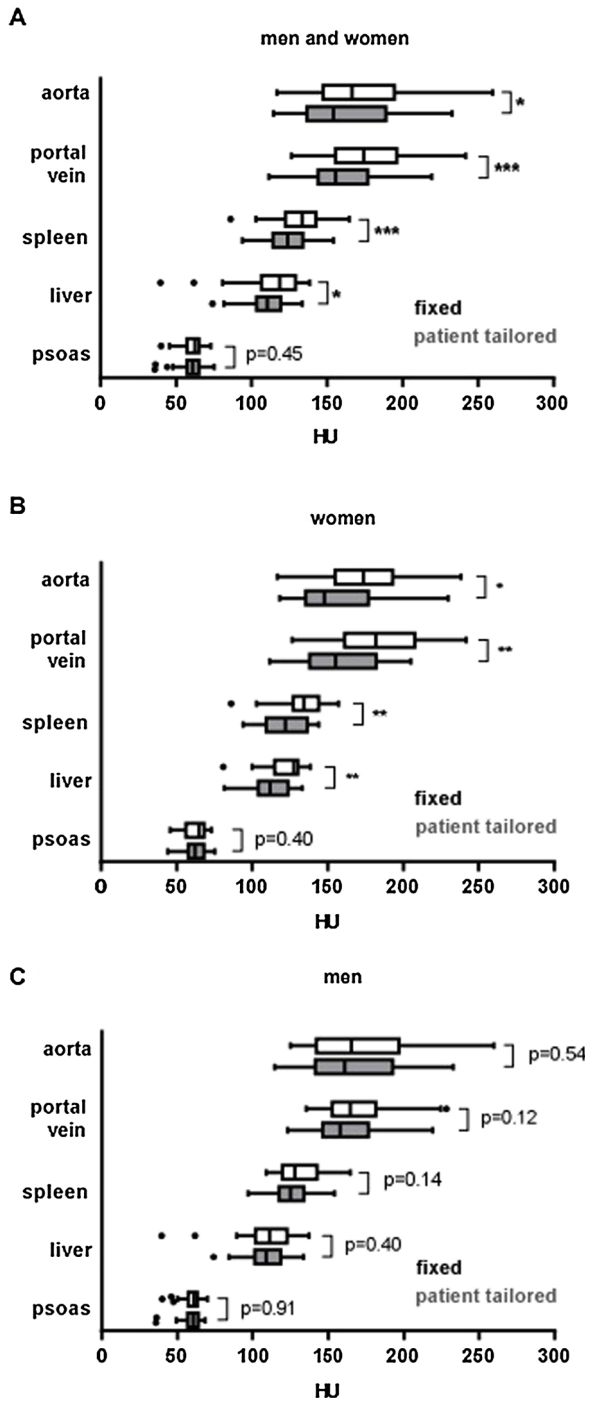

Fig. 4. Enhancement compared for the fixed and patient-tailored volume protocol. Boxplot showing median, IQR and outliers of enhancement in Hounsfield units per vessel/organ for all patients (A), for women (B) and men (C) respectively.
P-values of Mann-Whitney U test; * = $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$.

protocol. However, no significant reduction in mean contrast volume (90.7 ml versus 95 ml) was demonstrated comparing both protocols. This is in contrast with previous studies which compared the effect of patient-tailored contrast volumes on abdominal CT examinations [1,3,18,19]. This is due to the relatively low amount of contrast used in the fixed volume protocol in this study, which was already close to the mean contrast volume in the patient-tailored protocol. Fixed volumes in previous studies ranged from 100 to 150 ml [1,3,18,19]. The current study demonstrated a redistribution of contrast volumes in the patient-tailored volume protocol, with a reduction of mean contrast volumes in low (-33%) to normal (-15%) BMI patients and an increase of mean volumes (+16%) in high BMI patients. The reduction of contrast volumes in small patients is in accordance with a recent study of Perrin et al. [1], where small patients (i.e. weight < 76 kg) received less contrast in a weight-based volume protocol compared to a fixed volume protocol. Also, this study found a significant reduction of contrast volumes in women, with a mean contrast volume of 83.6 ml, accounting for a reduction of 12% compared to the fixed volume protocol. This is in accordance with a study of Megibow et al. [18] where a larger percentage of images in women was of acceptable quality with lower iodine doses compared to men. The lower iodine requirement in women can be understood because of their lower BSA compared to men with equivalent BMI [6], which was also demonstrated in this study (Table 3). Lowering the amount of contrast needed for CT examinations by using a patient-tailored volume protocol can lead to cost and material savings [1,3,18,19]. Also, contrast-induced acute kidney insufficiency is deemed to be dose related [20–22]. Lowering contrast volumes can therefore reduce unnecessary increases in risk and related costs of renal toxicity [20–22].

The current study showed a loss of direct relationship between enhancement and BMI or a positive correlation between enhancement and BMI (Fig. 3B, D, F) in the patient-tailored volume protocol. This is in contrast with a study of Perrin et al. [1] who found a negative correlation between enhancement of liver and BMI using a patient-tailored volume protocol solely based on patient weight. These different outcomes support the idea that BSA is a better parameter to adjust contrast dose for body size compared to body weight.

No significant differences in subjective image quality were found between both volume protocols, assessed by two independent radiologists. This is an important adjunct indicator that all images were diagnostic despite lower vessel/organ enhancement in the patient-tailored volume protocol.

This study was a single centre study and had some limitations. Firstly, the length and weight data provided by the patients were not verified prior to scanning. Secondly, because of practical considerations in our radiographer-led department, injection rates were not adapted to contrast volumes in the patient-tailored injection protocol. The fixed injection rate of 1.2 ml/s was rather slow for high patient-tailored volumes. This might have caused a lower than expected enhancement of visceral organs in this patient group because of longer injection duration, slow delivery rate and thus longer time to peak enhancement – as illustrated in the article of Bae et al. [6]. In a following study, a fixed injection time will be used with injection rates adapted to calculated volumes using a look-up table. This should render a more compressed injection bolus and a higher enhancement for large contrast volumes, which is also illustrated by Bae et. al [6]. This might cause a higher enhancement for the same amount of contrast in large patients. Also, keV was not adapted to patient size. It is well known that X-ray energy is an important factor to take into account when optimizing image contrast [6,23,24]. The closer the X-ray output energy approaches the k-edge of iodine (33 keV), the higher the CT attenuation of iodine will be [6]. Therefore, higher CT attenuation can be acquired with lower tube voltages, using the same amount of iodine [6]. However, lowering tube voltages without adapting tube current will lead to higher image noise, which comprises image quality, especially in larger patients [6,23,24]. Image noise has a great effect on the quality of abdominal images because the abdominal region is inherently of lower contrast [23,24]. Since the scope of this study was to investigate solely the effect of patient-tailored contrast volumes on contrast enhanced CT-images,and because of the complex, dual impact of tube voltage on contrast enhancement and image quality, adaptation of tube voltage was not implemented in the study design. In a next study it would be interesting to compare image quality using patient-tailored contrast volumes with fixed and adapted tube voltages. This will be especially

Table 5
Vessel/organ enhancement compared between fixed and patient-tailored protocol. Enhancement in Hounsfield units for all patients with median and IQR. Results of all patients and for men and women separately were compared between the fixed and patient-tailored volume protocol. *P*-value of Mann-Whitney U test for comparison between fixed and patient-tailored protocol (*p*-value ≤ 0.05 = significant).

		All		Women		Men	
		Fixed	Patient-tailored	Fixed	Patient-tailored	Fixed	Patient-tailored
Liver	Median	117	108	125	112	110	107
	IQR	104;129	102;119	107;130	104;121	102;119	99;115
	p-value*	**0.02**		**0.0082**		0.4	
Spleen	Median	132	122	134	122	126	124
	IQR	121;141	115;133	126;142	112;133	118;140	118;133
	p-value*	**0.0007**		**0.0025**		0.14	
Abdominal aorta	Median	166	154	173	148	155	164
	IQR	146;184	137;186	157;186	137;176	142;178	141;193
	p-value*	**0.048**		**0.02**		0.54	
Portal vein	Median	170	156	181	156	162	156
	IQR	153;196	144;176	161;206	143;180	149;179	146;173
	p-value*	**0.0005**		**0.0013**		0.12	
Psoas muscle	Median	63	61	65	61	60	61
	IQR	56;66	57;65	58;68	58;67	56;63	55;64
	p-value*	0.46		0.4		0.91	

* Mann-Whitney U test, IQR = Interquartile range, **p-value ≤ 0.05 = significant**.

Table 6
Subjective ratings of both readers separately for each protocol group. Six quality criteria were evaluated by two independent radiologists as defined in Table B. Results of both readers were analysed separately, producing 154 analyses per protocol group. The occurrence rate of each score is given for all criteria. *p*-value of Wilcoxon matched-pairs signed rank test for comparison between both protocols (*p*-value ≤ 0.05 = significant).

		Subjective assessment					
		1	2	3	4	5	TOTAL
Liver	Fixed	0	2	9	86	57	154
	Patient-tailored	2	1	15	83	53	154
	p-value*	0.2899					
Aorta	Fixed	0	0	11	77	66	154
	Patient-tailored	0	2	11	83	58	154
	p-value*	0.2665					
Kidney	Fixed	0	1	10	83	60	154
	Patient-tailored	0	1	9	88	56	154
	p-value*	0.8316					
Image noise	Fixed	0	2	22	111	19	154
	Patient-tailored	0	1	16	118	19	154
	p-value*	0.3577					
Image contrast	Fixed	0	0	10	60	84	154
	Patient-tailored	2	2	11	66	73	154
	p-value*	0.1081					
Overall image quality	Fixed	0	0	4	34	116	154
	Patient-tailored	0	1	6	39	108	154
	p-value*	0.1747					

*Wilcoxon matched-pairs signed rank test, *p*-value ≤ 0.05 = significant.

beneficial for small patients, since lower tube voltages in this patient population can lead to increased image contrast while reducing radiation dose [6,23,24]. Lastly, the number of patients in the extreme BMI-categories was rather low (5 patients with BMI < 18.49 and 11 patients with BMI > 30). A larger number of patients is needed to confirm our findings.

Overall, implementation of patient-tailored contrast volumes leads to a more constant interpatient contrast enhancement, less dependent on patient body habitus. This study offers a unique, user-friendly method to calculate personalized contrast volumes in a daily clinical context, both taking into account BSA and heart rate, which can be a further step in the re-evaluation and standardization of contrast administration protocols and in the continuous improvement of CT-image quality, both in interest of the patient and the radiologist.

5. Conclusions

This retrospective study evaluated the impact of a BSA-based patient-tailored contrast volume protocol in portal venous phase abdominal CT-examinations, compared to a fixed contrast volume protocol. Patient-tailored contrast volumes were calculated by a software application integrated in the interface of the contrast injector pump and were based on BSA, heart rate, contrast medium concentration and desired contrast dose. Interpatient enhancement was more constant over different BMI-categories using a patient-tailored contrast protocol. Also, with a patient-tailored volume protocol, a significant contrast volume reduction of 33% and 15% was achieved in low to normal BMI patients, and of 12% in women, while preserving subjective image quality.

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Declaration of Competing Interest

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