Image quality in dual‐source multiphasic dynamic computed tomography of the abdomen: evaluating the efects of a low tube voltage (70 kVp) in combination with contrast dose reduction

（腹部のデュアルソースでのダイナミック造影 CT の画質：低管電圧（70kVp）と造影剤量の減少を組み合わせた効果の評価）

氏名　三好啓介

所属　山口大学大学院医学系研究科

情報解析医学系専攻　放射線医学分野

令和 2 年 10 月

学位論文の関連論文の研究背景及び要旨

所属　放射線科
氏名　三好啓介

〔題名〕

Image quality in dual-source multiphasic dynamic computed tomography of the abdomen: Evaluating the effects of a low tube voltage (70 kVp) in combination with contrast dose reduction

（腹部のデュアルソースでのダイナミック造影 CT の画質：低管電圧（70kVp）と造影剤量の
減少を組み合わせた効果の評価）

Journal of Abdominal radiology doi: 10.1007/s00261-020-02565-9.　（令和 2 年 5 月掲載）

〔研究背景〕

CT 撮像においてヨード造影剤を使用する場合、基礎疾患の有無により造影剤腎症のリスクがあることから、画質を落とすことなくヨード量を低減させることが望ましいと考えられている。

ヨードの減弱係数は X 線のエネルギーが低くなるほど大きくなるため、低管電圧 CT を用いると造影効果も大きくなり、ヨード量も低減できることがいくつかの研究で示されている。ファントム研究では 120kVp から 70kVp まで管電圧を下げることで、ヨード量を 53% 減らせるという報告もある。

一方で、低管電圧 CT では管電流を上げなければノイズが増えるが、従来のシングルソース CT の管電流では最小管電圧は 80kVp が限界で、そのため造影剤量の低減は最大で 40%であった。これに対し、デュアルソース CT では 2 つの X 線管を同時に用いることから、管電流を 2 倍にでき、低管電圧（70kVp）と高い管電流出力を組み合わせることで、半分のヨード量でもノイズの低減した高画質が得られる。

しかしながら、低管電圧（70kVp）と半分のヨード量を用いたデュアルソースのダイナミック CT での画質を評価した検討はほとんどないため、今回の検討を行った。

〔要旨〕

目的：

腹部のダイナミック造影CT（動脈相、門脈相、平衡相）の画質について、低管電圧（70kVp）CT 撮影と低濃度造影剤(140mgI/mL)を用いて造影剤のヨード量を標準量の半分(300mgI/kg)にして投与したプロトコール（以下、低管電圧プロトコール）と、標準的な管電圧（120kVp）CT撮影と中濃度造影剤(300mgI/mL)を用いて造影剤のヨード量を標準量(600mgI/kg)にして投与したプロトコール（以下、標準管電圧プロトコール）を、同一患者で比較した。

方法：

患者背景

2018年11月～2019年4月に低管電圧プロトコールと標準管電圧プロトコールのそれぞれで腹部ダイナミック造影CTを撮像された55人(体重71kg以下)の患者を対象とした。

31人が男性、24人が女性、37-94歳、平均年齢は72.5歳。

各患者の原疾患は肝細胞癌が33人。肝転移は10人。膵胆管系疾患が12人。

CT

低管電圧プロトコールでは管電圧（70kVp）で、低濃度造影剤(140mgI/mL)を用いて造影剤のヨード量を標準量の半分(300mgI/kg)にして投与（造影剤総量は2mL/kg）。

標準管電圧プロトコールでは管電圧（120kVp）で、中濃度造影剤(300mgI/mL)を用いて造影剤のヨード量を標準量(600mgI/kg)にして投与（造影剤総量は2mL/kg）。

撮像機器にはデュアルソース CT（SOMATOM Force、Siemens）およびシングルソースCT(SOMATOM Definition or Sensation、Siemens)を用いた。

画像解析

画像は全て PACS（picture archiving and communication system）からワークステーション（EV InsiteS）に転送され、共同研究者による盲検読影のために患者情報を匿名化し、CTデータをランダム化した。

定量評価

7年目の放射線科医によって行われた。肝臓、腹部大動脈、門脈、脊柱起立筋のそれぞれのCT値とノイズをROIを用いて測定し、シグナルノイズ比（SNR）とコントラストノイズ比（CNR）も計算した。SNRは関心領域の平均CT値/背景の空気の標準偏差、CNRは（関心領域の平均CT値-脊柱起立筋の平均CT値）/関心領域の標準偏差として定義した。

被曝線量

CTDIvolを計測する。CTDIvolは患者全体の他に、サブグループとして体重55kg以下の群（30人）で測定した。さらに、性能指数（FOM）もCNR2/CTDIvolで計算し、2つのプロト

コールそれぞれで比較した。

定性評価

二人の腹部領域の専門家（7年目、28年目）で行った。

動脈相では多血性臓器である腎皮質と膵実質の造影効果を評価した。

門脈相では肝実質と門脈のコントラスト、肝実質と門脈の視認性、肝辺縁の肝静脈の視認性を評価した。

平衡相では肝実質と肝静脈のコントラスト、肝実質と肝静脈の視認性を評価した。

それぞれを5段階で評価した。

統計解析

データはWindowsのSPSS statisticsで解析した。

70kVpと120kVpそれぞれの定量解析と定性解析の検定にはMann-Whitney U検定を用いた。p 値は0.05以下を有意とした。κ 統計量の解析は定性評価における評価者間の比較に用いた。κ 値は以下のように解釈した。0.81-1.00は一致、0.61-0.80は実質的に一致、0.41-0.60は中程度の一致、0.21-0.40は程々の一致、0.20以下は一致は乏しいとした。

結果：

定量評価

肝実質は、平均CT値、SNRはいずれの時相でも低管電圧プロトコール群の方が有意に高く、ノイズはいずれの時相でも低管電圧プロトコール群の方が有意に低かった。肝実質のCNRは門脈相、平衡相で低管電圧プロトコール群の方が有意に高かった。

大動脈は、動脈相で平均CT値、CNR、SNRいずれも低管電圧プロトコール群の方が有意に高く、ノイズは低管電圧プロトコール群の方が有意に低かった。

門脈は、門脈相で平均CT値、CNR、SNRいずれも低管電圧プロトコール群の方が有意に高く、ノイズは低管電圧プロトコール群の方が有意に低かった。

被曝線量

CTDIvolは全時相で70kVpプロトコールが120kVpプロトコールより高くなったが、その差は1-2mGyであった。肝実質、大動脈、門脈のFOMは、動脈相の肝実質を除き、70kVpプロトコールの方が全時相で高かった。体重が55kg以下の患者（30人）では動脈相と平衡相で各プロトコール間のCTDIvolに有意差はなかった。

定性評価

評価者間の一致度はいずれのプロトコールでも κ 値では中程度の一致だった。

全体的な画質、ノイズはいずれの時相でも70kVpの方が120kVpより有意に良好だった。

門脈相での肝実質と門脈のコントラスト、平衡相での肝実質と肝静脈のコントラストはいずれも70kVpの方が有意に良好だった。
肝静脈分枝の視認性の平均スコアは70kVpの方が有意に良好だった。

結論：
腹部ダイナミックCTで不十分なヨード量だと、十分な造影効果が得られず、特に門脈相～平衡相での肝臓、膵臓、腎臓など実質臓器での正確な診断を妨げる。逆に過量の造影剤はコストと臓器障害リスクの不要な増加につながる。デュアルソースCTを用い、管電圧（70kVp）で、低濃度造影剤(140mgI/mL)を用いて造影剤のヨード量を標準量の半分(300mgI/kg)にして投与する低管電圧プロトコールは、腹部造影ダイナミックCTにおいて、十分な造影効果が得られ、画質も改善されることから、体重71kg以下の患者において有用な検査法と考えられる。

Abdominal Radiology
https://doi.org/10.1007/s00261-020-02565-9

HEPATOBILIARY

Image quality in dual-source multiphasic dynamic computed tomography of the abdomen: evaluating the effects of a low tube voltage (70 kVp) in combination with contrast dose reduction

Keisuke Miyoshi[1] · Hideko Onoda[1] · Mashiro Tanabe[1] · Sei Nakao[1] · Mayumi Higashi[1] · Etsushi Iida[1] · Munemasa Okada[1] · Matakazu Furukawa[1] · Katsuyoshi Ito[1]

Abstract

Purpose To compare the image quality of multiphasic (arterial, portal, and equilibrium phases) dynamic computed tomography (CT) of the abdomen obtained by a low tube voltage (70kVp) in combination with a half-dose iodine load using low-concentration contrast agent in high tube output dual-source CT with a standard tube voltage (120kVp) and full-dose iodine load using the same group of adult patients.

Methods Fifty-five patients who underwent both low-tube-voltage (70kVp) abdominal CT with a half-dose iodine load and standard-tube-voltage (120kVp) CT with a full-dose iodine load were analyzed. The mean CT values and signal-to-noise ratio (SNR) of the liver, aorta and portal veins were quantitatively assessed. In addition, the contrast enhancement of the abdominal organs and overall image quality were qualitatively evaluated.

Results The mean CT values and SNR of the liver parenchyma were significantly higher in 70-kVp protocol than in 120-kVp protocol in all 3 phases ($p = 0.018 \sim < 0.001$). Regarding the qualitative analysis, the overall image quality in the 70-kVp protocol was significantly better than in the 120-kVp protocol in all 3 phases ($p < 0.001$). In addition, the contrast enhancement scores of the liver parenchyma and hepatic vein in the equilibrium phase were also significantly higher in the 70-kVp protocol than in the 120-kVp protocol ($p < 0.001$).

Conclusion A low tube voltage (70kVp) in combination with a half-dose iodine load using a low-concentration contrast agent and an iterative reconstruction algorithm in high tube output dual-source CT may improve the contrast enhancement and image quality in multiphasic dynamic CT of the abdomen in patients under 71 kg of body weight.

Keywords X-ray computed tomography · Iodine · Diagnostic imaging · Low tube voltage

Abbreviations

CT	Computed tomography
CM	Contrast medium
ROI	Region of interest
AP	Arterial phase
PVP	Portal venous phase
EP	Equilibrium phase
SD	Standard deviation
CNR	Contrast-to-noise ratio
SNR	Signal-to-noise ratio
FOM	Figure of merit

Introduction

Although the incidence of contrast-induced nephropathy (CIN) after the administration of intravenous contrast medium (CM) is controversial [1], it is desirable to minimize the iodine load without the loss of image quality in patients believed to be at risk for the development of kidney injury, such as those with cardiovascular disease, diabetes mellitus, chronic hepatitis, cirrhosis, or malignant tumors [2–5].

Some studies have shown that the iodine doses can be reduced using a low tube voltage (kVp) for scanning, as the iodine attenuation increases due to the lower mean X-ray energy [6, 7]. In a phantom study, reducing the tube voltage

---

✉ Katsuyoshi Ito
itokatsu@yamaguchi-u.ac.jp

[1] Department of Radiology, Yamaguchi University Graduate School of Medicine, 1-1-1 Minami-Kogushi, Ube, Yamaguchi 755-8505, Japan

from 120 to 70 kVp allowed for a 53% reduction in the iodine dose of contrast agent while maintaining adequate image contrast [8]. However, low-tube-voltage imaging increases the image noise unless the tube current output is increased. With conventional single-source CT, it has not been possible to increase the tube current sufficiently, resulting in increased noise and subsequent deterioration in the image quality of abdominal CT [9].

Given the above, previous studies have used a minimum tube voltage of 80 kVp for abdominal CT in adult patients, which is accompanied by a 40% reduction in CM [10–12]. Conversely, in the latest dual-source CT, two more powerful X-ray tubes are used simultaneously at the same tube voltage. This technique offers the potential to double the total tube current, combining a low tube voltage (70 kVp) with a high total tube output and allowing images with reduced noise to be obtained even at a half-dose iodine load in abdominal CT [13]. However, few studies have evaluated the image quality of multiphasic dynamic CT in dual-source CT using a low tube voltage (70 kVp) and half-dose iodine load of CM in the same group of adult patients [14].

The purpose of this study was to assess the image quality of multiphasic (arterial, portal, and equilibrium phases) dynamic CT of the abdomen obtained with a low tube voltage (70 kVp) in combination with a half-dose iodine load using low-concentration contrast agent in high tube output dual-source CT in the comparison with a standard tube voltage (120 kVp) and full-dose iodine load in the same group of adult patients.

Materials and methods

Study population

This retrospective study was approved by the institutional review board, and the requirement for informed consent was waived.

The radiology information system in our institution was searched to identify patients who met the following inclusion criteria: (a) patients underwent multiphasic contrast-enhanced dynamic CT of the abdomen between November 2018 and April 2019; (b) CT was performed in the dual-power mode using a low tube voltage (70 kVp) with a half dose of iodine using low-concentration CM; and (c) CT had previously been performed using a standard tube voltage (120 kVp) and full-dose iodine using medium-concentration CM. Patients with portal vein thrombosis ($n = 1$) were excluded from the analysis.

Ultimately, 55 patients met these criteria and were included in this study (31 men, 24 women; age range, 37–94 years; mean age, 72.5 years). The average time intervals between 70 and 120 kVp CT were 391 ± 274 days (range: 63–1127 days). The body weight of all patients in this study was under 71 kg, based on the clinical decision concerning the use of the low-tube-voltage (70 kVp) CT protocol in our institution. The selection of these patients had been based on the body weight shown in the clinical request form of CT examination. The mean patient body weight was 55.1 ± 7.9 kg (range: 40.5–71.0 kg), and the mean body mass index (BMI) was 21.9 ± 3.0 (range: 16.4–31.8). All examinations were clinically indicated, including periodic surveillance of hepatocellular carcinoma (HCC) in patients with chronic hepatitis or cirrhosis ($n = 33$), screening of liver metastasis in oncology patients ($n = 10$) and the further evaluation of pancreatobiliary diseases ($n = 12$).

CT

In the low-tube-voltage (70 kVp) protocol, abdominal CT was performed with a dual-source CT scanner (SOMATOM FORCE; Siemens, Forchheim, Germany) equipped with 2 X-ray tubes (Vectron tube; 1300-mA maximum tube current) in dual-power mode using the tube current modulation algorithm (Care Dose 4D), and 2 corresponding Stellar detectors were installed with an angular offset of 95°. In dual-power mode, both X-ray tubes work simultaneously at the same voltage of 70 kVp, making it possible to double the total tube current. Craniocaudal CT from the top of the liver was performed with a dual-power protocol (detector collimation, 192×0.6 mm; pitch, 0.6; gantry rotation time, 0.5 s; matrix, 512×512). Tube voltages were set at 70 kVp, and the mAs were automatically calculated based on the localizer image. After performing a precontrast scan, contrast-enhanced dynamic CT including the arterial phase (AP), portal venous phase (PVP) and equilibrium phase (EP) was performed. AP and EP imaging covered the abdomen area while PVP imaging covered the abdominopelvic area. The total CM volume was individualized depending on each patient's body weight. In this protocol, half-dose (300 mg of iodine per kilogram of body weight [mgI/kg]) and low-concentration (140 mgI/mL) iodine CM (iohexol; Omniparque 140, Daiichi-Sankyo, Tokyo, Japan) was administered intravenously for 30 s using a pump-based injector system (CT motion; Ulrich Medical, Germany), followed by the injection of 30 mL saline solution at the same rate as the CM. The scanning delays of the AP after CM injection were individually determined using an automatic bolus-tracking program. A circular cursor was placed on the abdominal aorta, and the AP scan was started 20 s after a threshold of 100 Hounsfield units (HU) was reached. The PVP and EP were acquired 60 and 180 s after the start of administration of the CM, respectively. CT scans were reconstructed with a slice thickness of 2 mm in the axial plane using an iterative reconstruction (Adaptative Model-based Iterative Reconstruction [ADMIRE]) set at a level of 2.

In all patients, CT had previously been obtained with dual-source or single-source CT scanners (SOMATOM Definition or Sensation; Siemens) using the standard-tube-voltage (120 kVp) protocol. The scan parameters were as follows: detector collimation, 64 × 0.6 mm; pitch, 0.6; gantry rotation time, 0.5 s; matrix, 512 × 512. The tube current was automatically determined by the same automatic exposure control system (CARE Dose 4D) as used for 70 kVp protocol. Using a power injector (Dual shot GX; Nemoto Kyorindo, Tokyo, Japan), multiphasic (AP, PVP, EP) contrast-enhanced dynamic CT was performed using full-dose (600 mgI/kg) and medium-concentration (300 mgI/mL) iodine CM (iohexol; Omniparque 300, Daiichi-Sankyo, or iomeprol; Iomeron 300, Eizai, or iopamidol; Oypalomin 300, Fuji Pharma, Tokyo, Japan). The CM injection techniques in the standard-tube-voltage (120 kVp) protocol were the same as in the low-tube-voltage (70 kVp) protocol except for the trigger threshold (150 HU) and the start timing (17-s delay) in AP scanning. Axial CT images of 2-mm thickness were reconstructed using the filtered back projection (FBP) method. The total volume of injected CM was almost the same between the 70 and 120-kVp protocols (e.g. in a 50-kg patient, 107 mL and 100 mL, respectively).

Image analyses

All images were transferred from a hospital picture archiving and communication system (PACS) (Shade Quest; Yokogawa Medical, Tokyo, Japan) to the radiology department workstation (EV InsiteS; PSP Corporation, Tokyo, Japan) by a study coordinator (M.T.) to anonymize patients' information and scan parameters as well as to randomize CT data sets for blind reading purpose.

Quantitative analyses were performed by an experienced radiologist (K.M.) with seven years' experience in abdominal CT interpretation blinded to the clinical data and CT parameters. The mean CT values (HU) and image noise (standard deviation [SD] of measured HU values) were measured on axial images using regions of interest (ROIs) placed within the liver, abdominal aorta, portal vein, and spinal erector muscle. Attempts were made to maintain constant circular ROIs of approximately 25mm^2 in the aorta and portal vein. Image noise (SD) within the air space outside of the anterior abdominal wall was also measured. Circular ROIs were placed at the level of the main portal vein for all measurements. The size of circular ROIs were set at approximately 30mm^2 in the liver and spinal erector muscle to exclude areas of focal lesions, visible blood vessels, bile ducts, intramuscular fat and artifacts from the ROI measurements. The signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) were calculated for each image dataset using the following respective equations: SNR = (mean CT value of area of interest) / (SD of background air), CNR = (mean CT value of area of interest—mean CT value of spinal erector muscle)/(SD of area of interest). The mean CT values, image noise, CNR and SNR were measured and calculated in the liver parenchyma and abdominal aorta in the AP, in the liver parenchyma and the main portal vein in the PVP and in the liver parenchyma in the EP and were compared between the two protocols. The CTDI_{vol} was also recorded in the AP, PVP and EP to compare the radiation dose. The CTDI_{vol} was evaluated in the subgroup ($n = 30$) of patients with a body weight < 55 kg (mean body weight: 49.4 ± 3.7 kg, range: 40.5–54.5 kg) as well as in all patients ($n = 55$). In addition, a figure of merit (FOM) was calculated as the ratio of CNR^2 to CTDI_{vol} to compare the dose efficiency between the two protocols.

In the qualitative analyses, two board-certified radiologists (S.N., K.I.) with 7 and 28 years' experience in abdominal CT reading who were unaware of the clinical information and the CT parameters evaluated the images independently. In cases with discrepancy in image interpretation, the final decisions were reached by consensus. The window level and width setting were identical in all examinations during the blind reading process. All CT images were evaluated for contrast enhancement of the organs, image noise and overall image quality in each vascular phase, and the results were compared between the low-tube-voltage (70 kVp) and standard-tube-voltage (120 kVp) protocols. In the AP, contrast enhancement was assessed for the aorta, renal cortex and pancreas, which were the representative hypervascular organs. In the PVP, contrast enhancement was evaluated for the liver parenchyma and portal vein. In addition, clarity in contrast between the liver parenchyma and portal vein and the visibility of the peripheral branches of hepatic vessels were also evaluated. In the EP, contrast enhancement of the liver parenchyma and hepatic veins and clarity in contrast between the liver parenchyma and hepatic vein were assessed. Each item was graded using a 5-point scale as follows: contrast enhancement of organs (1 = poor and undiagnostic, 2 = suboptimal with low confidence, 3 = average, 4 = good, 5 = excellent), clarity in contrast between the liver parenchyma and the portal/hepatic veins (1 = no visible portal/hepatic vein, 2 = poor, 3 = moderate, 4 = good, 5 = excellent), visibility of peripheral branches of hepatic vessels and overall image quality (1 = poor, 2 = suboptimal, 3 = average, 4 = good, 5 = excellent) and image noise (1 = undiagnostic, 2 = severe, may impact the depiction of adjacent structures or lesions, but still diagnostic, 3 = moderate, not interfering with the depiction of adjacent structures or lesions, 4 = mild, sufficient diagnostic confidence, 5 = absent).

Statistical analyses

Data were analyzed using IBM SPSS Statistics for Windows (Version 22.0., IBM Inc., Armonk, NY, USA). The

Mann–Whitney U test was used to compare the results of quantitative image analysis between 70 and 120 kVp group. A p value of < 0.05 was considered to be statistically significant. The Mann–Whitney U test was also used to compare qualitative image analysis scores between 70 and 120 kVp group. Kappa statistical analysis for the comparison in qualitative parameters was performed to determine interobserver variability. The kappa value was interpreted as follows: 0.81–1.00, excellent agreement; 0.61–0.80, substantial agreement; 0.41–0.60, moderate agreement; 0.21–0.40, fair agreement; < 0.20, poor agreement.

Results

Quantitative image analyses

The results of quantitative analyses comparing the 70-kVp and 120-kVp protocols are shown in Table 1. The mean CT values (HU) of the liver parenchyma were significantly higher in the 70-kVp protocol than in the 120-kVp protocol in the AP (84.2 HU vs. 77.5 HU, $p = 0.018$), PVP (117.8 HU vs. 104.9 HU, $p < 0.001$) and EP (102.1 HU vs. 86.6 HU, $p < 0.001$) whereas image noise (SD) was significantly lower in the 70-kVp protocol than in the 120-kVp protocol in the AP (12.3 vs. 21.5, $p < 0.001$), PVP (15.3 vs. 21.9, $p < 0.001$) and EP (13.2 vs. 21.6, $p < 0.001$). There were significant differences in the CNR of the liver parenchyma between the 70-kVp and 120-kVp protocols in the PVP (3.5 vs. 1.9, $p < 0.001$) and EP (2.1 vs. 1.2, $p < 0.001$) (Fig. 1). The SNR of the liver parenchyma showed significant differences between the 70-kVp and 120-kVp protocols in all 3 phases (AP: 13.3 vs. 7.0, $p < 0.001$, PVP: 17.4 vs. 9.2, $p < 0.001$, EP: 15.7 vs. 7.7, $p < 0.001$, respectively).

The mean CT values and the CNR and SNR of the aorta in the AP were significantly higher in the 70-kVp protocol than in the 120-kVp protocol (398.9 HU vs. 313.2 HU, $p < 0.001$, 24.2 vs. 11.8, $p < 0.001$, 62.4 vs. 28.4, $p < 0.001$, respectively). Regarding the portal vein evaluation in the PVP, the mean CT values and CNR and SNR were significantly higher in the 70-kVp protocol than in the 120-kVp protocol (228.4 HU vs. 173.2 HU, $p < 0.001$, 11.4 vs. 5.0, $p < 0.001$, 34.0 vs. 15.2, $p < 0.001$, respectively). The image noise (SD) values of the aorta in the AP and the portal vein in the PVP were significantly lower in the 70-kVp protocol than in the 120-kVp protocol (14.3 vs. 31.9, $p < 0.001$ for the aorta in AP, 16.1 vs. 28.3, $p < 0.001$ for the portal vein in PVP).

Table 1 Quantitative analysis in the comparison between low-tube-voltage (70 kVp) and standard-tube-voltage (120 kVp) protocol

		70 kVp	120 kVp	*p* value
Arterial phase				
Liver	CT value	84.24 ± 14.18	77.48 ± 12.89	0.018
	SD	12.3 ± 2.48	21.45 ± 4.21	< 0.001
	CNR	1.42 ± 1.28	1.04 ± 0.63	0.26
	SNR	13.27 ± 4.46	6.99 ± 1.88	< 0.001
	FOM	0.21 ± 0.29	0.08 ± 0.08	0.265
Aorta	CT value	398.93 ± 73.54	313.17 ± 51.17	< 0.001
	SD	14.32 ± 3.65	31.87 ± 6.90	< 0.001
	CNR	24.21 ± 8.00	11.76 ± 3.28	< 0.001
	SNR	62.36 ± 19.74	28.41 ± 8.35	< 0.001
	FOM	37.75 ± 30.07	8.83 ± 5.06	< 0.001
Portal venous phase				
Liver	CT value	117.84 ± 22.21	104.9 ± 10.67	< 0.001
	SD	15.34 ± 13.21	21.88 ± 4.43	< 0.001
	CNR	3.48 ± 1.96	1.94 ± 0.87	< 0.001
	SNR	17.37 ± 4.67	9.23 ± 2.06	< 0.001
	FOM	0.77 ± 0.77	0.26 ± 0.16	< 0.001
PV	CT value	228.42 ± 38.15	173.15 ± 20.78	< 0.001
	SD	16.14 ± 3.49	28.33 ± 5.54	< 0.001
	CNR	11.38 ± 4.21	5.04 ± 1.34	< 0.001
	SNR	33.99 ± 9.88	15.2 ± 3.37	< 0.001
	FOM	7.12 ± 6.03	1.56 ± 0.73	< 0.001
Equilibrium phase				
Liver	CT value	102.09 ± 9.59	86.64 ± 7.47	< 0.001
	SD	13.22 ± 2.92	21.63 ± 4.00	< 0.001
	CNR	2.13 ± 0.79	1.15 ± 0.41	< 0.001
	SNR	15.72 ± 3.62	7.74 ± 1.84	< 0.001
	FOM	0.29 ± 0.24	0.08 ± 0.06	< 0.001

Data are the mean ± standard deviation

PV portal vein, *SD* standard deviation, *CNR* contrast-to-noise ratio, *SNR* signal-to-noise ratio, *FOM* figure of merit

Radiation dose

Although the $\mathrm{CTDI}_{\mathrm{vol}}$ in the 70-kVp protocol was significantly higher than in the 120-kVp protocol in the AP (12.4 vs. 11.8, $p = 0.013$), PVP (13.3 vs. 11.5, $p < 0.001$) and EP (12.5 vs. 11.6, $p = 0.014$), the difference in the $\mathrm{CTDI}_{\mathrm{vol}}$ between the two protocols was approximately 1–2 mGy. As a reference regarding the dose efficiency, the FOM values of the liver, aorta and portal vein were significantly better in the 70-kVp protocol than in the 120-kVp protocol in all 3 phases except for the FOM of the liver in the AP. Regarding the $\mathrm{CTDI}_{\mathrm{vol}}$, in the 30 patients with a body weight < 55 kg, there was no significant difference between the 70-kVp and 120-kVp protocols in the AP (11.0 vs. 10.9, $p = 0.66$) or EP (11.2 vs. 10.9, $p = 0.44$).

Qualitative image analyses

The mean values in the qualitative analyses are summarized in Table 2. Inter-observer agreement for the

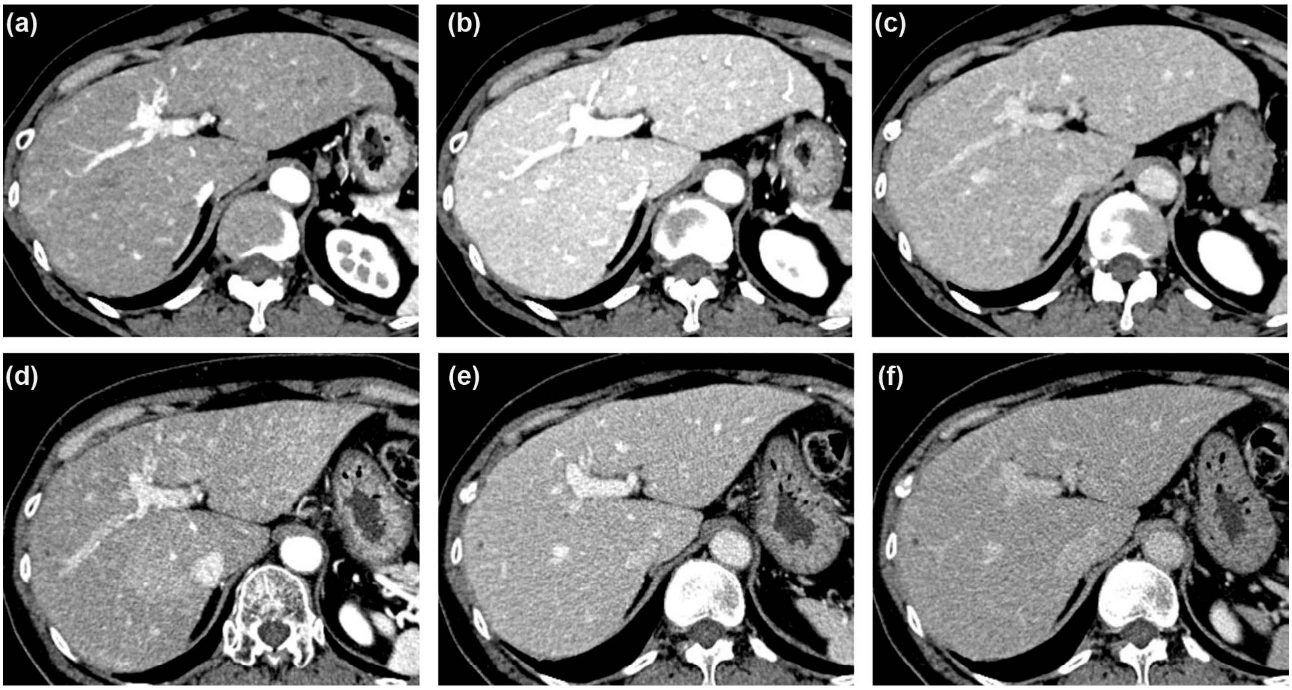

Fig. 1 Comparison of CT images between low-tube-voltage (70 kVp) and standard-tube-voltage (120 kVp) protocol obtained in the same patient. **a**–**c** CT images obtained with low tube voltage (70 kVp) and half-dose iodine load using low-concentration contrast agent during AP (**a**), PVP (**b**) and EP (**c**). **d**–**f** CT images obtained with standard tube voltage (120 kVp) and full-dose iodine load using medium-concentration contrast agent during AP (**d**), PVP (**e**) and EP (**f**). Contrast enhancement of the liver parenchyma and portal vein in PVP and EP, and overall image quality in all 3 phases were better in low tube voltage (70 kVp) protocol than in standard tube voltage (120 kVp)

qualitative analysis was moderate to excellent for both protocols (kappa value: 0.527–0.876). The overall image quality in the 70-kVp protocol was significantly better than in the 120-kVp protocol in all 3 phases (3.67–4.58 vs. 2.76–3.47, $p < 0.001$) (Fig. 1). Similarly, the mean scores for image noise in all phases were significantly better in the 70-kVp protocol than in the 120-kVp protocol (4.0–4.69 vs. 2.96–3.38, $p < 0.001$). Regarding the mean scores for contrast enhancement of the renal cortex and pancreas in the AP as well as the liver parenchyma and portal vein in the PVP, significantly higher scores were assigned in the 70-kVp protocol than in the 120-kVp protocol ($p < 0.001$ for all). In addition, the contrast enhancement scores of the liver parenchyma and hepatic vein in the EP were also significantly higher in the 70-kVp protocol than in the 120-kVp protocol (3.78 vs. 2.87, $p < 0.001$, 3.60 vs. 2.72, $p < 0.001$).

Regarding clarity in contrast between the liver parenchyma and portal vein in the PVP and between the liver parenchyma and hepatic vein in the EP, the 70-kVp protocol showed higher scores than the 120-kVp protocol (4.70 vs. 3.57, $p < 0.001$, 3.25 vs. 2.40, $p < 0.001$). The mean score for the visibility of peripheral branches of hepatic vessels in the PVP differed significantly between the 70-kVp and 120-kVp protocols (4.01 vs. 2.81, $p < 0.001$) (Fig. 2).

Discussion

Iodinated CM is widely recognized to have toxic effects on renal cells, carrying a risk of causing acute deterioration of the renal function after contrast-enhanced CT [15, 16]. Although the precise mechanisms underlying CIN remain unclear, a combination of renal medullary hypoxia resulting from renal vasoconstriction and direct renal tubular toxicity of CM as well as glomerular vascular endothelial cell injury induced by CM have been implicated in the pathogenesis [17]. Recently, some studies showed that the rate of acute kidney injury in patients who underwent contrast-enhanced CT was similar to that who underwent unenhanced CT, and raised question about whether CIN after contrast-enhanced CT has been overstated [18–20]. Although the true risk for nephrotoxicity after contrast-enhanced CT is still controversial, it appears certain that the use of the lowest iodine dose of CM possible will be recommended to reduce the risk of CIN in contrast-enhanced CT. For multiphasic dynamic CT of the abdomen, the use of an insufficient CM iodine dose can result in ineffective contrast enhancement, especially in the PVP and EP, hampering the accurate diagnosis of lesions in solid organs, particularly the liver, pancreas and kidney. Conversely, excessive CM iodine dose can lead to an unnecessary increase in the cost and risks of organ

Table 2 Qualitative analysis in the comparison of mean scores between low-tube-voltage (70 kVp) and standard-tube-voltage (120 kVp) protocol

	70 kVp	120 kVp	*p* value
Arterial phase			
Contrast enhancement			
Aorta	4.98 ± 0.13	4.98 ± 0.13	NS
Renal cortex	4.76 ± 0.57	4.43 ± 0.68	< 0.001
Pancreas	3.61 ± 0.77	3.05 ± 0.58	< 0.001
Image noise	4.58 ± 0.52	3.36 ± 0.64	< 0.001
Overall image quality	4.40 ± 0.77	3.47 ± 0.59	< 0.001
Portal venous phase			
Contrast enhancement			
Liver	4.25 ± 0.66	3.41 ± 0.49	< 0.001
PV	4.70 ± 0.56	3.61 ± 0.52	< 0.001
Contrast between PV and liver	4.70 ± 0.62	3.57 ± 0.56	< 0.001
Visibility of peripheral vessels	4.01 ± 0.94	2.81 ± 0.78	< 0.001
Image noise	4.69 ± 0.49	3.38 ± 0.61	< 0.001
Overall image quality	4.58 ± 0.59	3.40 ± 0.55	< 0.001
Equilibrium phase			
Contrast enhancement			
Liver	3.78 ± 0.52	2.87 ± 0.33	< 0.001
Hepatic vein (HV)	3.60 ± 0.67	2.72 ± 0.86	< 0.001
Contrast between HV and liver	3.25 ± 0.76	2.40 ± 0.82	< 0.001
Image noise	4.00 ± 0.42	2.96 ± 0.46	< 0.001
Overall image quality	3.67 ± 0.50	2.76 ± 0.50	< 0.001

Data are the mean ± standard deviation

PV portal vein

parenchymal toxicity [21, 22]. Thus, the ideal CM iodine dose must be determined to prevent renal injury and obtain a precise diagnosis.

This study showed that the mean CT values and CNR and SNR of the aorta in the AP were significantly higher in the 70-kVp protocol than in the 120-kVp protocol. Furthermore, the mean scores for contrast enhancement of the renal cortex and pancreas in the AP were significantly higher in the 70-kVp protocol than in the 120-kVp protocol. These findings suggested that sufficient arterial enhancement of hypervascular organs in abdominal CT can be achieved by half-dose iodine CM in the 70-kVp protocol. Low-tube-voltage CT improves the effect of the iodinated contrast agent, since the mass attenuation coefficient of iodine increases as the X-ray energy is reduced [13, 23]. Similar results have been reported in studies of CT angiography for the evaluation of the aorta [24] or transcatheter aortic valve implantation (TAVI) [13, 25].

Conversely, there has been concern that contrast enhancement of low-contrast structures, such as the liver parenchyma and the hepatic veins, might be deteriorated in the PVP and EP of abdominal CT because of the reduced total iodine dose of CM, even when using a low tube voltage (70 kVp). However, in the present study, the mean CT values and CNR and SNR of the liver parenchyma in the PVP and even the EP were significantly higher in the 70-kVp protocol, than in the 120-kVp protocol. Furthermore, the mean scores for contrast enhancement of the liver parenchyma, portal vein and hepatic vein in the PVP and EP were significantly higher in the 70-kVp protocol than in the 120-kVp protocol. These results suggested that the iodine dose of CM could be reduced by 50% for the satisfactory enhancement of the liver parenchyma using the low-tube-voltage (70 kVp) protocol. In clinical practice, the visualization of "washout" as a hallmark of hypervascular HCC, the detection of hypovascular HCC based on increased enhancement of background liver parenchyma and the demonstration of fibrotic components with delayed enhancement in cholangiocarcinoma are important roles of EP imaging. Therefore, further studies will be necessary to validate the utility of low-tube-voltage (70 kVp) CT in EP imaging for these clinical requirements.

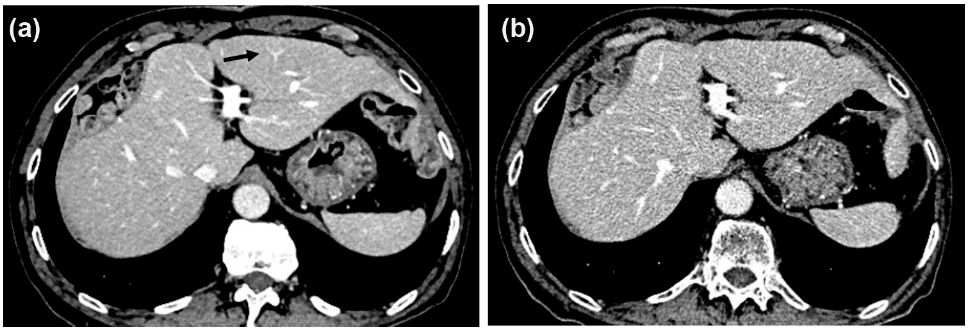

Fig. 2 Comparison of visualization of intrahepatic peripheral vessels between low-tube-voltage (70 kVp) and standard-tube-voltage (120 kVp) protocol obtained in the same patient. **a** CT image obtained with low tube voltage (70 kVp) and half-dose iodine load using low-concentration contrast agent during PVP. **b** CT image obtained with standard tube voltage (120 kVp) and full-dose iodine load using medium-concentration contrast agent during PVP. Visibility of peripheral branches of hepatic vessels (arrow) in the PVP CT was better in low-tube-voltage (70 kVp) protocol than in standard tube voltage (120 kVp)

In this study, we reduced the iodine dose (half dose = 300 mgI/kg) by using low-concentration CM (140 mgI/mL) instead of high- or medium-concentration CM (370 mgI/mL or 300 mgI/mL) for the low-tube-voltage (70 kVp) protocol. Consequently, the total injection volume and injection rate of CM in the 70-kVp protocol were almost the same as for the 120-kVp protocol. This means that we can apply the established routine method of contrast injection for low-tube-voltage (70 kVp) and half-dose iodine load abdominal CT. In addition, low-concentration CM (140 mgI/mL) is iso-osmotic to plasma, whereas medium-concentration CM (300 mgI/mL) is hyperosmotic, with its osmolality being about twice that of plasma. The osmotic pressure of contrast agent plays a role in the pathogenesis of CIN, and hyperosmolality can lead to renal vasoconstriction, osmotic diuresis, and renal ischemia [26]. Therefore, the use of low-concentration CM (140 mgI/mL) with iso-osmolality is reasonable and recommended for half-dose iodine load and low-tube-voltage (70 kVp) CT of the abdomen.

One common disadvantage of low-tube-voltage CT has been an increase in the background image noise and decreased overall image quality. However, in the present study, the SNR, CNR, image noise and overall image quality in quantitative and qualitative analyses were significantly better in the 70-kVp protocol than in the 120-kVp protocol. This result can be attributed to the fact that a high-tube-current output and iterative reconstruction algorithm were used for the 70-kVp protocol, whereas the standard-tube-current output and filtered back projection algorithm were used for the 120-kVp protocol because of the limited tube performance and availability of reconstruction software [27]. Regarding the SNR, CNR, image noise and the overall image quality, the use of an iterative reconstruction algorithm for both protocols may produce different results, requiring further evaluation in the next step although the CT value and contrast enhancement might not be affected.

Several limitations associated with the present study warrant mention. First, the number of patients was relatively small because this study was limited to the patients who underwent CT under both the 70-kVp and 120-kVp protocols and who weighed less than 71 kg, considering the known impact of a larger body size on the low-tube-voltage (70 kVp) CT image quality. Second, our study showed that the $\mathrm{CTDI}_{\mathrm{vol}}$ values at 70 kVp were slightly but significantly higher than those at 120 kVp, due to the automatic mAs calculation based on the default setting, although the FOMs were significantly better with the 70-kVp protocol. Therefore, there is a scope for careful adjustment in automated tube current algorithm if reduction in the radiation dose is desired. However, an increased $\mathrm{CTDI}_{\mathrm{vol}}$ at 80 kVp has been reported in a previous phantom study compared with that at 120 kVp [8]. A previous clinical study also showed that the average $\mathrm{CTDI}_{\mathrm{vol}}$ increased by about 6 mGy in the low-tube-voltage (70–80 kVp) group [14]. In addition, the $\mathrm{CTDI}_{\mathrm{vol}}$ at 70 kVp in this study was less than the diagnostic reference level (DRL) proposed for abdominal CT (15 mGy) [28], although the substantial radiation dose needs to be balanced against the advantages of a reduced CM iodine dose. Finally, we did not attempt to assess the diagnostic accuracy of the low-tube-voltage (70 kVp) CT protocol in the detection of hepatic lesions as we primarily focused on the contrast enhancement and image quality. However, more suitable patients should be involved in future studies to evaluate the diagnostic performance of the low-tube-voltage (70 kVp) CT protocol for hepatic lesions.

In conclusion, a low tube voltage (70 kVp) in combination with a half-dose iodine load using a low-concentration contrast agent and an iterative reconstruction algorithm in high tube output dual-source CT may improve the contrast enhancement and image quality in multiphasic (arterial, portal and equilibrium phases) dynamic CT of the abdomen in patients under 71 kg of body weight although the patients should be carefully selected for this technique without generalization in terms of body size.

References

1. McDonald JS, McDonald RJ, Carter RE, Katzberg RW, Kallmes DF, Williamson EE. Risk of intravenous contrast material-mediated acute kidney injury: a propensity score-matched study stratified by baseline-estimated glomerular filtration rate. Radiology. 2014;271(1):65-73.
2. Launay-Vacher V, Oudard S, Janus N, et al. Prevalence of Renal Insufficiency in cancer patients and implications for anticancer drug management: the renal insufficiency and anticancer medications (IRMA) study. Cancer. 2007;110(6):1376-84.
3. Garcia-Compean D, Jaquez-Quintana JO, Maldonado-Garza H. Hepatogenous diabetes. Current views of an ancient problem. Annals of Hepatology. 2009;8(1):13–20.
4. Stacul F, van der Molen AJ, Reimer P, et al. Contrast induced nephropathy: updated ESUR Contrast Media Safety Committee guidelines. European radiology. 2011;21(12):2527-41.
5. Cicin I, Erdogan B, Gulsen E, et al. Incidence of contrast-induced nephropathy in hospitalised patients with cancer. European radiology. 2014;24(1):184-90.
6. Hunsaker AR, Oliva IB, Cai T, et al. Contrast opacification using a reduced volume of iodinated contrast material and low peak kilovoltage in pulmonary CT angiography: Objective and subjective evaluation. AJR American journal of roentgenology. 2010;195(2):W118-24.
7. Huda W. Dose and image quality in CT. Pediatric radiology. 2002;32(10):709–13; discussion 51–4.
8. Thor D, Brismar TB, Fischer MA. Low tube voltage dual source computed tomography to reduce contrast media doses in adult abdomen examinations: A phantom study. Medical physics. 2015;42(9):5100-9.
9. Schindera ST, Nelson RC, Mukundan S, Jr., et al. Hypervascular liver tumors: low tube voltage, high tube current multi-detector row CT for enhanced detection--phantom study. Radiology. 2008;246(1):125-32.
10. Noda Y, Kanematsu M, Goshima S, et al. Reducing iodine load in hepatic CT for patients with chronic liver disease with a

combination of low-tube-voltage and adaptive statistical iterative reconstruction. European journal of radiology. 2015;84(1):11-8.

11. Botsikas D, Barnaure I, Terraz S, Becker CD, Kalovidouri A, Montet X. Value of liver computed tomography with iodixanol 270, 80 kVp and iterative reconstruction. World journal of radiology. 2016;8(7):693-9.
12. Araki K, Yoshizako T, Yoshida R, Tada K, Kitagaki H. Low-voltage (80-kVp) abdominopelvic computed tomography allows 60% contrast dose reduction in patients at risk of contrast-induced nephropathy. Clinical imaging. 2018;51:352-5.
13. Onoda H, Ueno H, Hashimoto M, Kuwahara H, Sobajima M, Kinugawa K. Clinical Advantages of Using Low Tube Voltage in Third-Generation 192-Slice Dual-Source Computed Tomographic Angiography Before Transcatheter Aortic Valve Implantation. International heart journal. 2019;60(5):1091-7.
14. Svensson A, Thor D, Fischer MA, Brismar T. Dual source abdominal computed tomography: the effect of reduced X-ray tube voltage and intravenous contrast media dosage in patients with reduced renal function. Acta radiologica (Stockholm, Sweden : 1987). 2019;60(3):293–300.
15. Peer A, Averbukh Z, Berman S, Modai D, Averbukh M, Weissgarten J. Contrast media augmented apoptosis of cultured renal mesangial, tubular, epithelial, endothelial, and hepatic cells. Invest Radiol. 2003;38(3):177-82.
16. Romano G, Briguori C, Quintavalle C, et al. Contrast agents and renal cell apoptosis. Eur Heart J. 2008;29(20):2569-76.
17. Persson PB, Tepel M. Contrast medium-induced nephropathy: the pathophysiology. Kidney Int Suppl. 2006(100):S8-10.
18. Rudnick MR, Leonberg-Yoo AK, Litt HI, Cohen RM, Hilton S, Reese PP. The Controversy of Contrast-Induced Nephropathy With Intravenous Contrast: What Is the Risk? Am J Kidney Dis. 2020;75(1):105–13.
19. Luk L, Steinman J, Newhouse JH. Intravenous Contrast-Induced Nephropathy-The Rise and Fall of a Threatening Idea. Adv Chronic Kidney Dis. 2017;24(3):169-75.
20. McDonald RJ, McDonald JS, Newhouse JH, Davenport MS. Controversies in Contrast Material-induced Acute Kidney Injury: Closing in on the Truth? Radiology. 2015;277(3):627-32.
21. Onishi H, Murakami T, Kim T, et al. Abdominal multi-detector row CT: effectiveness of determining contrast medium dose on basis of body surface area. European journal of radiology. 2011;80(3):643-7.
22. Kalra MK, Woisetschlager M, Dahlstrom N, et al. Radiation dose reduction with Sinogram Affirmed Iterative Reconstruction technique for abdominal computed tomography. J Comput Assist Tomogr. 2012;36(3):339-46.
23. Joemai RM, Geleijns J, Veldkamp WJ. Development and validation of a low dose simulator for computed tomography. European radiology. 2010;20(4):958-66.
24. Higashigaito K, Schmid T, Puippe G, et al. CT Angiography of the Aorta: Prospective Evaluation of Individualized Low-Volume Contrast Media Protocols. Radiology. 2016;280(3):960-8.
25. Schoenhagen P, Hausleiter J, Achenbach S, Desai MY, Tuzcu EM. Computed tomography in the evaluation for transcatheter aortic valve implantation (TAVI). Cardiovasc Diagn Ther. 2011;1(1):44-56.
26. Sharma SK, Kini A. Effect of nonionic radiocontrast agents on the occurrence of contrast-induced nephropathy in patients with mild-moderate chronic renal insufficiency: pooled analysis of the randomized trials. Catheter Cardiovasc Interv. 2005;65(3):386-93.
27. Marin D, Nelson RC, Schindera ST, et al. Low-tube-voltage, high-tube-current multidetector abdominal CT: improved image quality and decreased radiation dose with adaptive statistical iterative reconstruction algorithm--initial clinical experience. Radiology. 2010;254(1):145-53.
28. Yonekura Y. Diagnostic reference levels based on latest surveys in Japan. Report from Japan network for research and information on medical exposure (J-RIME). 2015:1–11.