

CT Venography for Deep Vein Thrombosis Using a Low Tube Voltage (100 kVp) Setting Could Increase Venous Enhancement and Reduce the Amount of Administered Iodine

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Objective: To investigate the validity of the 100 kVp setting in CT venography (CTV) in the diagnosis of deep vein thrombosis (DVT), and to evaluate the feasibility of reducing the amount of administered iodine in this setting.

Materials and Methods: After receiving the contrast medium (CM) of 2.0 mL/kg, 88 patients underwent CTV of the pelvis and lower extremities by using one of four protocols: Group A, 120 kVp setting and 370 mgI/mL CM; group B, 120 kVp and 300 mgI/mL; group C, 100 kVp and 370 mgI/mL; group D, 100 kVp and 300 mgI/mL. The groups were evaluated for venous attenuation, vein-to-muscle contrast-to-noise ratio (CNR_{VEIN}), DVT-to-vein contrast-to-noise ratio (CNR_{DVT}), and subjective degree of venous enhancement and image quality.

Results: Venous attenuation and CNR_{VEIN} were significantly higher in group C (144.3 Hounsfield unit [HU] and 11.9), but there was no significant difference between group A (118.0 HU and 8.2) and D (122.4 HU and 7.9). The attenuation value of DVT was not significantly different among the four groups, and group C had a higher absolute CNR_{DVT} than the other groups. The overall diagnostic image quality and venous enhancement were significantly higher in group C, but there was no difference between groups A and D.

Conclusion: The 100 kVp setting in CTV substantially help improve venous enhancement and CNR_{VEIN} . Furthermore, it enables to reduce the amount of administered iodine while maintaining venous attenuation, as compared with the 120 kVp setting.

Index terms: CT venography; Deep vein thrombosis; Low tube voltage; Contrast medium; Contrast enhancement

INTRODUCTION

Deep venous thrombosis (DVT) of the lower extremities is a common and serious clinical condition worldwide. It is

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often asymptomatic and therefore can remain undetected until a patient develops a life-threatening pulmonary embolism (1). Accurate diagnosis of DVT is therefore essential for quick and appropriate treatment.

Duplex sonography is commonly used to investigate patients with suspected DVT. Indirect computed tomography venography (CTV) has increasingly been used for the diagnosis of DVT as a rapid and available alternative to sonography. In previous studies, 89-100% sensitivity and 94-100% specificity of CTV were reported in the detection of DVT of the pelvis and lower extremities (2-5). CTV is superior to sonography in depicting DVT in the pelvis and inferior vena cava (6).

The degree of venous enhancement on CTV is important for DVT detection. To increase vascular attenuation in CT angiography, advanced contrast medium (CM) injection

protocols such as bolus-tracking or test-bolus methods are common. However, determining the period of peak enhancement is difficult in the venous system. Therefore, CTV is usually scanned in the equilibrium phase after injection of CM (2, 4, 7-13). A high concentration of iodine CM or a larger volume of CM must be used to increase venous attenuation in CTV (14).

A low tube voltage CTV protocol is a promising alternative method for increasing venous attenuation without increasing the amount of intravascular iodine. The use of a low tube voltage protocol in CT leads to higher attenuation levels for iodine due to the increased photoelectric effect (15). Recently, the application of low tube voltages for CT angiography has increased since this technique reduces patient radiation exposure and CM volume through increasing the vascular attenuation value (16-18). Recently, using low tube voltage (80 or 100 kVp) protocols for lower extremity CTV showed significantly higher venous attenuation compared to the conventional 120 kVp protocol (19-21). However, to our knowledge, the efficacy of a lower tube voltage protocol for the evaluation of DVT in the pelvis and lower extremities has not been analyzed.

We hypothesized that a lower tube voltage CTV protocol could improve the diagnostic accuracy of DVT through increased attenuation of the venous system. In addition, we hypothesized that this protocol might reduce the amount of administered intravenous iodine through the use of a lower iodine concentration CM or by decreasing the CM dose. Therefore, the purpose of our study was twofold: first, we prospectively investigated the validity of a low tube voltage (100 kVp) CTV protocol for the evaluation of DVT compared to the conventional 120 kVp CT; second, we evaluated the feasibility of reducing intravenous iodine administration using a moderate concentration of iodine CM (MC-CM) instead of a high concentration CM (HC-CM) when a lower tube voltage protocol was applied.

MATERIALS AND METHODS

We performed a phantom study to compare the attenuation values and contrast-to-noise ratios (CNR) of two different iodine concentration CMs (HC-CM and MC-CM) on two different tube voltage protocols (120 and 100 kVp) before conducting the clinical study. This enabled us to quantify the increase in enhancement in different settings. Subsequently, four groups of patients who were scheduled to undergo CTV for the evaluation of DVT in the lower

extremities were included in the clinical study to compare venous enhancement and image quality with two different CM iodine concentrations and two different tube voltage protocol settings.

Phantom Study

In clinical practice, CTV usually scans from the upper abdomen or pelvis to the knees or feet (3, 4, 8, 9, 11-13). Therefore, we used a 300 mm-diameter cylindrical water phantom to simulate the abdomen of patients with intermediate body weight (estimated body weight, 72-85 kg) (22, 23). A 25 mm-diameter tube filled with diluted CM was inserted into the center of the phantom (Fig. 1A). We prepared 13 different CM dilutions (0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 3.0, 4.0, and 5.0%) by diluting CMs with two different iodine concentrations (HC-CM: Iopromide 370 mg iodine/mL, Prosure 370; MC-CM: Iopromide 300 mgI/mL, Prosure 300, LG Life Sciences, Seoul, Korea) with distilled water.

We used two tube voltages (120 and 100 kVp) and chose effective tube current-time products so that the phantom volume CT dose index ($CTDI_{vol}$) was 9.8 mGy for both protocols. This was achieved using a pitch of 1.0, a rotation time of 0.5 s, a field of view of 200 mm, and 200 effective mAs (mAs_{eff}) with 100 kVp and 128 mAs_{eff} with 120 kVp. Thus, HC-CM and MC-CM with a tube voltage of 120 or 100 kVp were applied in the phantom study.

We measured the attenuation value of diluted CM using a 100 mm² region of interest (ROI) in the center of the tube. Image noise was defined as the average of the standard deviations (SDs) of Hounsfield units (HUs) measured at the center of the tube and at 0-, 3-, 6-, and 9-o'clock positions of equidistant levels along the z-axis of the cylindrical water phantom. CNR of the tube filled with diluted CM was calculated using following formula: $CNR = (\text{mean attenuation value of the tube} - \text{attenuation value of the water phantom}) / \text{image noise}$. The mean attenuation and CNR of the tube in the phantom were plotted against the CM dilutions. Data were analyzed by linear regression analysis and Pearson's correlation coefficients.

Patients

The Institutional Review Board approved the study, and written informed consent was obtained from all patients. We selected patients who were referred for CTV of the lower extremities for suspicion of DVT and those who agreed to enroll in this study. Patients who were expected to have

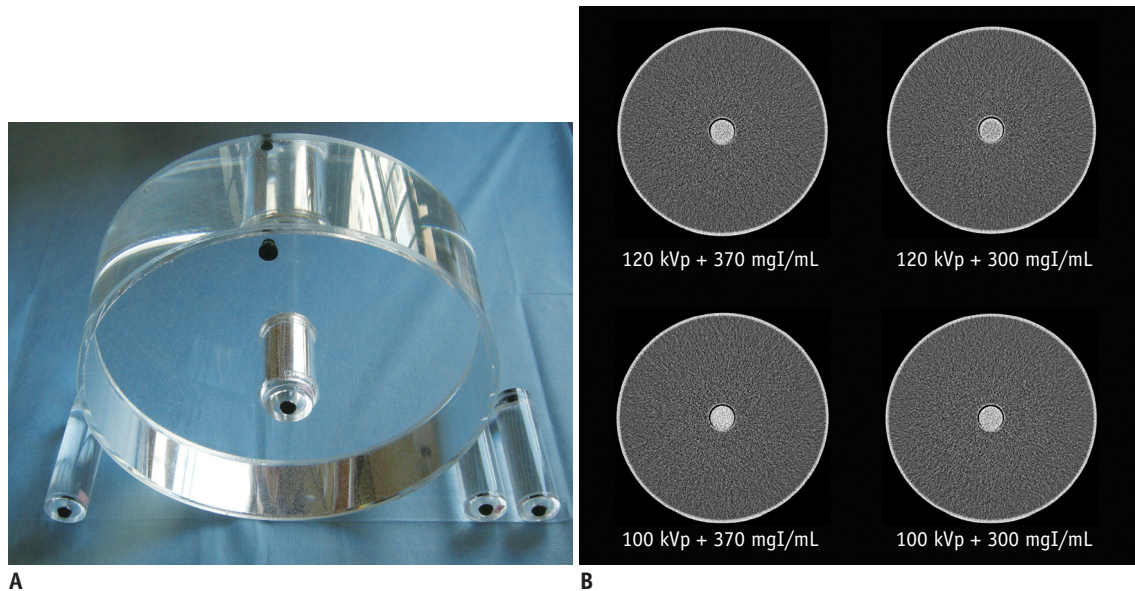


Fig. 1. Cylindrical water phantom and CT images of phantom.

A. 300 mm-diameter cylindrical water phantom simulated abdomen of patients with intermediate body weight. 25 mm-diameter tube filled with diluted contrast medium (CM) was inserted into center of phantom. **B.** Transverse 1 mm CT scans of phantom obtained at 120 kVp with 1.4% 370 mgI/mL CM, 120 kVp with 1.4% 300 mgI/mL CM, 100 kVp with 1.4% 370 mgI/mL CM, and 100 kVp with 1.4% 300 mgI/mL CM. 1.4% concentration of CM in tube resulted in mean CT attenuation values most similar to those obtained for CT venography in clinical studies (113.0 Hounsfield unit (HU) in 120 kVp with 370 mgI/mL CM, 94.2 HU in 120 kVp with 300 mgI/mL CM, 145.0 HU in 100 kVp with 370 mgI/mL CM, and 116.0 HU in 100 kVp with 300 mgI/mL CM).

severe beam-hardening artifacts from a metallic prosthesis were not included. Finally, we included 88 consecutive patients from a single institution. All patients were randomly assigned to one of four CTV protocols: Group A (120 kVp and HC-CM setting), Group B (120 kVp and MC-CM setting), Group C (100 kVp and HC-CM setting), and Group D (100 kVp and MC-CM setting).

Imaging Techniques

All CT examinations were performed using a 64-channel multidetector row CT scanner (Somatom Sensation 64; Siemens Medical Solutions, Erlangen, Germany) using real-time automatic tube current modulation software (CARE Dose 4D). The tube voltage for groups A and B was 120 kVp, and the quality reference tube current time product was set at 128 mAs. The tube energy was 100 kVp for groups C and D, and the quality reference tube current time product was 220 mAs. Scanning parameters for both protocols were 64 x 0.6 mm slice acquisition using a z-flying focal spot technique, a gantry rotation time of 0.5 seconds with a pitch of 1.0. The expected CTDI_{vol} of both protocols was 9.8 mGy. The scanning volume extended from the upper pole of the right kidney to the foot, and images were reconstructed using a section thickness of 3.0 mm without overlap.

On the CT table, extra support was provided for the heels

to prevent direct contact between the lower extremities and the CT table. CM at 2.0 mL/kg (maximum 150 mL) was injected with a power injector (Dual shot, Nemoto Kyorindo, Tokyo, Japan) over 50 seconds via an 18- or 20-gauge cannula placed in the antecubital vein of the arm. In groups A and C, HC-CM (Iopromide 370 mgI/mL, Prosure 370, LG Life Sciences, Seoul, Korea) was used. In groups B and D, MC-CM (Iopromide 300 mgI/mL, Prosure 300, LG Life Sciences, Seoul, Korea) was injected. Therefore, compared to groups A and C, 18.9% less iodine was administered to groups B and D. For example, if a patient weighed 75 kg, 55.5 g of iodine (370 mgI/mL x 150 mL) was injected in groups A and C, and 45.0 g of iodine (300 mgI/mL x 150 mL) was injected in groups B and D. A maximum of 10.5 g of iodine was reduced per patient in groups B and D. CTV was performed three minutes after administration of CM to produce near-optimum enhancement in the veins of the lower extremities (24).

Quantitative Image Analysis

For quantitative evaluation, attenuation (in HU) was measured in the veins of the pelvis and lower extremities. ROIs were carefully drawn to be the same diameter as the vessel lumen, omitting the outline of the vessel lumen to avoid partial volume effects (range of ROI size: 6.4-229.0

mm²) at the inferior vena cava (IVC), external iliac vein, femoral vein, and popliteal vein. These were measured at the level as the L4 vertebral body, the inferior margin of the sacroiliac joint, the greater trochanter of the femur, and the medial epicondyle of the femur, respectively. All measurements were performed by a board-certified radiologist with 5 years of experience in interpreting CTV. To quantify the attenuation differences with related surrounding tissues, muscle attenuation next to the IVC, external iliac vein, femoral vein and popliteal vein were measured using 100-300 mm² on the psoas, iliopsoas, iliacus and semimembranosus muscles at the same level of venous attenuation measurements. Image noise was defined as the SD of attenuation value measured within the surrounding air (25), which was measured at the same level as venous attenuation. The vein-to-muscle CNR (CNR_{VEIN}) was calculated using the formula (20, 26): $CNR_{VEIN} = (\text{mean venous attenuation value} - \text{muscle attenuation value}) / \text{image noise}$.

The mean DVT attenuation value was measured and recorded. In cases of two or more DVTs in a single patient, the attenuation level in the largest DVT was recorded. The DVT-to-vein CNR (CNR_{DVT}) was calculated using the formula: $CNR = (\text{mean attenuation value of DVT} - \text{adjacent venous attenuation value}) / \text{image noise}$. If DVT was in a short segment, venous attenuation value was measured in an adjacent normal vein. If DVT was in a long segment, venous attenuation value was measured in a contralateral non-thrombus normal vein. To minimize bias due to a single measurement, measurements were obtained three times for each venous system, image noise, muscle, and DVT. The mean of these values was used for calculations.

Qualitative Image Analysis

Two radiologists with 9 and 4 years of experience in extremity vascular imaging evaluated axial 3 mm-thickness CTV images on a picture archiving and communication systems workstation (Centricity RA1000, GE Healthcare, Milwaukee, WI, USA). Multiplanar reformations were not used for interpretation. CT datasets were randomized and the readers were blinded to the technical scanning parameters. To reduce interobserver variation, before starting the assessment, the readers were instructed on the criteria of image grading and assessed five additional test cases that were not included in the study. A window level of 50 and a width of 400 were fixed during the qualitative assessment of axial images to compare the differences

among the four patient groups.

The evaluation sheets used for qualitative image analysis were specially designed and contained two parts. In the first section, the observers independently assessed the contrast enhancement of the veins at the pelvis, thigh and calf using a three-point scale: 1, poor, attenuation of venous system similar to or less than adjacent muscle; 2, fair, venous enhancement slightly higher than adjacent muscular enhancement; and 3, good, venous enhancement greater than muscular enhancement. Image noise was recorded at the level of the pelvis, thigh, and calf using a three-point Scale: 1, major or substantial, impossible or difficult to diagnose; 2, moderate, acceptable; and 3, minor or no graininess.

Four weeks after the first section, the presence and location (femoral, popliteal, or iliac vein or inferior vena cava) of thrombi were analyzed and recorded by consensus. Thrombi were defined as low-attenuating partial or complete filling defects surrounded by enhanced blood seen on at least two consecutive axial images. The readers individually rated the overall diagnostic image quality for DVT using a three-point Scale: 1, substandard image quality and unsuitable visualization of DVT due to insufficient venous enhancement; 2, standard image quality and fair contrast difference between DVT and the enhanced venous system; and 3, excellent image quality and vivid visualization of DVT with fine venous enhancement.

Dose Calculation

Volume CT dose index and dose length product (DLP) provided by the CT scanner after scanning were recorded for each patient (26).

Statistical Analysis

All statistical analyses were performed using dedicated statistical software (SPSS 12.0; SPSS, Chicago, IL, USA). All data were tested for normality using Shapiro-Wilk tests and for equality of variances using Levene's tests. For data with normal distribution and equal variances, one-way analysis of variance with Scheffé post-hoc tests were used to compare the values among the four protocols. Differences were considered significant when a *p* value was less than 0.05. For data with nonnormal distribution or unequal variance, nonparametric Kruskal-Wallis tests were used. For multiple comparisons of nonparametric values, Mann-Whitney test and Bonferroni correction were applied. Bonferroni correction was applied to assess possible significance, with

a p value of $< 0.05 \times 2 / n (n-1)$, where n = the number of groups. The linear-weighted kappa statistic was used to assess interreader agreement in scoring and was interpreted using the guidelines of Landis and Koch (27).

RESULTS

Phantom Study

The mean attenuation values and CNR of the tube filled with diluted CM were increased as the tube voltage decreased from 120 to 100 kVp and as the CM iodine concentration increased from 300 to 370 mgI/mL (Fig. 2). For the 100 kVp protocol, the mean CT attenuation value was 28.5% higher and the CNR was 19.1% higher than the values of the 120 kVp protocol. For HC-CM, the mean CT attenuation value was 20.2% higher and CNR was 21.9% higher than those for MC-CM for both protocols. The 100 kVp protocol with MC-CM had a 7.1% higher mean CT

attenuation value and a 2.2% lower mean CNR than the values of the 120 kVp protocol with HC-CM (Fig. 1B).

Clinical Study

The four protocol groups had no significant differences in age, sex, height, weight, or body mass index (Table 1). Thus, further analysis and comparisons of attenuation measurements and radiation exposure were considered to be feasible and valid.

The attenuation value of the veins was measured in the IVC ($n = 88$), right external iliac vein ($n = 79$), left external iliac vein ($n = 60$), right femoral vein ($n = 79$), left femoral vein ($n = 60$), right popliteal vein ($n = 78$), and left popliteal vein ($n = 72$). Out of a total of 616 veins (seven veins per 88 patients), 102 could not be measured because of DVT (Table 2).

The mean attenuations of the measured veins and CNR_{VEIN} were 118.6 ± 13.9 HU and 8.3 ± 4.4 in group A, $105.5 \pm$

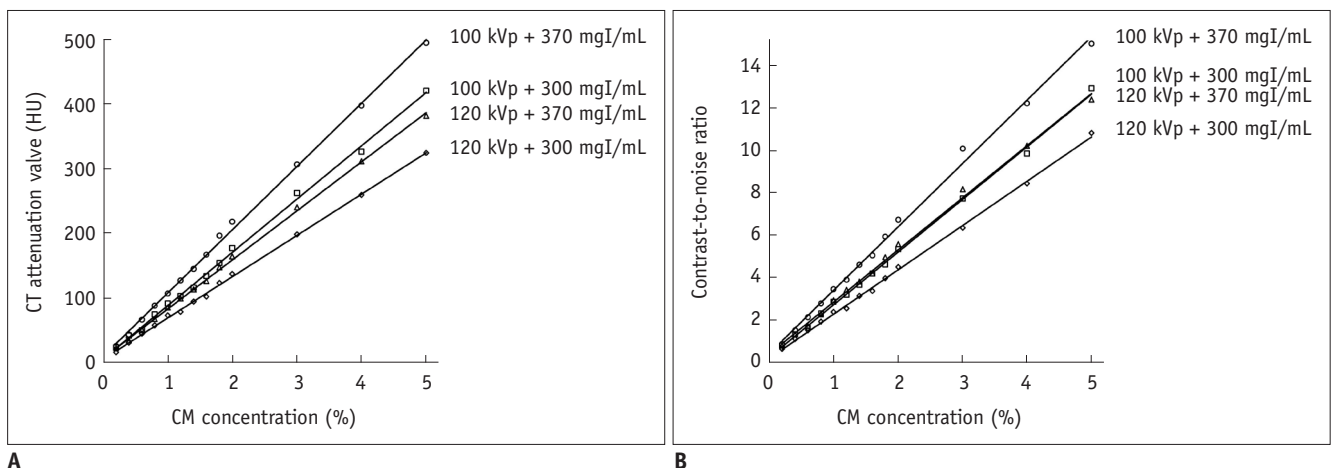


Fig. 2. Graphs showing results of phantom study.

A. Relationship between CT attenuation value and contrast medium (CM) concentration was: for 100 kVp with high concentration CM (HC-CM), $y = 97.7x + 10.3$ ($r = 0.999$); for 100 kVp with moderate concentration CM (MC-CM), $y = 82.2x + 6.4$ ($r = 0.998$); for 120 kVp with HC-CM, $y = 75.7x + 7.8$ ($r = 0.999$); and for 120 kVp with MC-CM, $y = 63.7x + 5.7$ ($r = 0.999$). **B.** Relationship between contrast-to-noise ratio (CNR) and CM concentration was: for 100 kVp with HC-CM, $y = 3.0x + 0.5$ ($r = 0.996$); for 100 kVp with MC-CM, $y = 2.5x + 0.3$ ($r = 0.998$); for 120 kVp with HC-CM, $y = 2.5x + 0.4$ ($r = 0.997$); and for 120 kVp with MC-CM, $y = 2.1x + 0.3$ ($r = 0.999$).

Table 1. Patient Characteristics

Characteristic	Group A	Group B	Group C	Group D	P
Age (years)	57.7 ± 18.3	59.8 ± 15.7	61.2 ± 13.0	59.4 ± 13.7	0.896*
Gender (male/female)	9/12	12/10	10/13	13/9	0.642*
Height (cm)	161.5 ± 11.1	164.6 ± 9.1	158.2 ± 8.3	156.9 ± 22.6	0.305*
Weight (kg)	60.8 ± 16.4	64.9 ± 14.8	59.2 ± 9.4	64.3 ± 11.9	0.447 [†]
BMI (kg/m^2)	21.3 ± 6.7	23.7 ± 3.8	23.7 ± 3.6	29.7 ± 22.4	0.186*

Note.— Data are means \pm standard deviations. *Kruskal-Wallis test and [†]One-way analysis of variance were used to compare values among four groups, and differences were considered significant when p was less than 0.05. Group A = 120 kVp setting and 370 mgI/mL contrast administration, Group B = 120 kVp and 300 mgI/mL, Group C = 100 kVp and 370 mgI/mL, Group D = 100 kVp and 300 mgI/mL. BMI = body mass index

Table 2. Numbers, Mean Attenuation Values, and Contrast-to-Noise Ratios (CNRs) of Measured Veins and DVTs and Radiation Exposure in CT Venography of Pelvis and Lower Extremities

	Group A	Group B	Group C	Group D	P
Number of vein/DVT					
IVC	21/0	22/0	21/2	22/0	-
REIV	17/4	21/1	21/2	20/2	-
LEIV	15/6	13/9	15/8	17/5	-
RFV	17/4	21/1	22/1	19/3	-
LFV	19/2	10/12	15/8	16/6	-
RPV	16/5	22/0	21/2	19/3	-
LPV	18/3	19/3	16/7	19/3	-
Total	123/24	128/26	131/30	132/22	-
Venous attenuation (HU)					
IVC	128.1 ± 15.9	110.0 ± 11.9	152.4 ± 15.3	130.9 ± 7.6	< 0.001*
REIV	122.3 ± 16.4	106.2 ± 10.8	145.2 ± 16.9	123.2 ± 10.1	< 0.001*
LEIV	109.9 ± 31.4	100.4 ± 11.9	140.6 ± 14.1	125.2 ± 11.0	< 0.001 [†]
RFV	119.1 ± 16.5	104.6 ± 13.6	146.4 ± 18.6	121.9 ± 13.4	< 0.001 [†]
LFV	113.0 ± 17.5	100.6 ± 9.4	143.2 ± 10.6	120.1 ± 8.6	< 0.001 [†]
RPV	115.4 ± 23.2	107.8 ± 15.0	146.3 ± 22.9	120.6 ± 20.2	< 0.001 [†]
LPV	115.9 ± 21.2	103.2 ± 17.8	142.6 ± 18.6	120.9 ± 14.8	< 0.001 [†]
Total	118.6 ± 13.9	105.5 ± 11.8	145.6 ± 15.5	124.1 ± 10.0	< 0.001 [†]
CNR _{VEIN}					
IVC	8.6 ± 2.3	6.8 ± 2.7	10.9 ± 2.7	8.1 ± 1.8	< 0.001 [†]
REIV	5.6 ± 2.2	5.1 ± 1.9	8.3 ± 3.0	5.3 ± 2.3	= 0.003*
LEIV	5.6 ± 2.2	4.4 ± 2.6	8.1 ± 2.9	5.5 ± 2.3	= 0.002 [†]
RFV	7.0 ± 3.6	6.2 ± 3.8	10.7 ± 3.1	6.8 ± 1.9	< 0.001 [†]
LFV	6.2 ± 2.8	6.0 ± 4.1	10.7 ± 3.4	6.7 ± 1.8	< 0.001 [†]
RPV	11.9 ± 6.0	9.9 ± 4.8	18.8 ± 7.5	11.9 ± 4.6	< 0.001 [†]
LPV	11.1 ± 5.4	8.9 ± 5.1	18.3 ± 6.4	11.0 ± 2.4	< 0.001 [†]
Total	8.3 ± 4.4	7.0 ± 4.1	12.1 ± 6.0	8.1 ± 2.1	< 0.001*
Attenuation of DVT (HU)					
CNR _{DVT}	50.7 ± 17.7	42.7 ± 15.3	45.5 ± 15.6	46.6 ± 15.1	= 0.523 [†]
CNR _{DVT}	-10.2 ± 2.6	-10.2 ± 3.5	-15.5 ± 7.3	-11.1 ± 4.5	= 0.048*
Radiation dose					
CTDI _{vol} (mGy)	5.46 ± 0.61	5.50 ± 0.60	5.45 ± 0.67	5.79 ± 0.55	= 0.249 [†]
DLP (mGy*cm)	644.0 ± 79.3	634.6 ± 111.6	621.7 ± 76.4	671.0 ± 71.1	= 0.315 [†]

Note.— Data are means ± standard deviations. *Kruskal-Wallis test and [†]One-way ANOVA were used to compare the values among the four groups and differences were considered significant when *p* was less than 0.05. Group A = 120 kVp setting and 370 mgI/mL contrast administration, Group B = 120 kVp and 300 mgI/mL, Group C = 100 kVp and 370 mgI/mL, Group D = 100 kVp and 300 mgI/mL, DVT = deep vein thrombosis, IVC = inferior vena cava, REIV = right external iliac vein, LEIV = left external iliac vein, RFV = right femoral vein, LFV = left femoral vein, RPV = right popliteal vein, LPV = left popliteal vein, CNR_{VEIN} = CNR of veins, CNR_{DVT} = CNR of DVT, CTDI_{vol} = volume CT dose index, DLP = dose length product, HU = Hounsfield unit

11.8 HU and 7.0 ± 4.1 in group B, 145.6 ± 15.5 HU and 12.1 ± 6.0 in group C, and 122.8 ± 8.1 HU and 8.1 ± 2.1 in group D (Table 2, Fig. 3). Based on the phantom study, the concentration of CM in the venous system of the lower extremities was about 1.4% (Fig. 1B).

For the 100 kVp protocol, the mean attenuation value of veins was 19.4% higher and the CNR_{VEIN} was 28.9% higher than those of the 120 kVp protocol. For HC-CM (groups A and C), the mean attenuation value was 15.5% higher and the CNR_{VEIN} was 35.4% higher than for MC-CM (groups B and

D). Image noise in the pelvis and lower extremities was not significantly different between the 120 kVp (7.5 ± 4.0) and 100 kVp (7.8 ± 6.4) settings. As expected, group C (100 kVp with HC-CM) had significantly higher venous attenuation and CNR_{VEIN} than the other groups. Venous attenuation and CNR_{VEIN} were not significantly different between group A (120 kVp with HC-CM) and group D (100 kVp with MC-CM) (Fig. 4).

The mean attenuations of DVT and CNR_{DVT} were 50.7 ± 17.7 HU and -10.2 ± 2.6 in group A, 42.7 ± 15.3 HU and -10.2 ± 3.5 in group B, 45.5 ± 15.5 HU and -15.5 ± 7.3

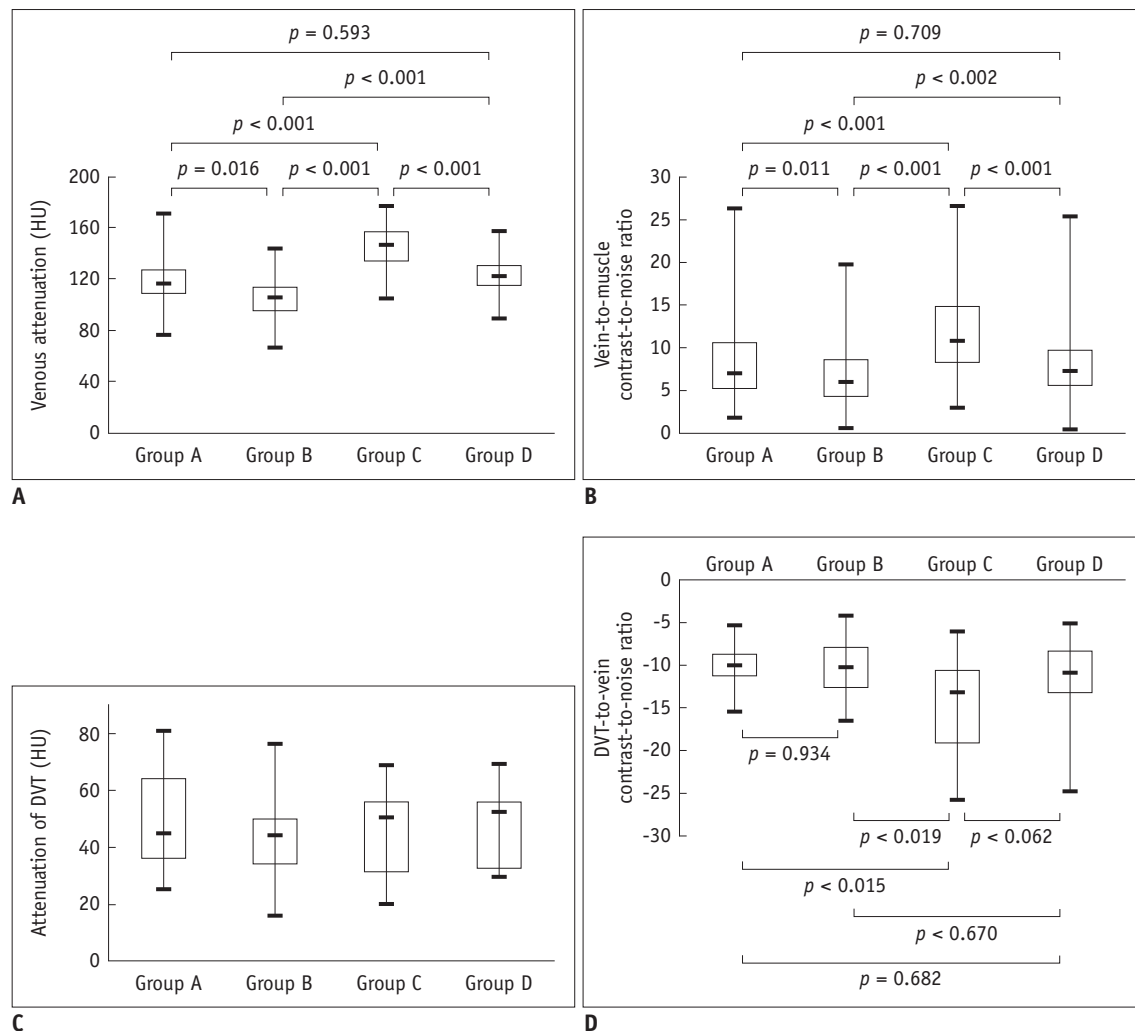


Fig. 3. Graphs showing results of clinical study.

Box-and-whisker plot showing median (middle line of each box), quartiles (top and bottom lines of each box), and upper and lower adjacent (upper and lower whiskers for each box) of mean attenuation value of veins (A), vein-to-muscle contrast-to-noise ratio (CNR_{VEIN}) (B), mean attenuation value of deep vein thrombosis (DVT) (C), and DVT-to-vein contrast-to-noise ratio (CNR_{DVT}) (D). Dotted lines = no significant difference between two groups. Solid lines = significant difference between two groups. A, B. Mean venous attenuation value and CNR_{VEIN} in group C (100 kVp and 370 mgI/mL setting) were significantly higher than those of other groups. There was no difference in venous attenuation value and CNR_{VEIN} between group A (120 kVp and 370 mgI/mL setting) and group D (100 kVp and 300 mgI/mL setting). C, D. Mean DVT attenuation value and CNR_{DVT} was not significantly different among four groups. CNR_{DVT} in group C was lower than that of other groups but this was not significant.

in group C, and 46.6 ± 15.1 HU and -11.1 ± 4.5 in group D (Table 2, Fig. 3). The mean attenuation of DVT was not significantly different between the four groups ($p = 0.587$). Group C had a higher absolute CNR_{DVT} than groups A, B and D ($p = 0.015$, 0.017 , and 0.062 , respectively). However, this was not significant after application of Bonferroni correction ($0.05 / 6 = 0.008$) for multiple comparisons. The mean $CTDI_{vol}$ ($p = 0.249$) and DLP ($p = 0.315$) were also not significantly different among the four groups (Table 2).

Interobserver agreement between the two readers for image quality was substantial, with a kappa value of 0.721. The scores of subjective assessment of venous

enhancement and overall diagnostic image quality for DVT were significantly higher in group C than those of the other groups, but not significantly different between groups A and D. The four groups were not significantly different in the subjective assessment of image noise (Table 3).

DISCUSSION

In this study, the lower tube voltage (100 kVp) CTV protocol showed significantly higher venous enhancement and CNR_{VEIN} , and had similar image noise to the conventional 120 kVp protocol. Even though 18.9% less

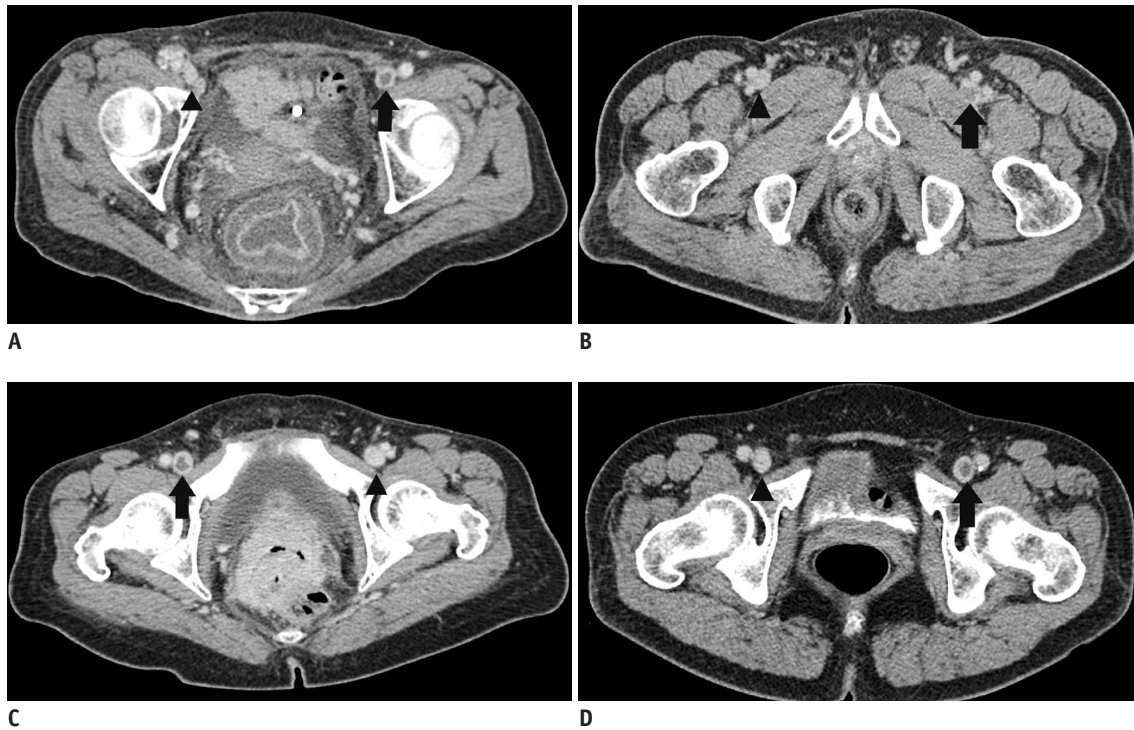


Fig. 4. Comparison of attenuations of veins and deep vein thrombosis (DVT) on axial CTV images obtained in (A) 120 kVp and 370 mgI/mL setting, (B) 120 kVp and 300 mgI/mL setting, (C) 100 kVp and 370 mgI/mL setting, and (D) 100 kVp and 300 mgI/mL contrast medium setting from representative patient of each group.

Attenuation values and vein-to-muscle contrast-to-noise ratio of non-thrombosed vein (arrow head) in these patients were 124.3 HU and 8.2 in (A), 98.1 HU and 6.5 in (B), 144.1 HU and 12.3 in (C), and 129.4 HU and 8.9 in (D). Attenuation values of DVT (arrow) and DVT-to-vein contrast-to-noise ratio were 32.8 HU and -14.8 in (A), 50.2 HU and -8.3 in (B), 43.4 HU and -16.8 in (C), and 28.4 HU and -14.9 in (D). Subjective scores for venous enhancement, image noise, and overall diagnostic image quality were 2.0, 3.0, and 3.0 in (A), 2.0, 3.0, and 2.0 in (B), 3.0, 3.0, and 3.0 in (C), and 2.0, 3.0, and 3.0 in (D). CVT = computed tomography venography, HU = Hounsfield unit

Table 3. Subjective Scoring of Pooled Data from Two Observers (Five-Point Scale)

	Group A	Group B	Group C	Group D	P
Venous enhancement	2.3 ± 0.5	2.0 ± 0.6	2.8 ± 0.4	2.4 ± 0.6	< 0.001*
Image noise					
Pelvis	3.0 ± 0.0	3.0 ± 0.0	2.9 ± 0.3	2.9 ± 0.2	= 0.070*
Thigh	3.0 ± 0.0	3.0 ± 0.0	3.0 ± 0.0	2.9 ± 0.2	= 0.110*
Calf	3.0 ± 0.0	3.0 ± 0.0	3.0 ± 0.0	3.0 ± 0.0	= 1.000*
Overall diagnostic image quality	2.7 ± 0.5	2.1 ± 0.7	2.9 ± 0.3	2.6 ± 0.5	< 0.001*

Note.— Data are means ± standard deviations. *Kruskal-Wallis test was used to compare values among four groups and differences were considered significant when *p* was less than 0.05. Group A = 120 kVp setting and 370 mgI/mL contrast administration, Group B = 120 kVp and 300 mgI/mL, Group C = 100 kVp and 370 mgI/mL, Group D = 100 kVp and 300 mgI/mL

iodine was administered by MC-CM (300 mgI/mL) instead of HC-CM (370 mgI/mL), the 100 kVp protocol (group D) showed the same venous attenuation and CNR_{VEIN} as the 120 kVp protocol with HC-CM (group A). The 100 kVp protocol had better overall diagnostic image quality for evaluating DVT by CTV.

Attenuation of a given concentration of iodine in CM depends on the mean photon energy used. X-ray absorption of iodine increases when the mean energy of a polychromatic X-ray beam is close to 33.2 keV (the k-edge

of iodine) (15, 18, 28). The mean photon energy in the X-ray spectrum was reported to be 61.5 keV with 140 kVp, 56.8 keV with 120 kVp, 51.6 keV with 100 kVp, and 43.7 keV with 80 kVp (28). Therefore, the application of lower tube voltage in CT increases the photoelectric effect, leading to a higher mean attenuation value of iodine (15). Therefore, using 100 kVp instead of 120 kVp in CTV should shift the mean energy of the X-ray beam closer to the k-edge of iodine and improve vascular enhancement.

This phenomenon suggests an important consideration

in the clinical applications of CTV. The degree of venous enhancement on CTV is essential to the detection of DVT. Application of lower tube voltage is a unique method to increase venous enhancement, except the administration of a higher iodine concentration CM or larger amount of CM. In previous studies with the 120 kVp protocol for CTV, the average attenuation of femoral veins varied from 84 HU to 135 HU according to the total injected iodine content (4, 8, 11, 19-21, 23, 29, 30). The mean attenuation of the femoral veins in the 120 kVp protocol of our study was 118.6 HU in group A (using HC-CM; 370 mgI/mL) and 105.5 HU in group B (using MC-CM; 300 mgI/mL). For the 100 kVp protocol, the mean attenuation of the femoral veins was 144.0 HU in group C (using HC-CM) and 122.8 HU in group D (using MC-CM). In our clinical study, we found no difference in venous attenuation and CNR_{VEIN} between group A and group D. Therefore, the 100 kVp protocol in CTV was not different in venous attenuation or CNR_{VEIN} from the 120 kVp protocol, despite the intravenous administration of 18.9% less iodine.

Without doubt, using a lower tube voltage in CT increases image noise and reduces image quality. A previous study on CT angiography of the aorta showed a 35% increase in image noise with the 100 kVp protocol in comparison with the 120 kVp protocol with a constant level of tube current (25). Therefore, we increased the tube current-time product (reference mAs) in the 100 kVp protocol to compensate for the increased image noise until the dose levels ($CTDI_{vol}$) were identical to the 120 kVp protocol in the phantom and clinical studies. In the phantom study, the 100 kVp protocol had 2.1 HU (6.9%) higher image noise than that of the 120 kVp protocol. In the quantitative and qualitative analyses of the clinical study, the image noise of the 100 kVp protocol was not significantly different from that of the 120 kVp protocol for either the pelvis or lower extremities.

In fact, the 80 kVp setting in CT increases the enhancement of iodine CM more than that of 100 or 120 kVp (20, 21). However, the 80 kVp setting could not be used for lower extremity CTV since it was not appropriate for maintaining an identical dose level ($CTDI_{vol}$, 9.8 mGy) and scan time for the 100 or 120 kVp protocols. Ideally, the 80 kVp setting requires a tube current of 996 mA to maintain a $CTDI_{vol}$ of 9.8 mGy at a gantry rotation time of 0.5 seconds and a pitch of 1.0. However, these parameters were not possible because most CT scanners have a maximum tube current capacity of 500 mA. If rotation time could be increased from 0.5 to 1.0 second, or if pitch could be

decreased from 1.0 to 0.5, the 80 kVp setting could achieve a 9.8 mGy $CTDI_{vol}$ by applying a tube current of 483 mA. This would increase the scan time from 27 to 60 seconds for the scan length of 113 cm, which was the average scan length for patients in this study. However, a CTV protocol with a high tube current and long scan time could cause tube overheating and motion artifacts, making it impractical for daily clinical practice.

Duplex sonography is the primary imaging method used to evaluate DVT, but has several limitations such as operator dependency and poor depiction of the pelvic, iliac, and calf veins. CTV has a high diagnostic accuracy that is similar to duplex sonography, and it can evaluate vessels, such as the pelvic vein and IVC, that are not always assessable to ultrasound in only a few minutes (6). Therefore, CTV has become commonly used to evaluate the deep venous system in spite of radiation exposure and intravenous administration of CM. The mean CT attenuation value of DVT is reported to be 31-65 HU (3, 4, 19). A venous attenuation of 80 HU or more can reasonably provide adequate contrast differentiation between a clot and opacified veins (29). To increase the degree of venous enhancement, a large volume of CM or a higher concentration of iodine CM must be used in CTV (14). However, the CM dose cannot be increased indefinitely due to the risk of contrast-induced nephropathy. Therefore, application of a low tube voltage protocol in CTV is beneficial for improving venous attenuation without administering additional CM. It can also reduce the amount of intravenous iodine administration through increased vascular attenuation by using either a lower volume of CM or CM with a lower iodine concentration.

Our study had several limitations. First, we could not perform intraindividual comparisons among the four scan protocols because of ethical concerns. Therefore, we could not compare the diagnostic accuracy of the four protocols. Second, the sample size in each group was relatively small. However, the phantom and clinical studies both showed good relationships between the CT attenuation value and CT tube voltage and between the CT attenuation value and CM iodine concentration.

In conclusion, the use of the 100 kVp protocol for CTV of the lower extremities and pelvis substantially improved venous enhancement and CNR_{VEIN} compared to the images acquired with the 120 kVp protocol. Therefore, we propose that the 100 kVp protocol could provide higher diagnostic accuracy for evaluation of DVT in clinical practice. Furthermore, the amount of administered iodine could be

reduced while maintaining venous attenuation in the lower kVp protocol.

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