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Adaptation of the Contrast Injection Protocol to Tube Potential for Cardiovascular Computed Tomography

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Abstract — **To investigate the adaptation of the contrast injection protocol for lower tube potential at cardiovascular computed tomography (CT) angiography, this study analyzed 83 patients (56 100kV vs. 27 120kV) imaged with a prospectively ECG-triggered axial technique for evaluation of aortic disease on a 256-slice CT scanner from 4/10/12 to 5/23/12. A custom algorithm was used to select tube potential and tube current based on patient size. The same contrast injection protocol (contrast concentration 370 mgI/mL, flow rate = 3.5 mL/s, volume = 90 mL) was applied to both cohorts. A Bae-Heiken-Brink pharmacokinetic model was utilized to simulate attenuation in the aorta for the applied contrast protocol in both cohorts and for 3 reduced volumes in the 100kV cohort (A: 72mL, -20%; B: 60mL, -33%; C: 50mL, -44%). Quantitative analysis revealed that 100kV cohort had significantly higher contrast attenuation and signal-to-noise ratio than the 120kV cohort but similar image noise. Simulation of protocol A and B in the 100kV cohort yielded significantly higher attenuation than that measured from the 120kV cohort ($p<0.05$); attenuation with protocol C showed no significant difference. Simulation results demonstrated that the amount of contrast material can be reduced by as much as 44% for 100 compared to 120 kV imaging but still yielded similar aortic attenuation. A prospective, randomized study should be conducted to validate the performance of the proposed contrast injection protocol at 100kV.**

I. Introduction

Common practice in cardiovascular computed tomography (CT) is to optimize tube potential for the individual patient manually based on weight or body mass index (BMI) [1]. Some late-model CT scanners enable automatic selection of tube potential based on patient and procedure attributes [2]. However, little attention has been paid to concomitant contrast protocol adjustment; even though it dramatically impacts image quality and a minimization of contrast exposure could reduce the risk of contrast-induced nephropathy (CIN). CIN is potentially higher in patients with cardiovascular disease [3, 4].

Lower tube potential scanning allows for reduction of contrast dose since the X-ray output energy at lower potentials is closer to the iodine K edge of 33 keV [5, 6] and iodine is the active ingredient of all commercially available contrast agents. In other words, the same attenuation can be achieved with less contrast at 100 vs. 120 kV. The purpose of this study was to investigate the adaption of contrast injection protocols to lower tube potential (100kV) scanning by using clinical data matched to physiologically based pharmacokinetic simulation data.

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II. Materials and Methods

A. Calibration

A calibration phantom study was conducted to obtain the iodine attenuation factors for the Philips iCT scanner. 4 separate test tubes were filled with different concentrations of contrast agent: 0, 5, 10, and 15 mgI/mL and scanned at 100 and 120 kV. 3 regions of interest (ROIs) were placed in each tube on the resulting images and the average attenuation recorded. Iodine-attenuation curves were generated and linear regression was performed. The slope of the regression line was used for scaling the predicted blood-plasma concentration of the contrast agents to aortic attenuation during the simulation experiments of various contrast agent protocols.

B. Patients

This study was approved by the Cleveland Clinic Institutional Review Board with waiver of individual consent and compliant with the Health Insurance Portability and Accountability Act (HIPAA). Consecutive patients imaged from 4/10/12 to 5/23/12 with a prospectively ECG-triggered axial technique for evaluation of aortic disease on a 256-slice CT scanner (iCT, Philips Healthcare, Cleveland, Ohio) were included in the study. Patients with standard contraindications to contrast-enhanced CT imaging were excluded. Patient parameters including age, sex, weight, and body mass index (BMI) were noted when available. Procedure parameters including scan duration, tube potential, diagnostic scan delay and contrast infusion were also recorded.

C. CT Protocol

A custom algorithm was used to select tube potential and tube current based on a patient size measurement extracted from the patient radiograph [7]. The same contrast media injection protocol was used for all patients independent of tube potential per our clinical standard (bolus monitoring was used to determine individual scan delays by setting a tracker in the descending aorta at the level of the pulmonary artery trunk; contrast protocol was concentration of contrast = 370 mgI/ml; volume = 90 mL; flow rate = 3.5 mL/sec.)

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D. Image Analysis

Baseline attenuation was determined by recording the mean attenuation in a region of interest (ROI) placed in the descending aorta at the level of PA trunk when no contrast media was present. The study measurements included attenuation signal, image noise, and signal-to-noise ratio (SNR). Five circular ROIs were drawn at multiple locations in the lumen of the aorta at the level of the aortic arch, the pulmonary trunk (in the ascending and descending aorta), the mid-heart, and the diaphragmatic hiatus. The mean and standard deviation (SD) of attenuation in the lumen were recorded for each ROI and averaged for each patient. The SD was used to define image noise. SNR was calculated by dividing the mean attenuation by the corresponding image noise.

E. Simulation of Aortic Contrast Attenuation

To investigate the adaptation of the contrast injection protocol to 100kV, the Bae-Heiken-Brink full body contrast pharmacokinetic model (Advanced Contrast Enhancement Simulator (ACES), Bayer Radiology)[8] was utilized. ACES, a computer-based tool, uses patient demographic parameters (age, height, and weight), baseline attenuation, contrast injection parameters (contrast media concentration, volume and flow rate) and scanner-specific iodine attenuation factors to simulate the transport of contrast medium and resulting attenuation. Contrast-attenuation curves were simulated for the applied contrast protocol in both cohorts and for 3 reduced volumes in the 100kV cohort; the peak attenuation of the aortic arch in the scan window was recorded for each simulation.

F. Statistical Analysis

All numeric values were expressed as mean (±SD). Patient demographics, including age, sex, height, weight and BMI, were compared between the two cohorts, scanned at 100kV and 120kV. Important scanning and radiation parameters (tube current, scan delay, scan duration, dose length product [DLP], and estimated effective dose using ICRP 103 "k-factor" methods) and all image measurements mentioned above were compared in the 100 and 120 kV cohorts. Simulated aortic attenuation values based on the applied contrast protocol were also compared to measured values in both 100kV and 120kV patients. Simulated aortic attenuation values for the 100kV cohort based on the 3 proposed contrast protocols were compared to attenuation measured from 120kV cohort.

Differences in mean values of the continuous parameters were determined either using a student t test (for normally distributed parameters) or Mann-Whitney U test (for non-normally distributed parameters). Fisher's 2-tails test was utilized for parameters with binary values. $P<0.05$ was considered significant in all statistical analyses.

III. RESULTS

A. Calibration

Analysis of phantom scans demonstrated a linear relationship between iodine concentration (x) and attenuation (y) at tube potentials of 100kV and 120kV: 100kV, $y=27.8x+9.2$ ($R^2=0.9996$); 120kV, $y=23.3x-4.0$ ($R^2=0.9987$). Attenuation per mgI of iodine at 100kV (27.8 HU/mgI) was 19% higher than the attenuation at 120kV (23.3 HU/mgI).

B. Patient Characteristics

Data from a total of 83 patients were collected (TABLE 1). No significant differences in the age (60±13 vs. 59±13 years, P=0.76) and scan duration (12±2 vs. 12±1 s, P=0.68) were found between groups scanned at 100 and 120 kV. However, the cohort scanned at 100kV had significantly lower height (1.75±0.09 vs. 1.78±0.07 m, P=0.05), weight (83±10 vs. 102±9 kg, P<0.0001), body mass index (BMI, 27.1±2.4 vs. 32.0±3.2 kg/m^2, P<0.0001) and percentage of males (70% vs. 93%, P=0.03) compared to the cohort scanned at 120kV. These findings were consistent with the patient-size based method of tube potential selection. The radiation exposure for the 100kV cohort was significantly lower than the 120kV, reflected by lower DLP values (171±31 vs. 260±30 mGy x cm, P<0.0001) and lower estimated effective dose (2.4±0.4 vs. 3.6±0.4 mSv, P<0.0001). The scan delay for the 100kV cohort was significantly shorter than the 120kV cohort (29±5 vs. 33±7 s, P=0.0069). The tube current-time product was greater in 100kV cohort compared to 120kV cohort (101±14 vs. 90±8 mAs, P=0.0006).

C. Quantitative Image Analysis

As shown in Fig. 1 and TABLE 2, mean CT attenuation in the aorta was significantly greater at 100kV (399±61 HU) vs. 120kV (281±48 HU) (P<0.0001); median CT attenuation was also 44% greater at 100kV (P<0.05). However, there was no significant difference in mean or median image noise between the groups (P=0.13). Because of the differences in attenuation, mean SNR was significantly higher at 100 vs. 120 kV (15±3 vs. 11±2) (P<0.0001); the median SNR was also 35% higher with 100kV (P<0.05).

D. Simulation of Aortic Contrast Attenuation

Fig. 2 shows aortic attenuation ranges and mean attenuation curves for patients scanned at 100kV (Fig. 2a) and 120kV (Fig. 2b); the mean and SD of average aortic attenuation measured from patients' images are superimposed on the simulation curves. In the averaged scan window for the 100kV cohort (scan duration = 12 s with 29 s scan delay, in TABLE 1), the mean value of peak simulated aortic arch attenuation was -3.5% lower than the measured mean aortic

TABLE 1. PATIENT DEMOGRAPHICS, PARAMETERS, RADIATION DOSE, AND SCANNING PROTOCOLS ON ICT SCANNER.

	100kV (n=56) mean(±SD)		**120kV (n=27)** Mean(±SD)		**P**
Age, y	60	(±13)	59	(±13)	0.76
Sex (male/female), n	39/17		25/2		0.03*
Height, m	1.75	(±0.09)	1.78	(±0.07)	0.05*
Weight, kg	83	(±10)	102	(±9)	<0.0001*
BMI, kg/m^2	27.1	(±2.4)	32.0	(±3.2)	<0.0001*
Tube current-time product, mAs	101	(±14)	90	(±8)	0.0006*
Scan delay, s	29	(±5)	33	(±7)	0.02*
Scan duration, s	12	(±2)	12	(±1)	0.68
DLP, mGy x cm	171	(±31)	260	(±30)	<0.0001*
Effective dose, mSv	2.4	(±0.4)	3.6	(±0.4)	<0.0001*

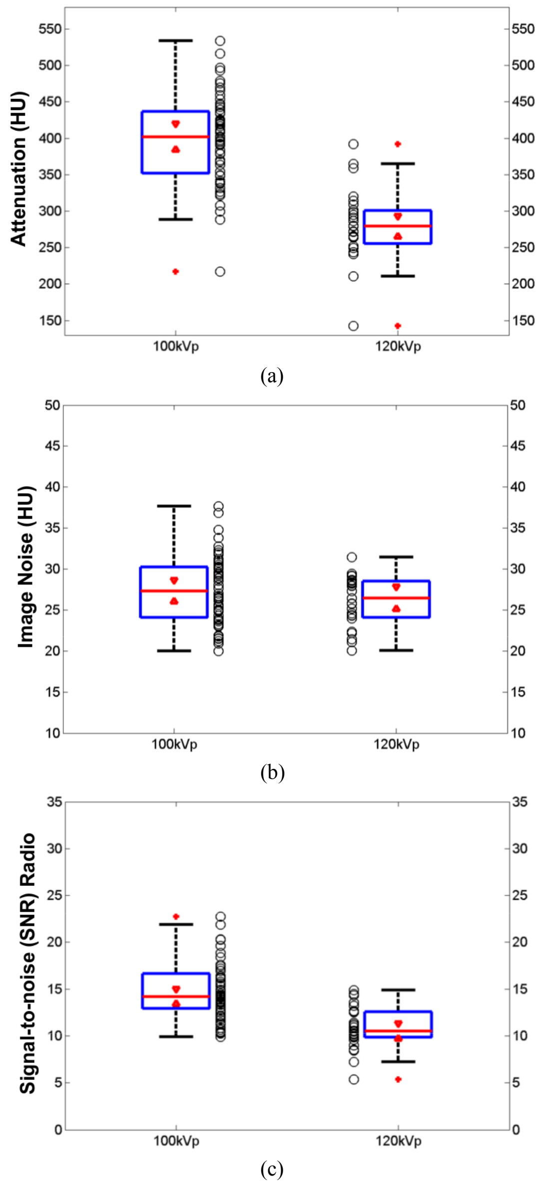

Figure 1: Box-whisker plots and scatter plots show attenuation (a), image noise (b), and SNR (c) measured from images of cohorts scanned at 100 and 120 kV. Error bars indicate 99.3% coverage of the values, boxes contain all values within the 25th and 75th percentiles (interquartile range), red lines represent medians, red dots indicate outliers, and red triangles indicate comparison intervals for median. No overlap in the intervals for attenuation (a) and SNR (b) demonstrate the median value for the cohort imaged at 100kV is significantly greater than the median value for the cohort imaged at 120kV.

attenuation, but showed no significant difference (385 ±59 vs. 399±61 HU, P = 0.21). The simulated peak range of aortic attenuation was 282-539 HU, compared to measured values of 217-534 HU in 100kV patients. In the averaged scan window for the 120kV cohort (scan duration = 12s with 33s scan delay, in TABLE 1), the simulated mean of peak value of aortic arch attenuation was -0.4% lower than the measured mean of aortic attenuation, but had no significant difference (280±35 vs. 281±48 HU, P = 0.95). The simulated peak range of aortic attenuation was 205-334 HU, compared to measured values of 143-392 HU in 120kV patients.

TABLE 2: ASSESSMENT OF IMAGE QUALITY ON ICT SCANNER.

	100kV (n=56) mean (±SD)	**120kV (n=27)** mean (±SD)	**P**
Attenuation, HU	399 (±61)	281 (±48)	<0.0001*
Image Noise, HU	28 (±4)	26 (±3)	0.13
SNR	15 (±3)	11 (±2)	<0.0001*

E. Simulation of Reduced Volume Contrast Injection Protocols

Three alternative contrast injection protocols were investigated by ACES simulation on the 100kV cohort. All three approaches utilized the same injection flow rate as our clinical practice (3.5 mL/s). Approach A reduced the injection volume by 20% (72 mL); Approach B by 33% (60 mL); and Approach C by 44% (50 mL). The threshold of bolus tracking and the post-threshold trigger delay were adjusted to capture the attenuation peak in the center of scanning window. TABLE 3 summarizes simulation results and statistical comparisons to measurement values from the 120kV cohort. Even with contrast dose reduction, simulated aortic arch attenuation in the 100kV cohort with Approach A (342±51 HU) and B (311±46 HU) was significantly greater than the measured attenuation in the 120kV cohort (281±48 HU) with P < 0.01; the attenuation with Approach C showed no significant difference compared to measurement from the 120kV cohort (275±39vs 281±48 HU).

IV. DISCUSSION

We retrospectively compared objective image measurements of cardiovascular CT patients scanned with 100kV and 120kV on a Philips iCT scanner. X-ray parameters (tube potential, tube current) were selected using a custom algorithm. 90mL of contrast material with a concentration of 370 mgI/mL were utilized in both groups with a flow rate of 3.5 mL/s. Our study demonstrated equivalent image noise in the 100kV cohort compared to the 120kV cohort with a significantly lower DLP. Aortic attenuation and SNR were significantly greater in the 100kV cohort, as expected. We used ACES, a contrast enhancement simulation tool using a physiologically based pharmacokinetic model, to simulate personalized aortic attenuation at 100 and 120 kV potentials. Simulated and measured results matched, validating our model. Then, the utility of 3 reduced volume contrast injection protocols was investigated at 100kV in simulation.

Maintaining contrast material concentration and injection flow rate, contrast injection volumes were reduced by 20%, 33% and 44%. Even though the contrast dose was decreased significantly for the 100kV cohort in simulation, aortic attenuation was either greater than or similar to the clinical measurements in the 120kV cohort. This implies the feasibility of reducing contrast media by at least 20%,

TABLE 3: SUMMARY OF THREE CONTRAST INJECTION PROTOCOLS AND THE CORRESPONDING SIMULATION RESULTS.

	Volume (mL)	**Threshold (HU)**	**Post-threshold trigger delay (s)**	**Attenuation (HU)**	**P[a]**
A	72 (-20%)	55	10	342(±51)	<0.01*
B	60 (-33%)	55	8	311(±46)	<0.01*
C	50 (-44%)	40	6	275(±39)	0.22

[a] Simulation results were compared to clinical measurements from the 120kV cohort, imaged with 90 mL of contrast resulting in mean aortic attenuation of 281±48 HU.

possibly up to 44% in 100kV patients compared to our clinical standard. The reduction percentage of 44% was the same as the discrepancy percentage between the attenuation medians measured from 100 and 120 kV cohorts. It reflected the higher attenuation resulting from both a greater iodine calibration factor (19%) and the lower weight/BMI of patients examined (~20%) at 100kV rather than 120kV. Similar results have been reported in the literature for other types of CT studies. Nakayama et al found that lower tube potential (90kV vs. 120kV) for abdominal CT yielded better enhancement of the aorta, liver, pancreas, etc. with reduction of contrast dose by 20% [9]. A study by Hunsaker et al supported at least 40% reduction (from 125 to 75 mL) of contrast medium for pulmonary CTA performed at 100, 110 kV vs. 120 and 130 kV[10].

A prospective, randomized study is necessary to validate our simulation results in cardiovascular CT patients imaged at 100kV. This work moves towards development of a patient-specific contrast dose factor at different tube potentials to optimize the contrast media injection along with scan protocols.

V. Conclusion

In conclusion, our clinical results demonstrated x-ray tube potential optimization using a custom algorithm without a change in contrast protocol yielded 100kV patient images with significantly higher image attenuation and SNR compared to 120kV, but with similar image noise. Initial simulation results suggest contrast protocol optimization in addition to x-ray parameter optimization would allow reduction of contrast volume by as much as 44% for cardiovascular CT patients imaged at 100kV. Further studies should be conducted to validate simulation results in vivo.

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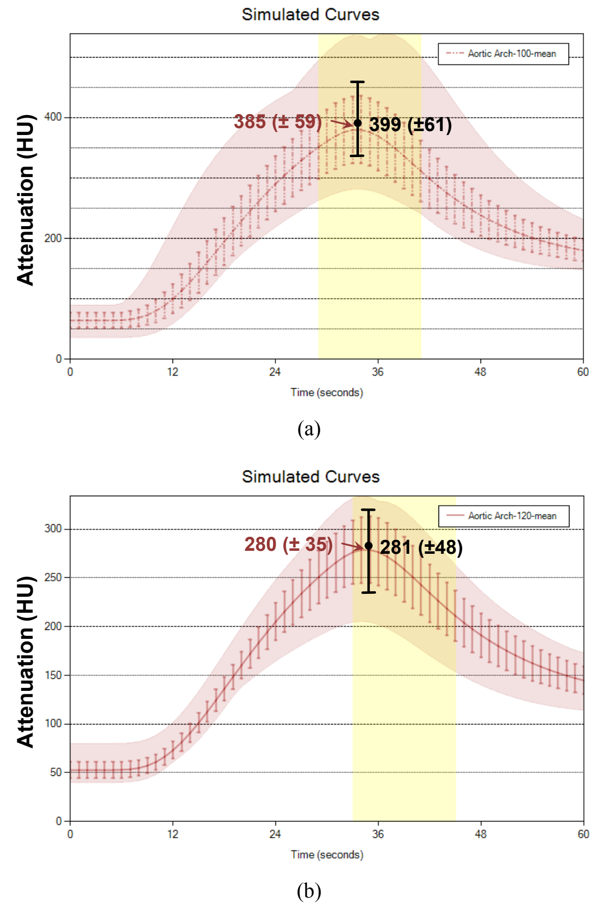

Figure 2: Simulated aortic attenuation curves for 100kV (a; n=56) and 120kV (b; n=27) patients imaged on a Philips iCT scanner. The shaded area indicates the result range of simulation on patient populations shown in TABLE 1 for 100 and 120 kV, respectively; the curves and error bars indicate the means and standard deviations (SD) of the simulated attenuation from 100kV and 120kV cohorts. In the averaged scan window for 100kV cohort (yellow shaded region, 29-41s), the mean value of peak aortic attenuation was 385±59 HU, which is not significantly different from aortic attenuation measured from patients' images. (399±61 HU; P=0.21). In the averaged scan window for the 120kV cohort (yellow shaded region, 33-45s), the mean value of peak aortic attenuation was 280±35 HU, which has no significant difference compared to the mean aortic attenuation measured from patients' images. (281±48 HU; P=0.95).