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Calibration of Computed Tomography System and Contrast Media Volume Tailoring for Optimal Hounsfield Units: A Theoretical and Experimental Study

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Abstract

Purpose: The purpose of this study is to test the linearity of the CT system and ascertain the relationship between Hounsfield Unit (HU) values and weight/weight concentrations of iodine (w_i) in mixtures. This aims to determine the iodine concentration thresholds for achieving effective contrasts with minimal iodine usage.

Materials and Methods: Aqueous solutions of Iopaque, with 300mgI/mL of iodine, were prepared for different weight/weight (w_i) iodine concentrations and filled in a water-pool phantom, and the HU observations were taken at different kVps for 10 different CT machines. The variation of HU with w_i was analyzed as, $HU(V;i) = b_0(V) + b_1(V)w_i$. From this, the w_i necessary for getting a required HU value is estimated.

Results: It is found that HU(V) varies linearly with w_i for low w_i values, although the coefficients $b_o(V)$ and $b_1(V)$ vary widely between machines. For optimal HU enhancement, it was found that a *0.01%* weight/weight concentration of iodine is adequate to produce an HU value of 450 at 80 kVp, while the corresponding concentration should be 0.025% weight/weight at 120 kVp.

Conclusion: Linear dependence of HU on w_i helps to reduce the contrast media volume by estimating the iodine concentration, necessary for obtaining a required HU. It also revealed that lower kVps could yield adequate HU enhancement with a reduced contrast agent, thus potentially minimizing patient exposure to radiation and contrast media.

Keywords: Linearity; Contrast Media; Hounsfield Unit; Computed Tomography.

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1. Introduction

Computed Tomography (CT) has emerged as an indispensable diagnostic tool in medical imaging. While the use of CT scanning in clinics is increasing significantly every year, producing high-quality CT images for fool-proof diagnosis remains the aim of many researchers [1, 2]. Importantly, a problem arises because many tissues in the human body have nearly the same X-ray attenuation coefficient, which means that the inherent contrast between adjacent tissues is low. This leads to the difficulty that different organs in the patient's body show very low differences, i.e. low subject contrast, in their Hounsfield Unit (HU) values, e.g., between the blood and the soft tissues that surround the blood vessels, and also between many different structures. To surmount this difficulty, iodinated contrast agents are administered to the patient. The regions into which the iodinated contrast penetrates would show high X-ray attenuation since iodine's X-ray attenuation coefficient is considerably higher, enhancing HU differences between different structures [3]. The level of image contrast in a CT scan depends mainly on two factors: (a) the X-ray source spectrum of the CT, which is determined by the kVp used in the machine, and (b) the amount of iodine injected into the body, i.e. it depends on the concentration and volume of the contrast agents. However, it is important to keep in mind the potential risks due to exposure to radiation and the toxicity of iodine [4, 5].

Although image the contrast improves with an increase in X-ray photon count, it also amplifies the risk of carcinoma due to exposure to X-rays. To mitigate this risk, the total photon count should not exceed a specific permissible value, and highly ionizing low-energy photons must be limited in number. This has to be optimized by choosing a suitable kVp and using necessary added filters [2, 6]. The other step is to improve image contrast by administering iodine [7]. However, concerns persist regarding the toxicity of iodine contrast in patients with kidney failure [8], particularly for those with eGFR<30 and undergoing chemotherapy [9-11]. To achieve optimal contrast, one must optimize iodine concentration in the body, tube voltage (kVp), and scan time while considering patient physiology [12, 13].

To estimate the necessary parameters for satisfactory contrast, the HU variation with iodine concentration must be known experimentally. This data enables one to calculate the required iodine concentration for a given kVp. This calculation can be quite reliable if HU varies linearly with w_i - an important issue that is addressed in the paper [14]. For this, eight aqueous solutions with different iodine concentrations were scanned at different kVps, ranging from 80 kVp to 140 kVp. This test serves to evaluate the CT system's linearity and calculate the rate of change of HU(V) with w_i, i.e. it gives us $\alpha(V)=dHU(V)/dw_i$.

With this known value of α(V) one can calculate the requisite contrast agent volume necessary to obtain the appropriate HU values at different kVps. This method enables us to estimate by how much the contrast can be reduced at a lower kVp to get an acceptable HU value or CT density enhancement.

2. Materials and Methods

2.1. Sample Preparation

In the present study, first, we made aqueous solutions of iodine of given concentrations, for which the iodine contrast agent, Iopaque 300mg I/mL (Daroopakhsh, Tehran, Iran) was used. The following method was used to calculate the volume of contrast agent solution to be added to water to obtain a certain concentration of iodine in the weight/weight percentage of the solution. This is explained below.

Let, x_i be the weight of iodine per unit volume of contrast agent (*0.3 gmI/mL*), ρ_c be the density of contrast agent measured by the specific gravity bottle method (1.328 gm/mL), and ρ_l be the density of the solvent (*1 gm/mL* for distilled water). Suppose we mix a volume 'V_l' of solvent with a volume 'V_c' of contrast. Therefore, the weight of the iodine (W_i), contrast media (W_c), solvent (W_l), and solution (W_s) are calculated by Equation 1(a-d) as given below. We have,

$$\text{weight of iodine} = x_i V_c = W_i \quad (1a)$$

$$\text{weight of contrast} = \rho_c V_c = W_c \quad (1b)$$

$$\text{weight of solvent} = \rho_l V_l = W_l \quad (1c)$$

weight of solution = $W_l + W_c = (\rho_l V_l) + (\rho_c V_c) = W_s$ (1d)

so that the *w/w* of iodine, which equals (W_i / W_s) is given by (Equation 2):

$$w_i = \frac{x_i V_c}{(\rho_c V_c) + (\rho_l V_l)} \quad (2)$$

We now consider that we have taken a volume V_l of the solvent, (e.g., here water), and want a solution in which the (*w/w*) concentration of iodine is to be w_i. It is easily found from Equation 2 that (Equation 3),

$$x_i V_c = w_i \rho_c V_c + w_i \rho_l V_l \quad (3)$$

giving the needed volume of contrast as:

$$V_c = \frac{w_i \rho_l V_l}{(x_i - w_i \rho_c)} \quad (4)$$

Equation 4 was used to calculate the volume of contrast agent (from Iopaque 300 mg I/mL) needed to make different weight/weight iodine concentrations (0.01, 0.02, 0.025, 0.03, 0.035, 0.04, 0.045, and 0.05 *w/w%*). In the present study, the volume of solvent (water) was fixed (30 mL) while the required volume of contrast agent was calculated by Equation 4.

Also, the weight/weight concentrations of the solvent and the contrast are given by (Equations 5, 6),

$$w_l = \frac{\rho_l V_l}{(\rho_l V_l + \rho_c V_c)} \quad (5)$$

$$w_c = \frac{\rho_c V_c}{(\rho_l V_l + \rho_c V_c)} \quad (6)$$

This means that the density of the solution is given by (Equation 7),

$$\rho_s = \frac{W_S}{V_S} = \frac{(\rho_l V_l + \rho_c V_c)}{(V_l + V_c)} \quad (7)$$

where we have considered the solution to be an ideal solution, i.e., without any volume of mixing. This results in giving us the total volume of the solution to be (Equation 8),

$$V_S = (V_l + V_c) \quad (8)$$

so that we get the density ρ_s of the solution to be,

$$\frac{1}{\rho_s} = \frac{(V_l + V_c)}{(\rho_l V_l + \rho_c V_c)} = \frac{w_l}{\rho_l} + \frac{w_c}{\rho_c} = \frac{1}{\rho_l} + \left(\frac{1}{\rho_l} - \frac{1}{\rho_c}\right) w_c \quad (9)$$

$$\rho_s = \frac{\rho_l \rho_c}{[w_l \rho_c + w_c \rho_l]} = \frac{\rho_l \rho_c}{[\rho_c + w_c(\rho_l - \rho_c)]} \quad (10)$$

For small values of w_c, Equation 10 can be approximated as a linear dependence,

$$\rho_s \approx \rho_l + w_c(\rho_c - \rho_l) \quad (11)$$

which is valid for $|w_c(\rho_l - \rho_c)| \ll \rho_c$.

Further, it is known that for any mixture the mass attenuation coefficient X_S, is the average mass attenuation coefficient of the components, with their *w/w* compositions as the corresponding weight factors. Let us consider a mixture (e.g. solution or a suspension) of iodine in a liquid (suffix *"l"*) in which the iodine concentration is w_i while the liquid's w/w concentration is $w_l = 1 - w_i$. This liquid may be a multiple-component one, e.g., the liquid component in the contrast solution, or the contrast solution being diluted with water, or the diluted contrast being mixed with the blood inside the patient's body. In that case, the mass attenuation coefficient of the suspension is given by (Equation 12),

$$X_s = w_l X_l + w_i X_i = X_l + (X_i - X_l) w_i \quad (12)$$

which is a well-known formula [15].

The attenuation coefficient of the solution is then given by (Equation 13),

$$\mu_s = \rho_s X_s = \rho_l \rho_i \frac{[w_l X_l + w_i X_i]}{[w_l \rho_l + w_i \rho_i]} = \rho_l \rho_i \frac{[X_l + w_i (X_i - X_l)]}{[\rho_i + w_i (\rho_l - \rho_i)]} \quad (13)$$

where the expression for ρ_s is taken from Equation 10 by replacing the symbols ρ_c and X_c by ρ_i and X_i respectively since iodine now acts as the additive to the liquid base (e.g. the liquid base can be a mixture of water and blood, whose densities and X-ray attenuation coefficients are very close). In this case, $|w_i(\rho_l - \rho_i)| \ll \rho_i$, Equation (13) can be linearized as (Equation 14),

$$\mu_s = \mu_l [\, 1 + w_i \{(X_i / X_l) + (\rho_i / \rho_l) - 2\}] \quad (14)$$

In deriving the above equations, a monochromatic X-ray source is assumed. In practice, the X-rays are distributed over a source spectrum. In this case, the linear Equation (14) can be averaged over the source spectrum $S(V)$ for the given kVp (V) and the quantities μ_s, μ_l, X_i, X_l are to be averaged over the source spectrum $S(V)$. We know that the HU value that is displayed by the CT machine relates the source-spectrum averaged attenuation coefficient ($<\mu_s>$) of the substance with that of water ($<\mu_w>$), and is defined as (Equation 15),

$$HU = 1000\left[\frac{(<\mu_s> - <\mu_w>)}{<\mu_w>}\right] \quad (15)$$

so that the HU value for the solution is given by,

$$HUs = HU_l + (1000 + HU_l)[<(X_i/X_l)> + (\rho_i/\rho_l) - 2]w_i \quad (16)$$

giving a linear dependence with respect to w_i. In Equation 16, the sign <…> implies an average over the source spectrum for the corresponding *kVp*.

We prepared (water+contrast) solutions with different concentrations (w_i) of iodine. For every case of w_i we measured the density of the solution by using the specific gravity bottle method. The weights were measured with a balance (Quintix, Sartorius, Göttingen, Germany) with $\pm 0.001\ g$ accuracy. The volumes V_c, and V_l were measured using a Transferpette pipette with $\pm 0.6\ \mu L$ accuracy. With w_i's being known, we measured the corresponding HU values. Finally, we made a HU versus w_i linear least-square fit as suggested by Equation 13. The parameters of this fit will be used for the purpose of computing the HU values when different amounts of iodine are mixed with 5 liters of blood, i.e., the volume of blood in an average adult male human being.

2.2. HU Value Measurement

For HU measurements, this study used the water phantom, constructed in-house by ourselves [16]. The performance of the phantom is described in detail in Ref [16]. The study was conducted with several materials and the observed HU values were found to be consistent with those obtained from calculations with known concentrations of the test materials. The HU values were found to be the same irrespective of the parts inside the phantom where the HU values of the test materials were recorded. This confirmed homogeneity. In the present case also the HU values of the iodine solutions in a given test tube were the same in all parts within the test tubes. The given phantom is a water-filled phantom that has 12 test tubes placed on two concentric circles, with 8 test tube holders being on the outer circle and 4 of them being fixed on the inner one. This arrangement helps to check the beam-hardening effect (beam-hardening effect is not central to our discussions here). We used 5 mL syringes as test tubes in the phantom, which were filled with iodine solutions. The front view of the water phantom is shown in Figure 1.

Different concentrations of iodine solutions in water (0.01, 0.02, 0.025, 0.03, 0.035, 0.04, 0.045, and 0.05 in *w/w%*) were prepared by using Equation 5. The test tubes were filled with solutions and inserted into the 8 test tube holders in the outer circle (test tube holders with numbers 1 to 8 contained the lowest to highest iodine concentrations in the increasing order of concentration). The inner test tube holders were filled with 0.02, 0.03, 0.04, and 0.05 *w/w%* (test tube holders' numbers 9 to 12, contained the lowest to highest iodine concentrations, respectively) iodine concentrations.

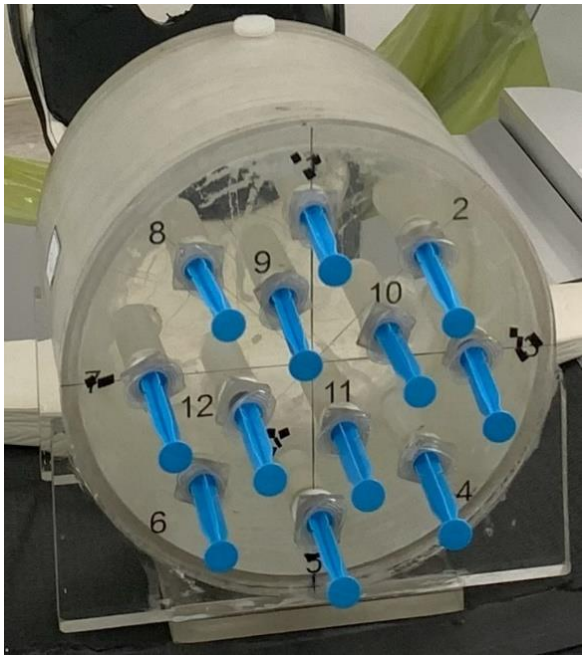

Figure 1. The front view of the water phantom with test tubes (or 5 mL syringes) being placed in the 12 holes

The CT systems of 5 main hospitals affiliated with the university were selected for this study. The models, manufacturers, and available kVps of these CT systems were different, and the details are presented in Table 1. It has to be mentioned that the performance of the generator and image quality were checked before scanning the samples.

At the start of the experiment, we positioned the water phantom on the scanning table with all the test tube holders being filled with distilled water (distilled water was used to make aqueous iodine) and scanned at all kVps that are available in the different CT systems (see Table 1). Then, without changing the position of the phantom, all the water-filled test tubes were replaced by different concentrations of aqueous solutions of iodine in the outer (0.01, 0.02, 0.025, 0.03, 0.035, 0.04, 0.045, and 0.05 in *w/w%*) and inner (0.02, 0.03, 0.04, and 0.05 *w/w%*) test tube holders.

The kVps available for each CT system are presented in Table 1. Except for the kVps, the rest of the acquisition parameters, such as slice thickness (*2mm*), tube current modulation (mAs about 200), and pitch factor (about 1), were the same (for water and contrast solutions) in all cases. All CT systems except 128-slices Ingenuity (Philips CT system) in the present study used standard filter-back projection to reconstruct images. The 128-slices Ingenuity (Philips CT system) was used "iDose level 4" to reconstruct images.

The CT images of different concentrations of iodine solutions in water in the given water-filled phantom were saved in the Picture Archiving and Communication System (PACS). The mean and standard deviation of HU values were extracted from the Region of Interest (ROI). The area of ROIs was between *30* to *40* mm^2 and contained *125-167* pixels, which were sufficient to avoid statistical fluctuations in the data. The ROI was suitably selected visually so as not to contaminate surrounding structures, as is seen in Figure 2 (a and b).

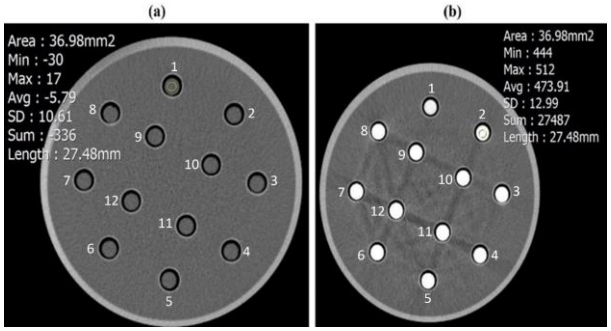

Figure 2. Region of Interest (ROI) and related HU values inside the test tubes containing (a) water and (b) iodine solution in an axial CT image of the water phantom

2.3. HU(V) Versus w_i Dependence and Iodine-Dose Reduction

The $HU(V)$ versus w_i dependence was analyzed as a least square fit (Equation 17):

$$HU(V)=b_0(V)+b_1(V)\,w_i \tag{17}$$

for different kVps, where from theory we know, by referring to Equation 16,

$$b_1(V) = (1000 + HU_l)[<(X_i/X_l)> + (\rho_i/\rho_l) - 2] \tag{18}$$

For iodine dose reduction, we consider a situation when the radiologist intends to obtain a certain $HU(V)$ value. Then, the *w/w* concentration of iodine should be, from Equation 17,

Table 1. The models' name, manufacturer of CT systems, their available kVps, and the number of machines tested for 5 hospitals affiliated with the university

CT system model	Manufacturer	Available kVps	No. of the machines tested
MX 16 slices	Philips	90, 120, 140	3
128-slices Ingenuity	Philips	80, 100, 120, 140	1
Emotion 16 slice	Siemens	80, 110, 130	1
BrightSpeed 16 slices	GE Health Care	80, 100, 120, 140	2
Aquilion Start 16 slices,	Canon medical systems	80, 100, 120, 135	2
Brilliance 16 slices	Philips	90, 120, 140	1

$$w_i = \frac{[HU(V) - b_0(V)]}{b_1(V)} \quad (19)$$

We now find the required volume (V_c') of the contrast that should be added to the volume V_{blood} of the blood pool in the patient's body so that the iodine concentration in the blood is w_i. By following the steps that lead to Equation 4, we find,

$$V_c' = \frac{w_i \rho_{blood} V_{blood}}{[x_i - w_i \rho_c]} \quad (20)$$

where we have simply replaced ρ_l and V_l, with those for blood (V_{blood}=*5000mL, the typical amount in an adult male* and ρ_{blood}=*1.0 gm/mL*). On substituting Equations 19 and 20 in Equation 17 we find the variation of HU(V) with the volume V_c' to be,

$$HU(V) = b_0(V) + \frac{b_1(V) x_i V_c'}{[\rho_{blood} V_{blood} + \rho_c V_c']} \quad (21)$$

Equations 19-21 can be used for planning the dose required for getting a certain value of HU(V). It is clear that Equation 21 is a non-linear equation in V_c' as V_c' appears both in the numerator and denominator. However, for small values of V_c', Equation 21 takes a linear form,

$$HU(V) = b_0(V) + \left[\frac{b_1(V) x_i V_c'}{(\rho_{blood} V_{blood})}\right] \quad (22)$$

Clearly, this condition of linear dependence of HU(V) on V_c' holds for $\rho_c V_c' << \rho_{blood} V_{blood.}$ and is independent of the CT system's parameters $b_0(V)$, $b_1(V)$.

3. Results

3.1. Sample Preparation

The required volume of the contrast agent, Iopaque, (from the contrast stock) for getting the necessary w_i values was calculated by using Equation 4 and is presented in Table 2. The corresponding contrast agent volume "V_c", needed to make a certain weight/weight percentage of iodine solutions is calculated by noting that the volume of water (V_l) was fixed at 30 mL in all solutions. Also, the densities for the different concentrations of iodine solutions, found by the specific gravity bottle method, are stated in Table 2. Temperatures of the lab and the CT room were maintained at 22°C.

Table 2. The volume of contrast agent (V_c) and density of iodine solutions (ρ_s) at 22°C for different concentrations of iodine (w_i), in weight/weight percentage. The volume of water is fixed for all solutions (V_l=30mL), also the density of water (ρ_l) and a contrast agent (ρ_c) were 0.998 and 1.328 gm/mL respectively

w_i* in w/w %	V_c** in mL	ρ_s*** in gm/mL
0.0	0.0	0.9980
0.01	1.046	1.0089
0.02	2.194	1.0202
0.025	2.811	1.0263
0.03	3.460	1.0309
0.035	4.142	1.0381
0.04	4.861	1.0439
0.045	5.620	1.0501
0.05	6.421	1.0570

*Concentration of iodine in weight/weight percentage, **Volume of contrast agent in mL (found by Eq. 4), ***Density of solution in gm/mL (determined by a specific gravity bottle method)

The least-square fit between ($1/\rho_s$) and w_c, as predicted in Equation 9, was made. This fit is completely linear the contrary hypothesis that the data points are not correlated linearly is rejected since it has a P value, $p< 0.01$) [17] and the actual data (shown by a square sign) are very close to this fit, as shown in Figure 3.

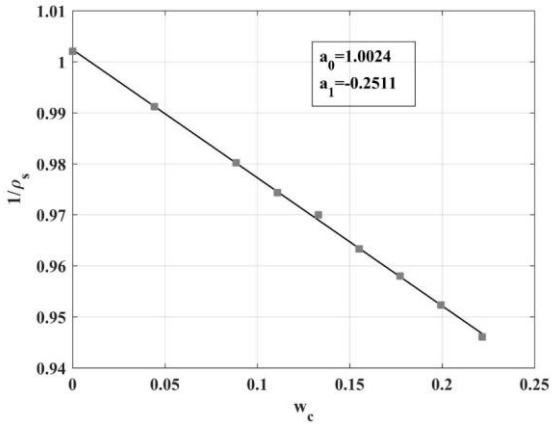

Figure 3. The least squares fit of the inverse of the density of the solution with the weight percentage of the contrast agent. The least-square coefficients are a_0=1.0024 and a_1=-0.2511

Table 3 compares the coefficients a_0 and a_1 values determined by the least squares fit, and those expected

from theory, i.e., $a_0(theoretical)=(1/\rho_l)$ and $a_1(theoretical)=(1/\rho_c-1/\rho_l)$, respectively. As is presented in Table 3, the experimental and calculated coefficients a_0 and a_1 differ by less than 1%. This level of accuracy allows us to conclude that an aqueous solution of iodine-contrast Iopaque can be considered to be an "ideal solution".

Table 3. The coefficients a_0 and a_1 were calculated from least square fit, $y=a_0+a_1x$, where $y=1/\rho_s$ and $x=w_c$, and their comparison with theoretical results

Coefficients	Least square fit	Theoretical	% differences
a_0	1.0024	1.0020	-0.0361
a_1	-0.2511	-0.2490	0.208

3.2. HU Measurements

The performance of the CT systems, X-ray generator, and image quality, used in the present study were verified beforehand by the standard quality control tests. The HU value of each iodine solution was measured at different kVps, available on each CT system (80, 90, 100, 110, 120, 130, and 140 kVps). The HU value of water was measured in all 12 test tubes to check the HU value of pure water, i.e., when $w_i=0.0$.

In Table 1, we have listed the models of the machines that were used in different hospitals of the university. We note that the kVps available are 80 (in 6 machines), 90 (4 machines), 100 (5 machines), 110 (1 machine), 120 (9 machines), 130 (1 machine), and 140 (7 machines). The variation of HU(V) with the iodine concentration, w_i, can be seen in Figure 4(a-d). Linearity of HU(V) versus w_i variation can be observed, with being about 0.998 for all CT systems. The values of $b_0(V)$ and $b_1(V)$ for the linear fit of the type given in Equation 20, for the different kVp values, for different machines, are given in Table 4. In all cases, the fits are excellent, with a *p*-value, of $p<0.01$, for a contrary hypothesis [17].

As is known, for the same iodine concentration, w_i, the HU(V) value always decreases with increasing kVp. This can be seen in the HU(V) versus w_i plot given in Figure 5 for the Emotion 16-slice CT system, for 80, 110, and 130kVps.

With the coefficients b_0 and b_1 found experimentally we have simulated, the variation of HU(V) versus the volume V_c' of the contrast for all the CT systems are calculated. In Figure 6 we present this variation for an Ingenuity machine as an illustration. The results for different machines and kVps are summarised in Table 5. This table gives us the value of V_c' that is needed to obtain the required value of HU(V) for a machine under different conditions of kVp. In calculating these values, we used b_0 and b_1 values given in Table 4 and used Equation 22.

Table 4. The values of $b_0(V)$ and $b_1(V)$ for the linear fit at different kVp values for different CT systems ($r^2\approx0.998$). Note, $b_0(V)$, $b_1(V)$ are dimensionless quantities

CT Systems	kVp Used													
	80		90		100		110		120		130		140	
	b_0	b_1	b_0	b_1	b_0	b_1	b_0	b_1	b_0	b_1	b_0	b_1	b_0	a_1
IN** (H_1*)	17	38307	-	-	12	28621	-	-	8	22780	-	-	12	19274
EM** (H_2*)	21	38919	-	-	-	-	14	26348	-	-	14	21756	-	-
BS** (H_4*)	20	38740	-	-	16	29498	-	-	8	22780	-	-	11	20071
BS** (H_5*)	22	37338	-		16	28507	-	-	34	22566	-	-	8	19171
MX** (H_1*)	-	-	10	32379	-	-	-	-	12	22670	-	-	10	18894
MX** (H_2*)	-	-	16	32183	-	-	-	-	11	22664	-	-	10	18992
MX** (H_3*)	-	-	20	32236	-	-	-	-	3	21995	-	-	10	18985
AS** (H_4*)	21	42602	-	-	12	37125	-	-	9	32590	-	-	-	-
AS** (H_5*)	18	43898	-	-	16	35229	-	-	15	30387	-	-	-	-
BR** (H_5*)	-	-	3	33382	-	-	-	-	10	23451	-	-	10	19677

*The 1st to 5th hospitals are shown by H_1 to H_5. **The following abbreviations are used for the CT systems' models: IN=Ingenuity (128-slice Philips system), EM=Emotion (16-slice Siemens CT system), BS=Bright Speed (16-slice GE system), AS=Aquilion Start (16-slice Canon Medical System), MX=MX 16-slice (Philips system), and BR=Brilliance (16-slice Philips system).

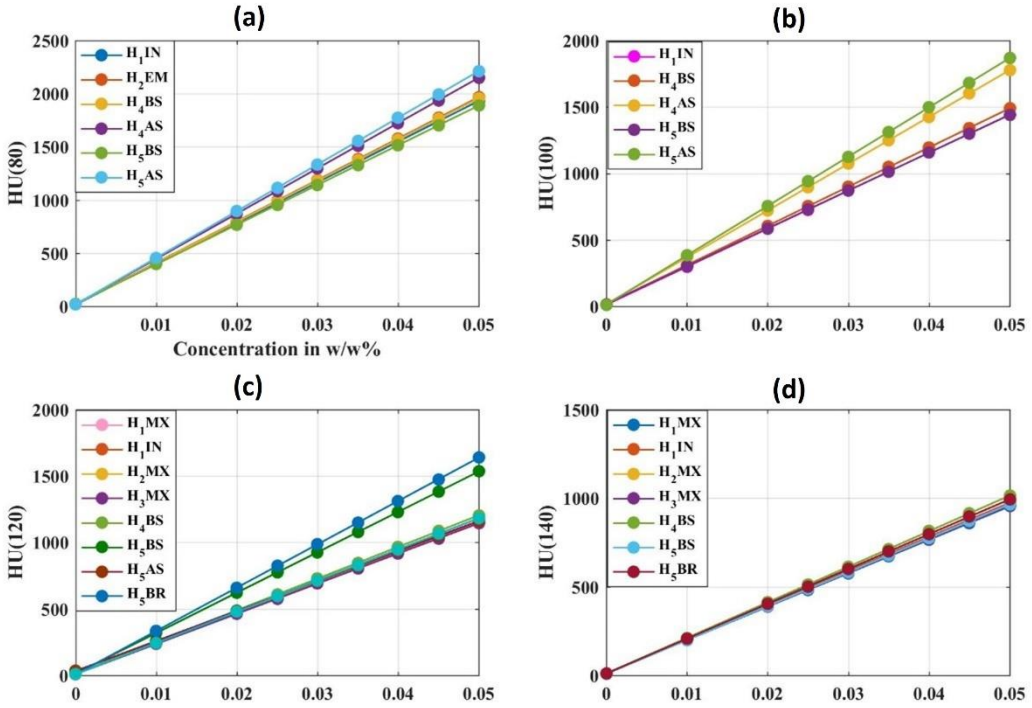

Figure 4. The variation of HU(V) with the iodine concentration, w_i, for (a) 80 kVp (in 6 machines), (b) 100 kVp (in 5 machines), (c) 120 kVp (in 9 machines), and (d)140 kVp (in 7 machines). The corresponding coefficients (b_0 and b_1) for each kVp and machine are given in Table 4. It has to be mentioned that the r^2 is about 0.998 for all least square fits

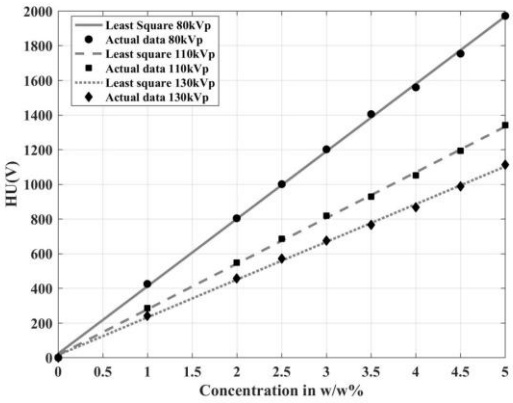

Figure 5. The variation of HU(V) with the iodine concentration, w_i, for 80, 110, and 130 kVp. The data were from the Emotion 16-slice CT system

4. Discussion

The present study showed that the HU value rises linearly with iodine concentration, between 0-5% of the w/w concentration of iodine in water, for all the machines that were at our disposal in the different hospitals affiliated with the University. This linear fit between HU and iodine concentration serves as calibration of the CT system; this helps to calculate the iodine dose to be injected into the patient's body, for obtaining suitable HU values (of the radiologist's choice) in the CT images.

In most hospitals, CT scanning is done at 120 kVp. We found that at V=120 kVp we have $b_1(120) \approx$ 23000-24000 cm^{-1} in most cases, i.e., the rise of HU (120) per iodine concentration is about 23-24 per mg/mL. This is also the value that is in the range of what is quoted in different publications [5]. Although our observations with different CT machines showed a 15% variation around this average, this mean value of $b_1(120)$ can be used for planning radiological imaging of patients.

Table 5. The volume contrast agent V_c' for necessary HU values. Calculation was made considering 5 liters of blood, as in a normal male adult, and using Equations 20, 22

V'_c in mL	HU(80)	HU(90)	HU(100)	HU(110)	HU(120)	HU(130)	HU(140)
10	44	35	33	30	29	27	22
20	68	54	52	45	44	40	33
30	91	73	71	61	58	53	44
40	115	92	90	77	73	66	56
50	138	112	108	92	88	78	67
60	162	131	127	107	102	91	78
70	185	149	145	123	117	104	90
80	208	168	163	138	131	116	101
90	231	187	182	153	145	129	112
100	254	206	200	168	159	141	123

Results concerning iodine dose estimation and dose reduction are as follows. For this, attention is drawn to the results in Table 5 (or Figure 6). It is seen that to obtain an HU value of 100, one is required to add 60 mL of Iopaque at 120 kVp while the same HU can be obtained by adding only 40 mL of contrast for imaging at 80 kVp, considering that the body contains 5 liters of blood and the iodine-contrast has mixed uniformly with the blood pool. This means that iodine dose reduction is more effective at lower kVps. Further, we believe that aiming an HU value of 100 must be considered adequate when the standard deviation of the CT machine does not exceed 10. This issue has to be checked experimentally. However, the following question remains. It is known from practice that on injecting 70 mL to an average patient (5-liter blood in the body) an HU value of 200 (and above, quite often) can be achieved at 120 kVp [18, 19]. The HU value that we have estimated above from the $b_1(120)$ value given in the paper is just about half of what is seen in practical situations. The reason for this can be as follows. These estimates apply to cases when the entire volume of contrast gets uniformly mixed with the total blood pool in the body. However, for CT imaging, the entire operation is conducted within one minute of contrast injection. It is not clear as to what fraction of the iodine-contrast ends up circulating in the whole body. Recent empirical studies show that the distribution of iodine in the body is not uniform when data were acquired 50 seconds after the injection of 100 mL of iodine-contrast, with the injection speed being 3.0mL/s [12]. The case considered in the present paper corresponds to a situation when the contrast has mixed uniformly with the blood pool, i.e., this corresponds to the case of imaging with a long delay after injection. This is a limitation of the present study. Even this "worst case scenario" (i.e. CT imagining

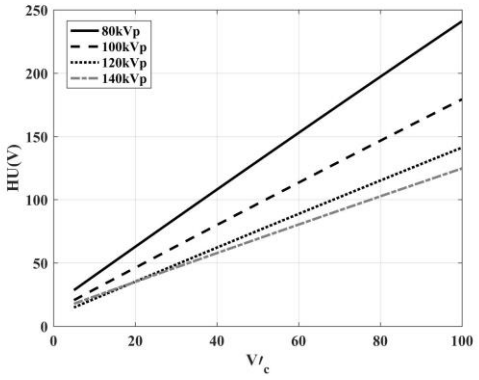

Figure 6. Variation of HU values versus the volume of contrast agent (V_c') for 80, 100, 120, and 140kVp. The data were from the Ingenuity CT system

with a long delay) shows that observations at lower kVps require much smaller amounts of contrasts than what would be needed at higher kVps [7]. Further, at lower kVps, a smaller number of photons are directed toward the patient's body [2, 6]. This additional advantage must be kept in mind for aiming at CT imaging at lower kVps. However, for more reliability in practical situations, we recommended animal studies involving CT imaging with different iodine concentrations and at different time delays. In these animal studies, it is necessary to measure the Contrast-to-Noise Ratio (CNR) and the Figure Of Merit (FOM) for different concentrations of iodine [20] which will give the full potential of iodine dose reduction.

In CT imaging, beam hardening effects give rise to many quantitative inaccuracies. Our experiments showed that the values of $b_0(V)$ and $b_1(V)$ do not differ between the inner and outer test tubes in the phantom. Though the mean values of the parameters b_0, and b_1 serve as important guides for many dose estimates, they should be independently measured for every individual instrument, if a CT machine is to be used

for quantitative analyses, as in DECT inversion [21-23].

5. Conclusion

By determining HU variations with the concentration of iodine (w_i) in aqueous solutions, it is possible to calculate the necessary iodine dose for suitable radiological imaging. Radiation dose reduction and iodine dose reduction can be reduced considerably on imaging at a lower kVp.

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