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Comparison between two methods for estimation of Equilibrium Dose in MSCT procedures

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ABSTRACT

The $CTDI_{100}$ underestimates the dose indicator due the scattering beyond the scanning length of 100mm of the measurement. A proposed method to obtain the dose (including the "tail" of the dose distribution) is a measurement on a large phantom to estimate the dose indicator on an ideal infinitum large phantom (*equilibrium dose*, D_{eq}). As the scanning length increases, the dose indicator grows asymptotically. Monte Carlo simulations previously obtained were adopted in the present work. It includes simulations performed considering different scan lengths and different combinations of protocols of voltage, pitch, diameter and axis of simulation. Using an empirically characterized function of the experimental data, two methods to estimate the equilibrium dose were evaluated. One method is algebraically manipulating the function, and another is using the Levenberg-Marquardt least squares method. The comparative evaluation of both methods demonstrates that higher values of the pitch results in a higher difference of both methods. The results demonstrate a good compatibility of the methods for the estimation of D_{eq}. However, the results for α (*scatter fraction*) and L_{eq} (*equilibrium length*) are significantly different when both methods are considered.

Keywords: **CTDI100, Equilibrium Dose, Computed Tomography.**

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1. INTRODUCTION

The use of Computed Tomography has been a great innovative method for medical imaging procedures. The adoption of this imaging technology on a wide scale around the world in the last decades introduced concerns on adequate quantification of the radiation doses associated with this practice. During decades, the Computed Tomography Dose Index ($CTDI_{100}$) and its derived metric Weighted Computed Tomography Dose Indicator ($CTDI_w$) were used as dose quantities for single slice CT. Subsequently, the Volume Computed Tomography Dose Indicator ($CTDI_{vol}$) was adopted after the introduction of the multi-slice CT (MSCT) procedures [1]. With the advent of broad fan-beam technologies, these quantities cannot adequately represent the CT dose. The equation for $CTDI_{100}$ is:

$$CTDI_{100} = \frac{1}{nT}\int_{-50}^{50} f(z)dz. \tag{1}$$

In equation (1), nT is the active detector length and $f(z)$ is the dose distribution associated to one axial rotation [2]. This integral considers only 100 mm (scanning length) of the beam extension. According to Boone [3], a problem of $CTDI_{100}$ is that this metric underestimates the dose contribution due the scattering beyond the scanning length. In 2010, the AAPM Report 111 [4] established a new paradigm on dosimetry of computed tomography, which includes a measurement of the dose using a large phantom to estimate the dose on an ideal infinitely large phantom (*equilibrium dose*). As the scanning length (L) increases, the *cumulative dose* (integrated dose over $-L/2$ to $+L/2$) grows asymptotically, converging to a maximum value. According to AAPM Report 111, an empirically characterized function that describes the asymptotic growth is:

$$D_L(z=0) = D_{eq} * \left(1 - \alpha \cdot e^{-\frac{4 \cdot L}{L_{eq}}}\right), \tag{2}$$

where D_{eq} represents the equilibrium dose, α is the *scatter fraction* and L_{eq} is the *equilibrium length*. These parameters can be estimated by fitting the simulated data.

In the present work, two methods for estimating the parameters D_{eq}, α and L_{eq} are compared. One method uses the Levemberg-Maquardt least-squares method [5], hereafter referred to as L-M Method, and the other method employs the algebraic manipulation of the Equation 2, as proposed by AAPM Report 200 [6], hereafter referred to as AAPM Method. Simulated data were used as input for running both methods.

2. MATERIALS AND METHODS

2.1. Data acquisition

Previously simulated [7] cumulative dose data, D(L) were used to evaluate the L-M and AAPM methods. The simulations were performed on an infinitely long phantom of PMMA for the center hole and on the peripheral holes. The peripheral value is averaged over the four peripheral holes. These simulated data were experimentally validated using three $CTDI_{100}$ phantoms joined along the axis to extend the measurement length, using voltages of 80, 100, 120 and 140 kV. The data collection adopted the Serial Method as defined in AAPM Reports 111 [4] and 200 [6]. The measurements were performed on a GE Discovery CT750HD (General Electric Company, Boston, USA) using different voltages, phantom diameters, simulation axis (center or periphery) and pitches. These measurements used cylindrical (14.5 cm long and 32 or 16 cm diameter) PMMA phantoms and a chamber 10×6-0.6CT ion chamber (S/N 02–4831) coupled to a digitizer module Accu-Gold+ (model AGDM+, S/N 48–1054) both manufactured by the Radcal, Co. (Radcal Inc, Monrovia, CA). [8].

2.2. The L-M Method

The Levenberg-Marquardt method (L-M Method) is used to fits empirical data to functions which presents non-linearity in the fitting parameters. It is a generic algorithm with fast and robust convergence. In the present work, it was used the least-squares algorithm Nonlinear Curve Fitting tool of the Origin 2020 software (OriginLab Corporation, Northampton, MA, USA) [9]. The parameters D_{eq}, α and L_{eq} were obtained by fitting eq.2 to the simulated data. Details of the applied methodology and the results are presented in Costa et al [7].

2.3. AAPM Report 200 method

This method to obtain the parameters D_{eq}, α and L_{eq} was proposed by AAPM Report 200, and consists on rewriting equation 2, resulting in equations 3 and 4 below:

$$g(L, D^*) \equiv log_2\left(1 - \frac{D_L(z=0)}{D^*}\right), \quad (3)$$

$$g\left(L, D_{eq}\right) = log_2(\alpha) - \frac{4}{ln(2) \cdot L_{eq}} \cdot L, \quad (4)$$

where D^* is and estimation of the equilibrium dose, $D_L(z = 0)$ is the simulated value of the cumulative dose (at the scanning length L). If D^* is different of D_{eq}, the function $g(L, D^*)$ is not a straight line. Obtaining the coefficients $coef_{linear}$ and $coef_{angular}$ of a linear regression of the function $g(L, D^*)$, the coefficient of determination, R^2, is evaluated for the values of the linear function ($coef_{linear}$ and $coef_{angular}$) and $g(L, D^*)$. The best estimate of D^* increases the value of R^2. The chosen method to obtain the value of D^* (also proposed by the AAPM Report 200) is a MS-Excel function named "Solver". This function has a first value (initial guess) of D^* and change it to maximize the coefficient of determination R^2.

The values of α and L_{eq} can be obtained, according to equations 5 and 6:

$$log_2(\alpha) = coef_{linear} \therefore a = 2^{coef_{linear}}, \quad (5)$$

$$\frac{-4}{ln(2) \cdot L_{eq}} = coef_{angular} \therefore L_{eq} = \frac{-4}{ln(2) \cdot coef_{angular}}. \quad (6)$$

The parameters D_{eq}^{L-M}, α^{L-M} and L_{eq}^{L-M} obtained with L-M method were compared to the corresponding ones, D_{eq}^{AAPM}, α^{AAPM} and L_{eq}^{AAPM} obtained applying the AAPM method. Therefore, ratios of these parameters can be defined as:

$$R_{D_{eq}} = \left[\frac{D_{eq}^{L-M}}{D_{eq}^{AAPM}} - 1\right] * 100, \quad (7)$$

$$R_{L_{eq}} = \left[\frac{L_{eq}^{L-M}}{L_{eq}^{AAPM}} - 1 \right] * 100, \quad (8)$$

$$R_{\alpha} = \left[\frac{\alpha^{L-M}}{\alpha^{AAPM}} - 1 \right] * 100. \quad (9)$$

3. RESULTS AND DISCUSSION

Figure 1 shows simulated data (dots) and calculations (solid lines) obtained using L-M and AAPM methods. Tables 1 and 2 shows the results for all combination of protocols for Central and Peripheral, respectively. On Figure 1, "c: Simulation" and "p: Simulation" are referred to the simulation on the central hole and peripheral holes, respectively; "c: AAPM" and "p: AAPM" are referred to the estimation of the curve by the AAPM method on the central hole and peripheral holes, respectively; "c: L-M" and "p: L-M" are referred to the estimation of the curve by the L-M method on the central hole and peripheral holes, respectively.

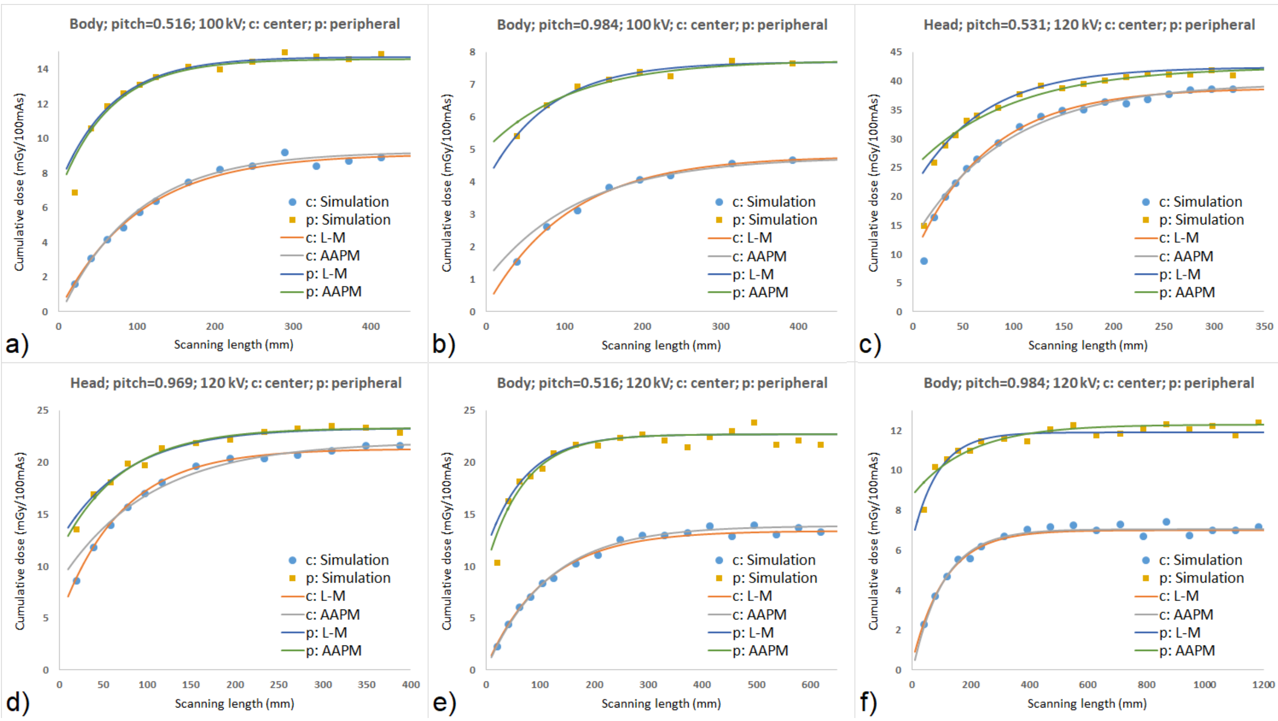

Figure 1. Comparison of both methods for different protocols with the simulated data. (a) Body; 100 kV; pitch=0.516. (b) Body; 100 kV; pitch=0.984. (c) Head; 120 kV; pitch=0.531. (d) Head; 120 kV; pitch=0.969. (e) Body; 120 kV; pitch=0.516. (f) Body; 120 kV; pitch=0.984. All the graphs compare results for center and peripheral axis of the phantom.

Table 1: Values of L-M method and the AAPM method for Central position.

		D_{eq} (mGy)		L_{eq} (mm)		α	
Voltage (kV)	**Pitch**	**L-M***	**AAPM**	**L-M***	**AAPM**	**L-M***	**AAPM**
			Head				
80	0.531	12.8(0.5)	12.9	281(7)	288.0	0.76(1)	0.78
	0.969	7.0(0.3)	6.8	272(12)	196.8	0.75(3)	0.96
	1.375	5.0(0.2)	5.0	275(7)	290.3	0.76(1)	0.71
100	0.531	24.6(1.0)	24.7	277(8)	335.0	0.77(1)	0.66
	0.969	13.5(0.6)	13.8	276(10)	342.1	0.77(2)	0.66
	1.375	8.4(0.3)	8.4	275(7)	295.3	0.76(1)	0.70
120	0.531	38.8(1.6)	39.6	297(7)	370.0	0.76(1)	0.69
	0.969	21.3(0.9)	22.0	281(10)	409.6	0.77(2)	0.62
	1.375	15.0(0.6)	15.6	285(10)	576.5	0.76(2)	0.45
140	0.531	55.3(2.3)	55.0	287(8)	274.1	0.75(1)	0.78
	0.969	30.3(1.2)	30.3	305(12)	351.7	0.71(2)	0.59
	1.375	21.3(0.9)	21.4	289(6)	291.3	0.75(1)	0.73
			Body				
80	0.516	4.0(0.2)	4.2	440(23)	499.8	0.94(3)	0.93
	0.984	2.1(0.1)	2.3	417(21)	832.4	0.96(3)	0.64
	1.375	1.5(0.1)	1.5	461(29)	377.5	0.95(4)	1.11
100	0.516	9.1(0.4)	9.2	410(11)	391.4	1.00(3)	1.04
	0.984	4.8(0.2)	4.8	427(15)	481.2	0.97(2)	0.80
	1.375	3.4(0.1)	3.4	428(28)	413.0	0.98(4)	1.01
120	0.516	13.4(0.5)	13.9	439(22)	460.1	0.98(3)	0.99
	0.984	7.0(0.3)	7.1	450(21)	425.8	0.95(2)	1.02
	1.375	5.0(0.2)	5.4	489(38)	128.1	0.92(5)	0.50
140	0.516	24.2(1.0)	24.3	458(23)	519.7	0.97(3)	0.89
	0.984	12.7(0.5)	12.9	472(19)	493.3	0.95(2)	0.94
	0.516	9.1(0.4)	9.8	463(33)	844.9	0.95(4)	0.67

*Source: Costa et al. [7].

Table 2: Values of L-M method and the AAPM method for Peripheral positions.

		D_{eq} (mGy)		L_{eq} (mm)		α	
Voltage (kV)	**Pitch**	**L-M***	**AAPM**	**L-M***	**AAPM**	**L-M***	**AAPM**
			Head				
	0.531	15.7(0.5)	15.8	241(8)	279.9	0.53(1)	0.48
80	0.969	8.6(0.3)	8.3	274(23)	196.4	0.48(4)	0.56
	1.375	6.1(0.2)	6.0	268(14)	236.1	0.50(2)	0.51
	0.531	27.9(0.8)	27.2	257(13)	198.0	0.52(2)	0.62
100	0.969	15.3(0.5)	15.1	295(16)	269.7	0.47(2)	0.47
	1.375	9.5(0.3)	9.4	268(14)	243.3	0.50(2)	0.53
	0.531	42.4(1.2)	42.5	277(10)	384.1	0.50(1)	0.42
120	0.969	23.3(0.7)	23.3	301(14)	279.6	0.47(2)	0.51
	1.375	16.4(0.5)	16.6	276(11)	305.6	0.51(1)	0.50
	0.531	59.1(1.7)	59.3	280(10)	323.3	0.50(1)	0.47
140	0.969	32.3(1.0)	31.0	288(20)	211.5	0.48(3)	0.53
	1.375	22.8(0.7)	22.7	273(13)	299.3	0.50(2)	0.43
			Body				
	0.516	7.3(0.2)	7.5	261(19)	558.1	0.49(3)	0.31
80	0.984	3.8(0.1)	3.7	295(34)	374.3	0.47(4)	0.23
	1.375	2.7(0.1)	2.6	394(64)	320.8	0.39(5)	0.32
	0.516	14.7(0.4)	14.6	267(17)	259.4	0.51(3)	0.53
100	0.984	7.7(0.2)	7.7	320(28)	441.0	0.48(3)	0.35
	1.375	5.5(0.1)	7.7	360(30)	446.3	0.40(3)	0.35
	0.516	22.7(0.7)	22.7	289(23)	280.6	0.49(3)	0.56
120	0.984	11.9(0.3)	12.3	350(29)	769.7	0.46(3)	0.29
	1.375	8.5(0.2)	9.1	358(61)	773.8	0.44(7)	0.35
	0.516	32.5(0.9)	31.6	261(22)	222.6	0.49(3)	0.62
140	0.984	17.0(0.5)	17.4	387(28)	965.8	0.44(2)	0.23
	1.375	12.2(0.3)	12.1	372(28)	300.6	0.42(3)	0.50

*Source: Costa et al. [7].

Table 3 shows the results of the ratios for all combination of protocols evaluated applying the equations (7), (8) and (9).

Table 3: Ratios of parameters by L-M method and AAPM method on all protocols (in %).

		Center			Peripheral		
Voltage (kV)	**Pitch**	$R_{D_{eq}}$(%)	$R_{L_{eq}}$(%)	R_{α}(%)	$R_{D_{eq}}$(%)	$R_{L_{eq}}$(%)	R_{α}(%)
				Head			
	0.531	-0.7	-2.4	-2.0	-0.4	-13.9	11.2
80	0.969	2.9	38.2	-21.7	3.4	39.5	-14.2
	1.375	-0.3	-5.3	7.1	1.7	13.5	-1.8
	0.531	-0.6	-17.3	17.0	2.7	29.8	-15.5
100	0.969	-1.8	-19.3	16.8	1.4	9.4	0.7
	1.375	-0.2	-6.9	9.0	0.8	10.2	-4.8
	0.531	-2.1	-19.7	10.3	-0.1	-27.9	19.7
120	0.969	-3.1	-31.4	25.0	-0.1	7.7	-8.7
	1.375	-3.6	-50.6	69.9	-1.2	-9.7	2.4
	0.531	0.5	4.7	-4.1	-0.4	-13.4	6.7
140	0.969	0.1	-13.3	20.1	4.2	36.2	-10.3
	1.375	-0.5	-0.8	2.2	0.3	-8.8	16.5
				Body			
	0.516	-4.9	-12.0	0.9	-2.8	-53.2	59.8
80	0.984	-7.5	-49.9	49.0	2.6	-21.2	104.0
	1.375	2.1	22.1	-14.3	3.5	22.8	20.4
	0.516	-1.4	4.7	-3.6	0.8	2.9	-4.2
100	0.984	0.6	-11.3	21.9	-0.6	-27.4	36.1
	1.375	-0.4	3.6	-3.1	0.0	-19.3	34.9
	0.516	-3.5	-4.6	-1.5	0.0	3.0	-13.1
120	0.984	-0.7	5.7	-6.9	-3.2	-54.5	58.5
	1.375	-8.0	-61.8	82.3	-6.9	-53.7	24.5
	0.516	-0.4	-11.9	9.5	2.8	33.9	-20.5
140	0.984	-1.8	-4.3	1.3	-2.6	-59.9	89.5
	1.375	-7.0	-45.2	41.1	0.7	23.8	-16.5

The method proposed by the AAPM Report 200 results in different values of D^* according to the initial guess. It so happens because, as can be seen on Equation 3, if D^* is lower than an simulated data $D_L(z=0)$, the argument of the logarithm becomes negative. In these cases, an simulated data that has a cumulative dose lower then D^*, and all others with higher scanning length, are disregarded. The D^* considered (on the method proposed by the AAPM Report 200) was the one which more closely approximates to the D_{eq} Levenberg-Marquardt least-squares method.

4. CONCLUSION

A comparative evaluation shows that the largest difference of $R_{D_{eq}}$ was 4% for Head protocol (peripheral protocol; pitch=0.969; 140 kV) and -8% for Body protocol (central protocol; pitch=1.375; 120 kV). Comparing $R_{L_{eq}}$ and R_α on center and peripheral protocol, the largest difference of $R_{L_{eq}}$ was -62% for central protocol (Body protocol; pitch=1.375; 120 kV) and -60% for peripheral protocol (Body protocol; pitch=0.984; 140 kV). For R_α, the largest difference was 82% for central protocol (Body protocol; pitch=1.375; 120 kV) and 104% for peripheral protocol (Body protocol; pitch=0.984; 80 kV). As can be perceived, higher values of the pitch results in a higher difference for both methods. The results demonstrate a good compatibility of the methods for the estimation of the quantity D_{eq}. However, the results for α and L_{eq} are significantly different when both AAPM and L-M methods are considered. This low compatibility of the methods may be associated to the high sensitivity of the AAPM method on the choice of the initial guess D^*. The evaluation of this sensitivity will be evaluated in future works.

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