Romanian Reports in Physics, Vol. 63, No. 1, P. 137–146, 2011

ON DOSIMETRY OF RADIODIAGNOSIS FACILITIES, MAINLY FOCUSED ON COMPUTED TOMOGRAPHY UNITS*

ZOE GHITULESCU [1,2]

[1] Faculty of Physics, University of Bucharest
[2] National Commission for Nuclear Activities Control

Received August 20, 2009

Abstract. The "talk" has been thought and structured in three parts: 1. Basics of image acquisition using computed tomography technique. 2. Effective Dose calculation for a patient and its assessment using BERT concept.3. Recommended actions of getting a good compromise in between related dose and the image quality. The aim of the work is that the reader to become acquainted with the CT technique and able of understanding the Effective Dose calculation and its conversion into time units using the BERT concept. A good image quality involves several factors which take into account the fact that the dose should be "as low as reasonable achievable" (**ALARA** *principle of Radiation Protection*)**.** The drown conclusion is that**:** effective dose calculation converted in time units by the medical physicist could be then communicated to the patients by the radiologist together with the diagnostic notes and a minimum informal regarding the nature and type of radiation.

Key words: efective dose, back projection, line integrals, CTDI (computed tomography dose index), DLP (dose length product), image quality.

1. BASICS OF IMAGE ACQUISITION USING COMPUTED TOMOGRAPHY TECHNIQUE

Radiology as a good method of inspection and diagnostic in healthcare domain, it also brings a significant contribution of 0.4mSv to the annual effective dose within artificial radiation for the population. Particularly, computed tomography contributes with 40% to the collective effective dose. Therefore, in order to upraise the X-ray exposure's related risk in radiology, it is necessary to define the effective dose (E)

$$E = \Sigma_T w_T H_T = \Sigma_T w_T \Sigma_R w_R D_{T,R}, \tag{1}$$

where: $D_{T,R}$ is the average absorbed dose on organ/tissue T due to R type of radiation, W_R is the weighting factor for radiation, W_T is the weighting factor for tissue; E_{SI} = 1Sv.

* Paper presented at the Annual Scientific Session of Faculty of Physics, University of Bucharest, June 5, 2009, Bucharest-Măgurele, Romania.

A precise calculation of that is quite difficult within variouse RDG examinations, as it needs dose calculation knowledge for 22 organs.

Speaking about X-ray investigations, a good assessment of the effective dose is recommended using dose-length product (DLP) for CT units, while in fluoroscopy inspections, either by the dose-aria product (DAP) measurements or the entrance skin dose (ESD) measurements multiplied then by the suitable conversion coefficients(CC). These could be determined by using Monte Carlo simulation technique on phantoms [1].

$$(\mathrm{DLP}) \sim 1\mathrm{mGy}\cdot\mathrm{cm};\ (\mathrm{DAP}) \sim 1\mathrm{mGy}\cdot\mathrm{cm}^2.$$

Computed tomography based on X-ray investigation method allows a complete visualization of human body and the small details of low contrast and uses the computer to reconstruct an image from a cross section plane of an organ/object.

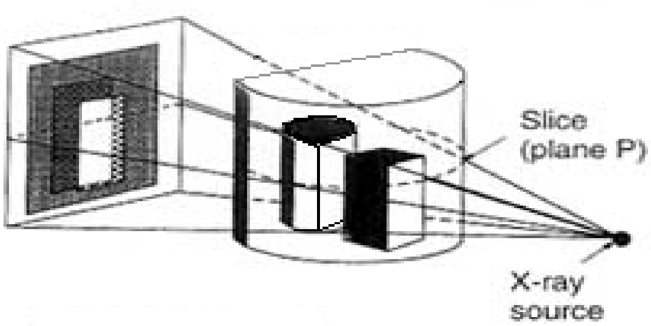

Fig. 1 – A conventional X-ray and a CT image acquisition.

▪ **The detection** of specified details can be achieved by "cutting" a part of the body in perpendicular slices along the scan axes of 1cm or even thinner, for various angles, thus leading for instance, to a better chest visualization.

The 2D image of a cross-section is like a map of the linear attenuation coefficient, in each point describing the instant local rate for which X-rays during scanning are absorbed through photoelectric effect or are Compton scattered. Image acquisition consists of X-ray attenuation measurements along the back projections of a test object for its different peripherical position and the considered angle (Fig. 2a). Each of these attenuation measurements of the image is digitalized and stocked by the computer, being meanwhile normalized, corrected and convolved using special math reconstruction filters.

▪ **Back projecting** the views along a line integral leads to the image reconstruction of the object (Fig. 2b).

▪ **Reconstruction** math algorithms of an image are based on Radon Transform (RT), but being more efficient it is used the reconstruction method named Filter Back Projection (FBP) [7].

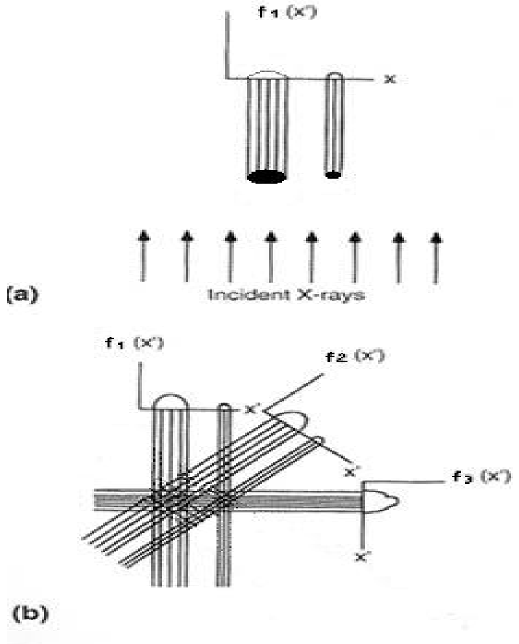

Fig. 2– a) Attenuation measurement at a given angle for a single view $f(x')$, where x‘shows the linear position of it; b) back projections.

▪ **The object projection** at a certain angle (θ) is made up of *line integrals*, each one bringing its contribution to the total attenuation $\mu(x, y)$ of the X-ray beam which passes through the object (Fig. 3).

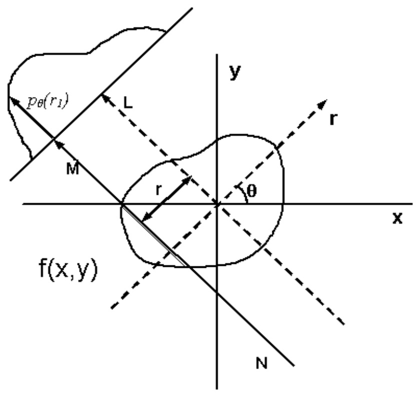

Fig. 3

The evolution of various constructive CT scanner starting with the first and second generation of single/multiple pencil beam translate/rotate scanner is followed by third generation-rotate/rotate fan beam scanner, fourth generation-rotate/stationary inverted fan beam scanner and fifth generation-cone beam cylindrical scanner.

2. EFFECTIVE DOSE CALCULATION FOR A PATIENT AND ITS ASSESSMENT USING BERT CONCEPT

2.1. Local (a) and Integral (b) dosimetrical quantities

a) – These amounts measure the radiation intensity within the limits of exposed body regions:

- **Computed Tomography Dose Index (CTDI)** is the sum of the dose contributions along a parallel line with the scan rotation axe (z); (CTDI) ~ mGy/mAs (~mGy/100 mAs)
- **Free dose in air along the rotation axe (CTDI-air)** is a CTDI which measures air kerma, without phantoms measurements; (CTDI-air) ~ 1Gy;
- **Absorbed dose by the organ (Dorg)** measures the ratio of absorbed radiation by the organ and its mass taking into account the extended irradiated region; (Dorg) ~ 1Sv;

b) – They measure the absorbed radiation taking into account the extension of exposed region:

- **Dose Length Product (DLP)** ; (DLP) ~mGy · cm;
- **Effective Dose (*E*)** it is a certain amount of the dose corresponding to a part of the body exposure in terms of equivalent radiations exposure of the whole human body; **(*E*) ~ 1Sv**.

Defined 1) CTDI and 2) DLP used for 3) effective dose calculation (*E*) considering the constructive type of the CT scanners [2]

1) Computed Tomography Dose Index (CTDI)

$$\mathrm{CTDI} = \frac{1}{h} \cdot \int_{-\alpha}^{+\alpha} D(z) \cdot \mathrm{d}Z; \qquad \mathrm{CTDI}_{100} = \frac{1}{h} \cdot \int_{-50}^{+50} K_{air} \cdot (Z) \cdot \mathrm{d}Z; \tag{2}$$

(CTDI defined for 100 mm length)

$$\mathrm{CTDI_W} = \frac{1}{3} \cdot \mathrm{CTDI}_{100,C} + \frac{2}{3} \cdot \mathrm{CTDI}_{100,P}; \qquad \mathrm{CTDI}_{W,eff} = \frac{1}{p} \cdot \mathrm{CTDI}_W; \tag{3}$$

(Weighted CTDI) (Effective, weighted CTDI)

$${}_n\mathrm{CTDI} = \frac{\mathrm{CTDI}}{Q}; \qquad p = \frac{\mathrm{TF}}{h}; \tag{4}$$

(CTDI-normalized) (*p*–pitch; TF–table feed; *h*–nominal slice thickness)

$$D_{org} = \frac{1}{p} \cdot \mathrm{CTDI}_{air} \cdot \sum_{z-}^{z+} f\left(org, z\right) \tag{5}$$

(Dose per organ); f = weighted conversion coefficients for an organ.

2) Dose-length product (DLP)

$$\mathrm{DLP}_W = \mathrm{CTDI}_{W,eff} \cdot p \cdot n \cdot h = \mathrm{CTDI}_{W,eff} \cdot n \cdot \mathrm{TF} = \mathrm{CTDI}_{W,eff} \cdot L\,; \tag{6}$$

$$\mathrm{DLP}_W = \mathrm{DLP}_{air} \cdot P_{H;B}\,; \quad P_H = \frac{\mathrm{CTDI}_{W,H}}{\mathrm{CTDI}_{air}} \quad P_B = \frac{\mathrm{CTDI}_{W,B}}{\mathrm{CTDI}_{air}}\,; \tag{7}$$

(DLP-air is the ratio of DLP-w and phantoms factors for head and body).

3) The effective dose (E)

$$E = {}_n\mathrm{CTDI}_{air} \cdot Qq \cdot F \cdot k_{CT}\,, \tag{8}$$

$$F = \frac{1}{p} \cdot \sum_{z-}^{z+} f(z) \tag{9}$$

(total conversion factor per organ for the scanned region);

$$E = \mathrm{DLP}_{air} \cdot \overline{f} \cdot k_{CT} \tag{10}$$

(effective dose).

2.2. An effective dose (*E*) calculation example

The acquired data are for a patient under a CT examination of a Spiral CT type, SOMATOM BALANCE-Siemens, see Fig. 4.

Fig. 4 – SOMATOM BALANCE-Siemens.

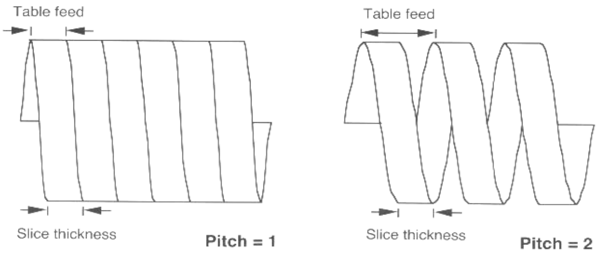

Fig. 5

The constancy tests were within the limits for: noise, uniformity, average value of CT numbers, slice thickness.

Acceptability criteria for the Roentgen-diagnostic CT units [8, 4]

- Image noise

$$\sigma_{CT,c}\left(\mathrm{ROI}_{500\mathrm{mm}^2} - \mathrm{water/echiv.Tissue}\right) \le \pm 20\% CT_{ref} \tag{11}$$

- CT numbers value

$$\sigma^2_{CT_{XYZ},water/echiv.T,\rho dif.} < \pm 20\mathrm{HU}(5\%) \tag{12}$$

- Uniformity of CT numbers

$$\sigma_{\overline{CT},}(\mathrm{ROI_c} - 500\mathrm{mm}^2)_{P_c,P_p} \le 1.5\%\ \mathrm{CT}_{ref} \tag{13}$$

- Dose index for CT (Fig. 8)

$$\mathrm{CTDI_{slice}}(\forall h, \mathrm{filter}) = \mathrm{CTDI_{slice}} \pm 20\% \mathrm{CTDI_{ref}} \tag{14}$$

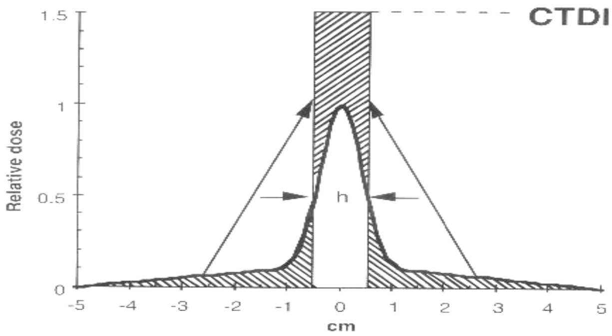

Fig. 6

- Irradiated slice thickness (15)

$$h = h \pm 20\% h_{ref}$$

- Spatial resolution

$$\mathrm{PSF}_{\mathrm{FWHM}}(\delta_{\mathrm{answer}}) = \mathrm{PSF}_{\mathrm{FWHM}} \pm 20\% \mathrm{PSF}_{\mathrm{FWHM,ref}} \tag{16}$$

- Small contrast resolution

Perspex slits of 0.35 cm in diameter inserted into a uniform water phantom should be visible in the image [4].

Exam and scan type details:

a) **DLP air calculation**:
Zone: Abdomen (superior)
Tube voltage: 130 kV
Time-current product (Q): 110 mAs
Rotations number: 13
Slice thickness (h): 8 mm
TF (table feed): 16 mm

$$\mathrm{DLP}_{\mathrm{W}} = \mathrm{CTDI}_{\mathrm{W,eff}} \cdot p \cdot n \cdot h = \mathrm{CTDI}_{\mathrm{W,eff}} \cdot n \cdot \mathrm{TF} = \mathrm{CTDI}_{\mathrm{W,eff}} \cdot L \tag{17}$$

$$\mathrm{DLP}_{\mathrm{W}} = 7.92 \cdot 13 \cdot 1.59 = 163 \mathrm{mGy} \cdot \mathrm{c} \tag{18}$$

$$\mathrm{DLP}_{\mathrm{W}} = \mathrm{DLP}_{\mathrm{air}} \cdot P_{H;B} \tag{19}$$

$$\mathrm{DLPair} = 1/0.42 \cdot 163 = 388 \mathrm{mGy} \cdot \mathrm{cm} \tag{20}$$

b) **Effective dose (*E*) calculation**:
(CTDI w): 7.92 mGy
(DLP w):163 mGy · cm
P-B (body phantom factor): 0.42
f(*z*) abdomen:0.011 mSv/mGy · cm
k-T(II scanner category): 0.8

$$E = \mathrm{DLP}_{\mathrm{air}} \cdot \overline{f} \cdot k_{CT} = E = 388 \cdot 0.011 \cdot 0.8 = 3.41 \mathrm{mSv} \tag{21}$$

– Proposed value by the *European Guidelines on Quality Criteria*, on the 32cm PMMA phantom for abdomen (total) by multiple scanning is: DLP-w = 780 mGy · cm.

– Proposed value by the *German Federal Chamber of Physicians*, on the 32cm PMMA phantom for abdomen (total) through a single scanning series is: DLP-w= 490mGy · cm.

Table 1

Specified factors for the utilized scan (k_{CT}) – it allows effective dose calculation when known CTDI-air

Scan	Head/Neck/Children	Body (adults)
0	1.10	1.25
I	1.00	1.00
II	0.90	0.80
III	0.80	0.65
IV	0.70	0.50
V	0.60	0.40

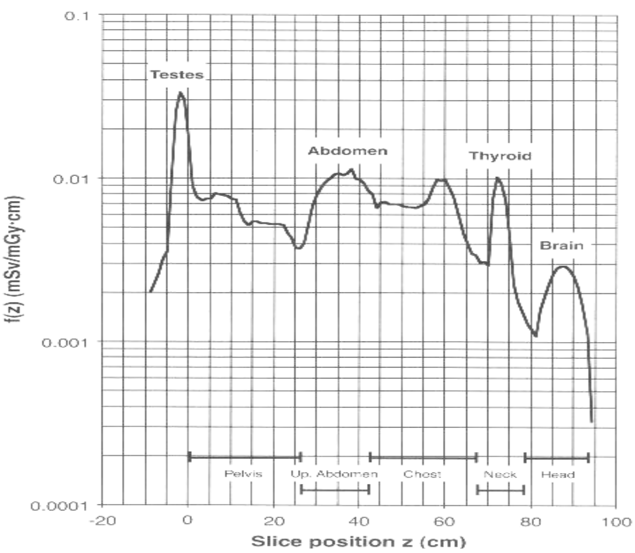

Fig. 7 – The conversion factor $f(z)$ for a male patient.

2.3. BERT concept

The fact that we all are radioactive and surrounded by radiation it is well known. For an easier understanding, the *effective dose* **(*E*)** could be expressed in time units if taken into account the average of **3 mSv/year** background radiation in U.S.A., recommended by the *U.S. National Council for Radiation Protection and Measurements* (NCRP) as *an assessment method for radiation* called background equivalent radiation time or BERT [5].

Table 2

Time of intake the same effective dose from nature

RDG exam	Effective dose (mSv)	BERT (time of intake the same effective dose from nature)
Abdomen (superior)	3.41	1 year and 7 weeks
Neck	4.3	1 year, 5 month, 2 ½ weeks
Dental, intra-oral	0.06	a week

2.4. Conclusions

Effective dose calculation accomplished by the medical physicist (using a special soft for the CT scanner and the exam type) and, converted in time units through BERT concept, could be then communicated by the radiologist together with the diagnostic notes.

Thus, it is obviously necessary a minimum informal of the patients as regards the nature and type of radiation, for instance, by the help of some leaflets.

3. RECOMMENDED ACTIONS OF GETTING A GOOD COMPROMISE IN BETWEEN RELATED DOSE AND THE IMAGE QUALITY

3.1. Dose and Image Quality

Brooks analytical assessment expresses the modification of dose for the patient if a specified parameter is changed, while the noise stays the same:

– a double dose, if the slice thickness gets to its half;

– a double dose, if the object diameter increases with 4 cm;

– an eight times increase of the dose it is necessary to the spatial resolution to become double (by reducing at its half the beam width and the sample increment);

$$D \propto \frac{\exp(\mu \cdot d)}{\sigma^2 \cdot a^2 \cdot b \cdot h}, \tag{23}$$

where: D = dose for the patient, μ = average value of the attenuation coefficient, d = selected diameter of the object, σ = standard deviation of CT numbers (noise), a = sample increment, b = beam width, h = nominal slice thickness.

The contrast and the electronic noise are not upraised here.

3.2. Recommended actions for keeping the patient dose as low as reasonable achievable and getting a good image quality [2, 3]

– using a rather smaller value of Q (mAs) in order to reduce the noise,

– as short as possible exposure time,

– an increased tube voltage and an adjusted current, so that the image contrast can not be affected,

– a good adjustment of the tube current related to the patient size (or to the selected diameter of the test object) and to the slice thickness, not to increase the noise,

– using a pitch greater than one ($p > 1$) especially for spiral CT units, even the spatial resolution slowly decreases along the rotation axe,

– scanning length should be as small as possible,

– a large tolerable windowing for a sufficient noise reduction and for keeping the contrast,

– a tolerable kernel filter which could reduce the noise,

– selected tolerable small matrix of the visual field so that the noise does not excessively increase.

REFERENCES

1. Ainchinger H. and Dierker J., *Radiation Exposure and Image Quality in X-ray. Diagnostic Radiology*, Springer, pp. 28–103 2003.
2. Nagel H.D.'s 4-th revised Updated Edition, *Radiation Exposure in Computed Tomography*, Ed. CTB Publications, 2002.
3. *International basic safety standards for protection against ionizing radiation and for the safety of radiation sources*, Safety Series No. 115/CD, IAEA, Vienna, 2004.
4. ICRP Publication 60, *Recommendations of the International Commission of Radiological Protectio*n, 1991, pp. 1–81.
5. Cameron JR: *Are X-Rays safe? A radiation unit for the public*, Ed. Physics and Society News, 1998 and 1991, 1–5.
6. Sherrow V., *Medical Imaging*, Ed. Benchmark Books, 2006.
7. Katsevich A.I., Ramm A.G, *Radon transform and local tomography*, CRC-Press, 1996, pp. 155–157, 265–267.
8. European Commission, *Radioprotection*, Series no.91/1997.