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ORIGINAL ARTICLE

Patient radiation biological risk in computed tomography angiography procedure

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Abstract Computed tomography angiography (CTA) has become the most valuable imaging modality for the diagnosis of blood vessel diseases; however, patients are exposed to high radiation doses and the probability of cancer and other biological effects is increased. The objectives of this study were to measure the patient radiation dose during a CTA procedure and to estimate the radiation dose and biological effects.

The study was conducted in two radiology departments equipped with 64-slice CT machines (Aquilion) calibrated according to international protocols. A total of 152 patients underwent brain, lower limb, chest, abdomen, and pelvis examinations. The effective radiation dose was estimated using ImPACT scan software. Cancer and biological risks were estimated using the International Commission on Radiological Protection (ICRP) conversion factors.

The mean patient dose value per procedure (dose length product [DLP], mGy·cm) for all examinations was 437.8 ± 166, 568.8 ± 194, 516.0 ± 228, 581.8 ± 175, and 1082.9 ± 290 for the lower limbs, pelvis, abdomen, chest, and cerebral, respectively. The lens of the eye, uterus, and ovaries received high radiation doses compared to thyroid and testis. The overall patient risk per CTA procedure ranged between 15 and 36 cancer risks per 1 million procedures. Patient risk from

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CTA procedures is high during neck and abdomen procedures. Special concern should be provided to the lens of the eye and thyroid during brain CTA procedures. Patient dose reduction is an important consideration; thus, staff should optimize the radiation dose during CTA procedures.

1. Introduction

The exposure to X-ray radiation during imaging procedures may generate biological effects. Ionizing radiation is capable of cell killing by apoptosis or radiation-induced reproductive failure, which can lead to changes in the genes involved in cell growth regulation, loss of normal nuclear structure, degradation of DNA, and tumorigenesis (Shah et al., 2012). These effects include cancer and hereditary effects, which increase an individual's lifetime risk of developing cancer or a hereditary effect in future generations. Tissue reaction effects have precise radiation dose thresholds which induce radiation risks in relatively high doses (ICRP, 2007a). The International Commission on Radiation Protection (ICRP) adjusted nominal radiation detriment coefficients for cancer and hereditary effects as follows: 5.5×10^{-2} and 0.2×10^{-2} S v^{-1} for the whole population (ICRP, 2007a). In addition to these effects, radiation exposure has an association with certain diseases (non-cancer effect), such as respiratory diseases, stroke, heart diseases, and digestive disorders (Brenner and Hall, 2007; ICRP, 2007a). Although, radiation risks of non-cancer diseases at low doses remain uncertain, patient radiation doses must be kept at a minimum value to ensure maximum patient protection (ICRP, 2007a; Shah et al., 2012). Since the introduction of angiography in 1927, X-ray instrumentation technology has advanced. Currently, computed tomography angiography (CTA) is frequently used in the evaluation of cardiovascular system disorders with a sensitivity and specificity of 95% and 93%, respectively (Boesiger and Shiber, 2005; Willinsky et al., 2003). Consequently, the use of CT in medical imaging procedures has increased considerably over the past several decades since its introduction in 1971 (Brenner and Hall, 2007). The technological improvement of CT has resulted in the development of spiral CT technology in the 1990s and improvement of image quality in terms of temporal (165–175 ms) and isotropic spatial resolution (0.3–0.4 mm), and in reduction of image acquisition times, which permits angiographic procedures associated with higher patient doses (Sun et al., 2012; McCollough et al., 2009). Therefore, patient health care has improved significantly due to accurate diagnosis of cardiovascular system disorders compared to other imaging modalities (Brenner and Hall, 2007; Sun et al., 2012); however, CT procedures convey radiogenic risk due to the high radiation dose during image acquisition, which depends on age, gender, and health status (ICRP, 2007b). Recent studies have estimated that 1.5–2% (29,000 cancer cases) of the cancers diagnosed annually in the USA are associated with CT exposure (Brenner and Hall, 2007; Berrington de Gonzalez et al., 2009). Due to the increasing concern regarding radiogenic risk to patients during CTA procedures, a number of studies have been published internationally, which have focused on patient radiation during CTA procedures due to the large anatomic volumes included and acquisition of thinner slices. A large variability in patient radiation dose has been reported (Mafalanka et al., 2015; Brenner and Hall, 2007; Berrington de Gonzalez et al., 2009; Oca Pernas et al., 2014; Sabarudin and Sun, 2013). Further, it has been reported that patient effective doses during CTA procedures range between 2.2 and 24.4 mSv (Mafalanka et al., 2015). It addition, limited data are available worldwide regarding patient radiation doses and the related risk. Therefore, it is essential to evaluate patient doses during CTA procedures to justify and optimize the procedure and balance the benefit against radiation risk (ICRP, 2007a,b). Radiation sensitivity, which is defined as the relative vulnerability of cells, organs, or tissues to the detrimental effect of ionizing radiation, varies for different tissues and organs depending on age, and physical and biological factors (ICRP, 2007a; McCollough et al., 2009). Gonads, red bone marrow, and the lens of the eye are the most radiosensitive tissues. It has been estimated that $<1\%$ of people are extremely radiosensitive because of inherited transformations in DNA harm-sensing or repair genes, while the remaining tissues have a variety of sensitivities (ICRP, 2007a). Therefore, estimation of organ doses is essential to estimate the risk of procedures. Due to partial exposure of radiosensitive organs during CTA procedures, the estimation of organ and effective doses provide essential data regarding individual radiogenic risk. Regular patient dose measurements are recommended to improve clinical practice during CT procedures. Even though the risk to an individual patient may be small, the increasingly large number of people exposed, coupled with the increasingly high exposure per examination, could translate into many cases of cancer resulting directly from radiation exposure during CT. The increase in patient doses in CT procedures is attributed to a tendency to increase the scanned volume during CT procedures, the possibility of overlapping scans in advanced CT machines, repeat CT examinations, and the use of inappropriate exposure factors. The objectives of this study were to measure patient radiation dose during CTA imaging and to estimate the radiation and biological effects.

2. Materials and methods

2.1. Patient data

A total of 152 adult patients (55.3% males and 44.7% females) underwent brain, limb, chest, pelvis, and abdomen CTA (Table 1). The Ethics and Research Committee approved the study and informed consent was obtained from all patients prior to the procedure. All patients were referred for CTA procedures for a variety of clinical indications. All CTA procedures were performed for clinical indications. The angiographic procedures included cerebral, chest, abdomen, pelvis, and limb procedures. Patient-related parameters (age, gender, and diagnostic purpose of the examination) and radi-

Table 1 Patient data distribution according to gender for angiographic procedures.

Gender	Limbs	Abdomen	Chest	Head	Pelvis	Total	Percentage (%)
Male	31	15	15	12	11	84	55.3
Female	14	9	11	11	23	68	44.7
Total	45	44	26	23	34	152	100

ation exposure-related parameters (tube potential [kVp], tube current [mA], exposure time, slice thickness, and number of slices) were taken into consideration.

2.2. CT machines and patient dose measurements

A 64-slice CT scanner (MSCT, Toshiba Sensation Aquilion 64; Otawara, Japan) was installed in 2011. The MSCT consists of 64×0.5 mm detector rows, and a maximum gantry rotation speed of 0.4 s. All quality control tests were performed on the machine prior to data collection. All the parameters were within acceptable ranges. Radiation dose estimates were determined using the volume CT dose index ($CTDI_{vol}$) in mGy and the dose-length product (DLP) in mGy·cm, as provided on the scanner console. Organ doses were estimated using normalized CTDI values, as published by the ImPACT group (ImPACT, 2011).

2.3. Effective and organ doses estimations

DLP (mGy·cm) was used to estimate the organ-equivalent dose (H) using software provided by the National Radiological Protection Board (NRPB-SR250, 1996) and patient exposure parameters.

The organ equivalent dose (mSv) is given by

$$H_T = \sum_R w_R \cdot D_{T,R} \tag{1}$$

where $D_{T,R}$ indicates the mean absorbed dose to the organ (T) from radiation (R) and w_R is the radiation-weighting factor (ICRP, 2007b).

2.4. Cancer risk estimation

The overall cancer risk per procedure was obtained by multiplying effective dose with the risk coefficients (f_T) ($5.5\ \mathrm{S\ v^{-1}}$). The risk (R_T) of developing cancer in a particular organ (T) was determined by multiplying the mean organ-equivalent (H_T) dose with the risk coefficients (f_T) obtained from ICRP 103 (ICRP, 2007a). The risk of genetic effects in future generations was obtained by multiplying the mean dose to the ovaries by the risk factor (ICRP, 2007a) as follows:

$$R_T = f_T \cdot H_T \tag{2}$$

3. Results

The mean age of the 152 patients was 51.3 and 59.7 years for males and females, respectively, as presented in Table 2. Constant tube potential and pitch were used with manual settings of tube current, as shown in Table 2. The measured patient doses with respect to $CTDI_{vol}$ (mGy), DLP (mGy·cm), and effective dose values for all patients are shown in Table 3. The results are presented per department, per procedure, and per gender, according to the examination type. The results of patient dose showed a large variation. The highest dose values were for the cerebral CTA procedure, while the lowest dose values were for the lower limb procedure. This difference may be due in part to the type of procedure and exposure parameters, which were based on patient demographic data and covered volume. The lens of the eye received 41.2 mSv per procedure, on average (Table 4). Table 5 presents the estimated cancer risk for both genders. The cancer risk order of magnitude ranged between 10^{-3} and 10^{-4} per procedure. Thus the risk value is considered high when compared with conventional CT chest procedure, which ranges between 10^{-5} to 10^{-6} (Sulieman et al., 2015).

4. Discussion

4.1. Patient dosimetry

CTA examinations in adult patients have contributed greatly to the diagnosis of different diseases; however, the radiation exposure to the patient is significantly higher compared with other radiologic examinations. Table 2 represents the scan parameter per procedure. A constant voltage potential (120 kVp) was used for CTA procedures with variable mAs, which ranged from 100 to 250. This variation in mAs could be attributed to different patient size, and also differed based on the different type of CTA examination (i.e., lower limbs, abdomen, chest, head, and pelvis). In addition, variation between DLP values may have resulted from differences in mAs, and pitch values (proportion inverse to the dose) for all CTA examinations. In general, the patient radiation dose

Table 2 Show image acquisition parameters according to gender.

Gender	Age (year)	Total time (s)	Tube voltage	Tube current (mA)	Pitch
Male	51.4 ± 19.41 25–88	61.99 ± 21.43 18.60–121.00	120*	150 ± 70 (100–250)	0.92
Female	59.7 ± 20.70 19–100	56.78 ± 21.45 16.00–16.00	120*	150 ± 70 (100–250)	0.92

* Constant potential.

Table 3 Patients' doses during CTA procedures.

Procedure	$CTDI_{vol}$ (mGy)	DLP (mGy·cm)	Effective dose (mSv)
Cerebral	70.8 ± 4 (60.2–80.0)	1082.9 ± 290 (809.0–1272.8)	2.3 ± 0.6 (1.7–2.7)
Chest	30.5 ± 13 (20.0–42.0)	581.8 ± 175 (307.0–828.4)	8.1 ± 2.6 (4.3–11.6)
Abdomen	37.7 ± 16 (18.0–40.0)	516.0 ± 228 (446.0–749.0)	7.4 ± 3.4 (6.7–11.2)
Pelvis	27.2 ± 10.0 (11.1–34.5)	568.8 ± 194 (405.0–709.0)	8.9 ± 3 (6.1–10.6)
Lower limbs	14.7 ± 8 (7.0–25.0)	437.8 ± 166 (357.0–884.0)	3.9 ± 1.4 (3.2–8.0)

Table 4 Organ dose equivalent for certain radiosensitive organs during CTA procedure.

CT procedure	Organ equivalent dose (mSv)					
	Eye lens	Thyroid	Breast	Uterus	Ovaries	Testis
Cerebral	41.2	2.2	0.03	0	0	0
Chest	0.1	1.4	13.3	0.04	0.05	0
Abdomen	0	0.05	0.6	7.4	7.5	0.6
Pelvis	0	0	0.02	24	23	1.6

Table 5 Patient organ dose and risk estimation per gender and procedure type.

CTA procedure	Organ	Organ equivalent dose (mSv)	Risk coefficient 10^{-4}	Cancer probability 10^{-6}
Cerebral	Thyroid	2.2	33	73
Chest	Breast	12.3	112	1377
Abdomen	Uterus	24	143	3432
Pelvis	Ovaries	23	11	253
Pelvis	Testis	1.6	20[#]	32
Overall cancer risk per procedure				

[#] Hereditary.

is proportional to tube current–time product (mAs). Therefore, reduction of the tube current will also decrease the radiation dose by the same value. In an ideal situation, image acquisition parameters were adjusted according to scanned anatomy. Table 3 shows the mean and range of values of $CTDI_{vol}$ (mGy), DLP (mGy·cm) and effective dose (mSv) per procedure. Effective dose, which is gender-averaged and risk-adjusted dosimetric quantity, allows the estimation of nominal risk coefficients for uniform external radiation exposure. It also allows the comparison with patient doses in other imaging modalities and reference levels. The highest radiation dose per CTA procedure involved cerebral CTAs and the highest effective dose involved pelvic CTAs. This finding can be explained given that the trunk includes the most radiosensitive organs with tissue weighting factors. The results obtained in this study are within the ranges reported in previous studies (Fink et al., 2011; Loader et al., 2012; Qi et al., 2014). There are many factors that affect the radiation dose from CTA. These factors include beam energy, tube current, rotation or exposure time, slice thickness, pitch, and dose reduction techniques, such as the tube current modulation technique. It has been reported that the effective dose from CT procedures can often approach or exceed levels known to increase the probability of cancer (Brenner and Hall, 2007).

4.2. Dosimetry of critical and non critical organs

Estimation of patient radiation risks due to CT procedures is essential to assess procedure justification (benefit versus the expected risk). CT procedures entail direct irradiation of certain radiosensitive organs, such as the lens of the eye, breast, thyroid, or gonads, based on the type of the procedure (Table 4). The radiation risk of CT procedures is directly proportional to organ doses. Other adjacent organs which lie nearby the field will possibly be exposed to considerable doses (Table 4). The lens of the eye is a radiosensitive organ and radiation effects include opacities and visual impairment (cataracts). In this study the lens of the eye received 41.2 mSv per cerebral CTA procedure. This value is lower compared to that of previous studies (Suzuki et al., 2010). Suzuki et al. (2010) reported the dose to the lens of the eye during CT of the brain ranging between 50.9 and 113.3 mSv per CT brain procedure. Recently, the ICRP (2012) reported that the radiation effect on the lens of the eye and circulatory diseases is lower than that previously considered based on linear dose–response assumptions (ICRP, 2012). The threshold of the lens of the eye decreased from 5.0 to 0.5 Gy, while the threshold of occupational exposure, the equivalent dose limit for the lens of the eye, was reduced from 150.0 mSv/year to only 20.0 mSv/year. The mechanism underlying cataract induction; however, whether deterministic (tissue reaction) or stochastic (non-threshold), has yet to be determined (ICRP, 2012). Although, the dose limit was significantly reduced, a cataract of the lens is a non-cancerous and non-fatal effect compared to cancer and non-cancer effects induced by radiation, such as coronary heart disease. In light of this information, the lens of the eye dose during CTA and other imaging procedures should be reassessed and rigorous justification of the procedure is needed. Moreover, other alternatives should be considered, such as magnetic resonance imaging (MRI). The breast has the highest equivalent dose for chest procedures with the highest cancer probability compared to the thyroid and uterus (Einstein et al., 2007). Therefore, CT procedures of the chest in girls and young females need to be carefully justified in view of the high radiation dose and probability of cancer.

4.3. Cancer risks

Table 5 presents the radiation risk per CT procedures for selected organs that received the highest radiation dose per each procedure. The thyroid has a high radiosensitivity in both males and females. Three organs have high carcinogenic radiosensitivity in females (i.e., breast, uterus, and ovary) and one organ has high carcinogenic radiosensitivity in males (i.e., testis). Organ doses were converted to radiation risks using the age- and gender-specific patient risk values provided by the ICRP (2007a). The thyroid, breasts, uterus, ovaries, and

testes are the organs with the highest exposure to radiation, and thus the highest risk per procedure because these organs are exposed to primary radiation during cerebral, chest, abdomen, and pelvis procedures, respectively. It has been reported that females are 1.6 times more radiosensitive to radiation than males (ICRP, 2007a). Therefore, extra concern should be paid to female patients, especially young patients. Patient age is a crucial factor in cancer risk estimation. It has been estimated that increasing the patient age (years) from 20 to 80 resulted in a reduction in patient risks of a factor of 5 for CT abdomen (Huda and He, 2012). Table 5 shows the cancer risk induction per procedure. The uterus and ovaries were exposed to the highest dose compared to other organs. The risks of radiation-induced cancer and hereditary effects are illustrated in Table 5 based on the risk coefficient from the ICRP (2007a). As shown in Table 5, the patient cancer risk is one cancer case per 1000 CTA chest procedures and three cancer cases per 1000 CTA abdomen procedures. The least risk for CTA procedures is thyroid cancer. The hereditary effect is low (three genetic effects per 100,000 procedures). The overall patient risk per CTA procedure ranges between 13 and 49 cancer risks per 10^5 procedures (Table 6). The highest cancer risk for patients occurs during chest (45×10^{-5}), abdomen (41×10^{-5}), and pelvis ((49×10^{-5}) CTA procedures (Table 6). This finding can be attributed to the fact that radiosensitive organs are exposed to the primary beam, hence the effective dose is higher compared to cerebral and extremity CTAs. Huda and He (2012) reported that at radiation intensity, the radiation induced cancer for females are obviously higher than those for males, while for procedures that incorporate the pelvic region, radiation risks in males were slightly higher than those in females. The risks for male and females were similar for CT abdomen. Based on the results of the current study, it is apparent that a dose below the tissue reaction effect, such as erythema and epilation, indicates tissue reaction effects occur at a certain threshold [2.0 Gy (ICRP, 2007a; UNSCEAR, 2000)]. Therefore, tissue reaction effects are not anticipated during CTA procedures in light of current practice standards. Certain measures are recommended in the literature to reduce patient risk from CTA procedures, such as use of patient dose optimization protocols, increased staff awareness, use of advanced imaging technology, and use of lead or bismuth shields during CT procedures (Deak et al., 2009; Yu et al., 2009; Sulieman et al., 2015). It is important to note that radiation risk estimation from low-dose values has many uncertainties due to long latent periods, which range between several years up to decades. In addition, radiation effects cannot be distinguished easily in low radiation dose levels from other causes due to the long latent stage between radiation exposure and cancer development (Berrington de Gonzalez et al., 2009). The cancer effect has no threshold (linear non-threshold model), hence any dose can cause cancer or genetic mutations because any DNA damage can initiate loss of cell division control. Therefore, radiation protection against ionizing radiation is crucial to the dose received during diagnostic medical exposure in CTA procedures, regardless of the quantity, and is highly relevant.

Table 6 Overall cancer risk per procedure.

CTA procedure	Mean effective dose (10^{-3} Sv)	Risk coefficient ($S\ v^{-1}$)	Cancer probability 10^{-5}
Cerebral	2.3	5.5×10^{-2}	13
Chest	8.1		45
Abdomen	7.4		41
Pelvis	8.9		49

5. Conclusions

- Patients are exposed to considerable radiation doses. Estimation of patient radiation risk helps to improve staff awareness of radiation exposure consequences from medical procedures to keep the patient radiation dose as low as reasonably achievable.
- Radiosensitive organs receive a significant radiation dose during CTA procedures, therefore rigorous reassessment of justification criteria and optimization measures of the procedure are needed and other non-ionizing radiation alternatives should be considered.
- Special concern is recommended in justifying CTA procedures for young female patients. Comprehensible justification of examinations is highly recommended, and repetition of examinations should be avoided.
- A national survey is highly recommended to establish a national diagnostic reference level for CTA. A CTA procedure is operator-dependent. Therefore, continuous training in CTA use and safety is crucial.

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