ESTIMATION OF FEMALE RADIATION DOSES AND BREAST CANCER RISK FROM CHEST CT EXAMINATIONS

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Breast organ doses, effective doses and lifetime attributable risk (LAR) of breast cancer from chest CT scans are presented for 200 female patients surveyed from 10 hospitals in the West Bank and Gaza Strip, Palestine. Patient data were collected and organized in a database from May to November 2016. Data include age (15–80 years), weight, height, and calculated body mass index. Exposure data were also recorded for every examination. Exposure data includes milliampere-second (mAs), X-ray tube kilovoltage (kVp), computed tomography dose index, dose length product, manufacturer, name and type of operated CT scanner. Organ and effective doses were evaluated using a web-based commercially available Monte Carlo software: VirtualDose™CT, a product of Virtual Phantoms, Inc. The software utilizes male and female tissue equivalent phantoms of all ages and sizes including pregnant patients. The corresponding phantom was selected for every patient according to patient's tomographic parameters. Calculated organ doses were used to estimate the LAR of breast cancer according to BEIR VII Phase 2 report. It was found that radiation doses resulting from the same exam vary widely between different hospitals, depending on the parameters used and the type of scanner. For all patients, the breast organ dose ranged from 6.5 to 28 mGy per examination, with an average breast organ dose of 15 mGy. The effective dose from chest CT scan per examination ranged from 3 to 14.7 mSv with an average of 7 mSv. For younger females (15–29 years), the LAR of breast cancer risk was estimated to be around 0.05%. For older female patients (60–79 years), the risk was ~0.001%. It was found that LAR decreases remarkably with patient's age. Values obtained in this study vary between hospitals, they are generally low and consistent with other studies reported worldwide.

INTRODUCTION

The computed tomography (CT) imaging plays a necessary role in modern medicine. CT scan is especially useful because it can simultaneously show many different types of tissue including the lungs, heart, bones, soft tissues, muscle and blood vessels. This medical diagnosis modality delivers radiation doses to patients higher than those from conventional medical imaging. CT scans account for ~20% of the total medical X-ray procedures performed worldwide. This high-dose procedure however contributes ~43% of the annual collective dose from all medical X-ray examinations to the population[1, 2]. Its rapid adoption has resulted in a dramatic increase in the average medical radiation exposure. For example, a chest CT scan typically delivers more than 100 times the radiation dose of a routine frontal and lateral chest radiograph. Furthermore, radiation exposure from CT examinations has also increased, in part due to the increased speed of image acquisition allowing vascular, cardiac and multiphase examinations, which are associated with higher doses[3]. Lack of optimized protocols could be an additional source of increased radiation dose to patients. It is also very important to keep the radiation dose as low as reasonably achievable. The optimization of radiation dose is a legal requirement in medical exposure[4].

Patients have benefited from the rapid diagnoses made possible by CT scan and from its value for monitoring chronic disease. However, there is an increasing concern regarding the risks of such radiation exposure. The typical estimated dose associated with proper use of CT scan is in the range of 2–10 mSv in which the deterministic effects are not normally a concern. Induction of cancer by radiation is a probabilistic (stochastic) effect. That is, higher radiation doses are associated with a higher likelihood of carcinogenesis, but even low doses of radiation could potentially induce carcinogenesis[5]. Major international organizations share the belief that the risk of developing cancer in patients exposed to radiation from CT scans is very low but appears to be more than hypothetical[6]. The ICRP Special Task Force 2000 reported that the doses from CT often approach or exceed levels that are known to increase the probability of nonfatal and fatal cancers[7]. Because this topic has recently attracted the attention of both the scientific community and the general public, it has become increasingly important for physicians to understand the cancer risk associated with CT scans[8].

The breast tissue of young women is one of the most radiation sensitive tissues in a human body. The sensitivity of breast tissue has been demonstrated in

the Japanese atomic bomb survivors[9]. A significant increased risk in the incidence of breast carcinoma has been demonstrated in patients who have received substantial cumulative doses to the breast from multiple diagnostic x-ray procedures and from radiation therapy for benign diseases. It has been reported that the delivery of 0.01 Gy to a woman younger than 35 years can increase the lifetime risk of breast cancer by 13.6%[10]. The breast weighting factor was increased to 0.12 from 0.05 as reported in ICRP publication 60 and ICRP publication 103[11, 12]. This is due to recent research showing the increased radiation sensitivity of breast tissue and the fact that breast cancer accounts for about one quarter of the total detriments in females[13].

The radiation dose to particular organs from any given CT scan depends upon a number of factors: the most important are the number of scans, mAs, patient size, axial scan range, scan pitch (the degree of overlap between adjacent CT slices), maximum kVp and the particular scanner design[14]. In addition, there are some factors that have an indirect effect on radiation dose. For example, choice of image reconstruction filter affects noise level and image quality, which could drive an operator to change exposure settings, and therefore affecting the radiation dose[15].

Several methods have been described in the literature on the assessment of effective from CT examinations. The most direct way of estimating doses to patients undergoing CT examinations is to measure organ doses in patient-like phantoms using dose length product (DLP) and body region-specific coefficients. These coefficients are published values of (effective dose)/DLP that can be used to convert calculated values of DLP into patient effective dose[16]. Another way of obtaining the pattern of energy deposition in patients undergoing CT examinations is by Monte Carlo calculations[17]. Patient and scanner-specific Monte Carlo simulations have been used to accurately estimate radiation dose from CT examinations[18]. To calculate patient effective and organ doses, normalized dose data based on simulation measurements published in the literature can also be used[19, 20]. Because the use of the effective dose is not recommended for the evaluation of sex-specific risks and because of the importance of the patient's age at the time of exposure in terms of breast cancer risk and other solid cancer induction risks, BEIR VII risk estimates are used to estimate the risks of radiation-induced cancer incidence and mortality from breast imaging studies rather than ICRP effective dose methods[21].

Although not intended for individual patient dose assessment, effective dose can be used for comparison and summation of dose from different modalities[22]. Such relative comparisons can be used for both generic justification and optimization of medical exposures, but not to predict absolute risk levels. Values have been derived for a variety of diagnostic procedures in radiology and nuclear medicine in order to provide a relative index of harm that can be considered for justification of medical exposures[23].

Currently, there are ~28 CT scanners in Palestine, 24 in the West Bank and 4 in Gaza Strip. CT scans account for ~20% of the total medical X-ray procedures performed in the country, and chest CT scan is one of the most frequently requested procedures. There are no local studies concerning risk evaluation from radiation exposure in CT. This work aims at the assessing breast organ doses, effective doses and quantifying the radiation risk of breast cancer incidence during chest CT examinations performed on 200 female patients randomly selected from 10 Palestinian hospitals in the West Bank and Gaza Strip.

MATERIALS AND METHODS

Assessment of organ and effective doses was performed theoretically using commercially available web-based Monte Carlo simulation software: VirtualDose™ developed by Virtual Phantoms, Inc, New York. The software is based on a comprehensive database of organ doses derived from MC simulations involving a library of 25 anatomically realistic phantoms that represent patients of different ages, body sizes and masses, and pregnancy stages[24]. VirtualDose enables users to assess organ doses, in addition to the CTDI and DLP data provided by each CT scanner. A comprehensive library of patient models covers both males and females of various ages and body weights. It is ready for use with the latest CT scanners and utilizes both ICRP-60 and ICRP-103 standards on effective dose[25].

Lifetime attributable risk (LAR) of breast cancer incidence was estimated from absorbed organ doses using age specific cancer risk models in the biological effects of ionizing radiations (BEIR) VII Phase 2 report. For each patient age, the estimated LAR of cancer incidence from 100 mSv organ equivalent dose was determined using tabulated risk values of the BEIR VII report. If data were not available for a specific age, then linear interpolation was performed from the nearest two tabulated ages[26, 27].

Demographic data for 200 female patients were collected in order to maintain consistency of the information displayed during CT scan examinations. Patient data includes age, height, weight and body mass index (BMI). The age, weight and height of patients ranged from 15 to 80 years, 50 to 110 kg and 150 to 185 cm, respectively. BMI was calculated from the average weights and heights for each hospital according to the equation BMI = weight/(height in meter)^2. Calculated average body mass indices for the 10 hospitals ranged from 25.28 to 30. The average x-ray tube voltage used in all scanners was 120 kVp. Table 1 presents the number of patients, average BMI, scanner specifications and

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Table 1. Number of patients, average BMI, scanner specifications and exposure parameters for 10 surveyed hospitals.

Hospital	No. of patients	Average BMI (kg/cm^2)	Scanner model	FID (mm)	mAs	Scan time (s)
H1	10	26.5	Philips Brilliance iCT BIG Bore, 128 slices	570	200	4
H2	15	25.4	Philips Brilliance iCT BIG Bore, 128 slices	570	200	4
H3	15	27.4	Philips Brilliance iCT BIG Bore, 128 slices	570	216	6
H4	30	28	Philips Brilliance 16 slices	570	300	20
H5	30	25.3	Siemens SOMATOM AS + 128 slices	595	168	4
H6	20	26	Philips Brilliance 64 channel with Essence technology	570	200	6
H7	20	27	Siemens SOMATOM Emotion 16 slices	535	240	20
H8	20	30	Philips Brilliance 16 slices	570	250	21
H9	20	26.6	Philips Brilliance iCT BIG Bore, 128 slices	570	200	8
H10	20	27	Philips Brilliance 16 slices	570	350	21

BMI, body mass index; FID, focus isocenter distance.

exposure related parameters for all surveyed hospitals. All scanner protocols utilized fixed mAs values. The automatic tube current modulation feature was not used in any of scans included in the study.

For the calculation of breast organ absorbed dose and total effective doses, VirtualDose requires the following input data: virtual patient, scanner type, scan protocol, kVp, mAs, pitch, bow tie filter type (head or body), beam collimation (mm), Z-over beaming length (mm) if available, the weighted computed topography dose index (CTDI$_w$), and organ weighting scheme (whether ICRP 60 or ICRP 103). These parameters were recorded for every patient based on her demographic data. Patient's virtual phantoms were selected according to International Classification of Adult Underweight and Obesity according to BMI[28] specific dose metrics (radiation dose indicators). Additionally, DLP and CT volume dose index (CTDI$_{vol}$) were recorded for every patient and every CT scan. They were obtained from a dose summary page, which appears on each CT scanner monitor and includes information about the CT scan examination. CTDI$_{vol}$ allows the comparison of scan protocols or scanners and is useful for obtaining data to compare techniques. DLP is an indicator of the dose imparted to the patient and is estimated by multiplying CTDI$_{vol}$ and scan length. In addition to being affected by the issues associated with CTDI$_{vol}$, DLP can be problematic in a limited scan range. CT scanners record the radiation exposure as a DLP in mGy cm. DLP can be multiplied by the appropriate conversion factor to calculate the effective dose in mSv. The dose length is typically saved on picture archiving and communication system (PACS) within a radiation report that appears as a separate series in the form of a screenshot[29]. CTDI$_w$ was calculated as CTDI$_w$ = CTDI$_{vol}$ × pitch. For every patient undergoing chest CT scan, VirtualDose calculates organ doses and total effective dose. Table 2 presents

Table 2. Average radiation dose indicators for all surveyed hospitals.

Hospital	CTDI$_{vol}$ (mGy) per 100 mAs	CTDI$_w$ (mGy)	Pitch	DLP (mGy cm)
H1	6	6	1	423
H2	8	8	1	410
H3	7.7	7.7	1	410
H4	11	10	0.9	978
H5	5.6	5	0.9	427
H6	6	6	1	406
H7	8	7	0.9	967
H8	15	13.5	0.9	1000
H9	3.75	3.75	1	407
H10	16.6	14.8	0.9	1067

CTDI$_w$ = CTDI$_{vol}$ × pitch; DLP = CTDI$_{vol}$ × scan length.

the average values of dose metrics for all surveyed hospitals. It also shows average values of CTDI$_{vol}$, DLP and pitch for patient during chest CT scan in each hospital.

RESULTS AND DISCUSSION

There are wide variations in patient CT dose indicators among investigated hospitals. Variations in DLP and CTDI$_{vol}$ for chest CT examination were 410–1067 mGy cm and 3.75–16.6 mGy, respectively. Additionally, mAs varied widely from 168 to 350, whereas kVp values were the same for all scanners. The variation of mAs per given examination could be expected due to the difference in patient demographics and number of detectors raws for each scanner. A low detector raw number CT scanner could result in higher patient dose due to shorter volume coverage and slower rotation times. It takes more
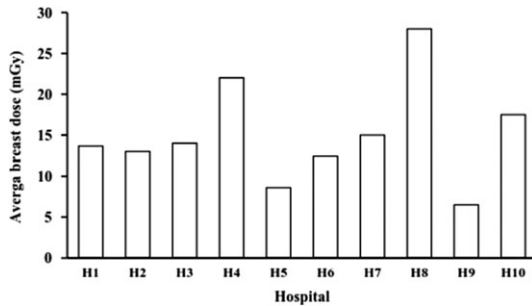
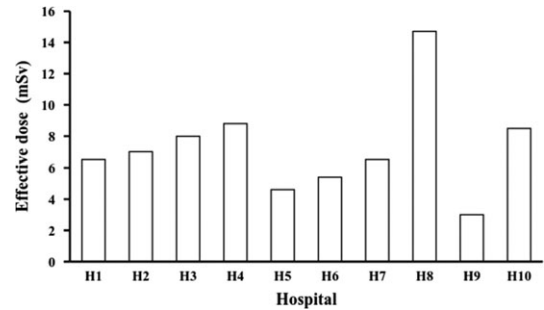Figure 1. Average breast organ doses for all hospitals.

Figure 2. Average effective doses received by patients from different hospitals.

time to cover anatomical parts, which is expected to result in higher radiation dose. Other indicators such as pitch and scan time also affect the amount of radiation dose delivered. It is interesting that mAs varied by a factor of 1.45 between hospitals H8 and H10, both of which employ the same CT scanner (16-raw number, pitch, scan time and BMI). This might indicate that scanning protocols are not standardized between hospitals.

The breast organ dose for all patients ranges from 6.5 to 28 mGy, with an average dose of 15 mGy. Variation of organ dose between individual hospitals are relatively high reaching a factor up to 4.3. In a work published by Angel *et al.*[30], they reported breast organ doses from chest CT scans in the range from 14 to 29 mGy with a mean of 19 mGy. Figure 1 presents the average organ doses obtained in this study for all investigated hospitals.

The values of calculated effective doses for all hospitals are also widely distributed between hospitals ranging from 3 mSv average value for H9 and 14.7 mSv average value for H8. The total average of effective dose for all investigated patients is 7 mSv. Figure 2 shows the average values of effective doses from all hospitals. Table 3 presents a comparison between effective doses received in this work and published in the literature.

These variations are related to the utilized protocols as well as the different methods used for the estimation of the organ dose

The tendency for variations in organ and effective doses for the same examination are seen similar for all investigated hospitals with H4 and H8 having the highest doses delivered to patients as it is the case of DLP and CTDI$_{vol}$. H5 and H9 have the lowest organ and effective doses. Again, these differences could be explained due to different scanner type, mAs, scan time and also BMI, which is high in the cases of H4 and H8, whereas H5 and H9 had low BMI values. Although the doses used in CT are higher than those used in conventional radiographic examinations, they are still 10–100 times lower than

Table 3. Estimated effective doses from chest CT examinations of the adult female patient compared with reported values in the literature[31–34].

Work	Effective dose (mSv)	
	Range (mSv)	Average (mSv)
This work	3–14.7	7
Tsai *et al.*	3.8–9.2	5.6
Origgi *et al.*	2.8–16	7.9
Aldrich *et al.*	3.8–26	9.3
Osei *et al.*	3.6–13.8	7.9

the dose levels that have been reported to increase the risk of cancer[35].

Although effective dose best reflects a patient's overall exposure to radiation, organ-specific dose may be more appropriate for estimating lifetime cancer risk for nonuniform exposures such as CT. For example, if a patient undergoes an imaging study that only irradiates the breast, her risk of cancer from that examination will primarily reflect her increased risk of breast cancer[36].

Calculated breast absorbed doses were used for risk assessment of medical radiation exposure that can induce cancer according to the Committee on the Biological Effects of Ionizing Radiations Phase 2 modeling (BEIR VII Phase 2). The BEIR VII has been derived by lifetime risk estimates for cancer incidence and mortality resulting from a single dose of 0.1 Gy at several specific ages. Estimates are shown for all cancer, leukemia, breast, all solid cancer and cancer of several specific sites. For each patient, the estimated LAR of cancer incidence from 100 mSv organ equivalent dose was determined using the table published in BEIR VII report for lifetime attributable breast cancer risk of incidence. If data were not available for a specific age, a linear interpolation was performed from the nearest two tabulated ages. This LAR from a theoretical 100 mSv organ dose was scaled linearly based on the
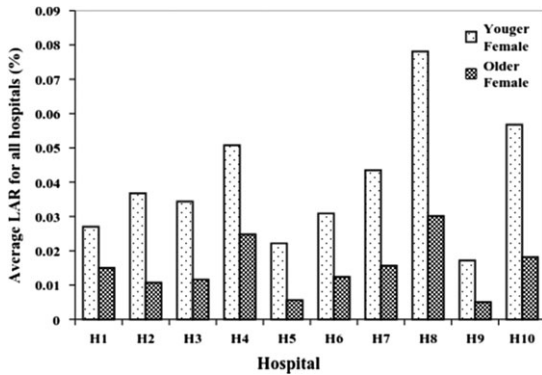
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Figure 3. Average lifetime attributable breast cancer risk incidence for two age groups: younger (15–39 years) and older (40–60 years) females.

Figure 4. Lifetime attributable risk of breast cancer incidence from female chest CT scan in hospital H5.

Table 4. Lifetime attributable breast cancer risk incidence for different age groups.

Age group (y)	15–29	30–39	40–49	50–59	60–69	70–79
LAR (%)	0.054	0.03	0.02	0.009	0.004	0.001

actual organ dose determined in the Monte Carlo simulation. For example, the breast equivalent dose for a 50-year-old woman from a standard chest CT scan is 12 mSv; the LAR of breast cancer incidence for this woman from a 100 mSv Breast dose is 70 cases per 100 000 according to the BEIR VII preferred model, so the LAR from a 12 mSv dose is (12/100) × (70/100 000) or 0.008% or 100 000/(12/100) × 70 = 1 in 6803. The normalized Lifetime attributable breast cancer risk (nLAR) was then calculated as follows:

$$nLAR(\%) = \frac{\text{Breast organ dose}}{100 \text{ mSv}}$$
$$\times \frac{\text{LAR for patient of specific age}}{100\,000} \times 100$$

(1)

This method of LAR calculation is consistent with the concept of 'Effective risk' suggested by Brenner in 2008. According to Brenner and Huda[37], the whole-body effective risk of cancer incidence R is defined as follows:

$$R = \sum r_\tau \, H_\tau \qquad (2)$$

where R is the whole-body cancer risk, r_τ is the lifetime tissue-specific cancer risk (per unit equivalent dose to tissue T) and H_τ is the tissue-specific equivalent dose for tissue T.

Figure 3 shows the average LAR of breast cancer incidence for all investigated hospitals.

Figure 4 shows the LAR of breast cancer incidence as a function of age for 26 female patients undergoing chest CT scan in hospital H5. Table 4 presents the mean LAR for breast cancer incidence for different age groups from all investigated hospitals.

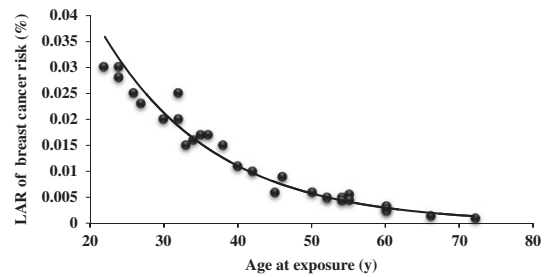Table 4 presents the lifetime attributable breast cancer risk for different age groups. The LAR decreases with age as also indicated in Figure 4. Radiosensitivity of many organs such as the breast has been observed to decrease with age[38]. Moreover, a long lag time is typical from acute radiation exposure to the development of malignancy, e.g. a 12-year minimum latency period from radiation exposure to excess breast cancer risk has been described in Japanese atomic bomb survivors[39]. Consistent with this, older patients in this study who were both less radiosensitive and less likely to survive to the development of a radiation-attributable cancer, had lower LARs than younger patients.

CONCLUSION

This work has discussed the radiation doses and associated breast organ cancer risk to female patient undergoing chest CT scan in 10 hospitals from the West Bank and Gaza Strip. Obtained dose values and risks are variable from hospital to hospital depending on the used protocols and techniques for chest CT scans. Variations between hospitals as well as average values of breast organ and effective doses are comparable with values reported in literature. This, however, raise the need for responsible national authorities to optimize CT scanning protocols for the same examinations to reduce the patient's dose as low as reasonably achievable. The radiation doses and associated risks of breast cancer incidence from chest CT scan are generally low and the benefits of using CT technology makes it indispensable in medical imaging of the chest.

REFERENCES

1. Strauss, K. J., Goske, M. J., Kaste, S. C., Bulas, D., Frush, D. P., Butler, P., Morrison, G., Callahan, M. J.

5

and Applegate, K. E. *Image gently: ten steps you can take to optimize image quality and lower CT dose for pediatric patients*. AJR Am. J. Roentgenol. **194**, 868–873 (2010).

2. Bushong, S. Radiologic Science for Technologists: Physics, Biology, and Protection, tenth edn. Riverport Lane, St. Louis, Missouri: Elsevier Mosby) (2013) ISBN 978-0-323-08135-1.

3. Smith-Bindman, R., Lipson, J., Marcus, R., Kim, K., Mahesh, M., Gould, R., Berrington de González, A. and Miglioretti, D. L. *Radiation dose associated with common computed tomography examinations and the associated lifetime attributable risk of cancer*. Arch. Intern. Med. **169**(22), 2078–2086 (2009) doi:10.1001/archinternmed.2009.427.

4. Tootell, A., Szczepura, K. and Hogg, P. *An overview of measuring and modeling dose and risk from Ionizing radiation for medical exposure*. Radiography **20**(4), 323–332 (2014).

5. Cochrane Miller, J. *Radiology rounds: ionizing radiation: CT dose reduction strategies*. A newsletter for referring Physicians Massachusetts General Hospital Department of Radiology. **8**(3), 1–2 (2010). http://www.massgeneral.org/imaging/news/radrounds/march_2010/march_2010.pdf.

6. ICRP. *Radiological protection in cone beam computed tomography（CBCT）*. ICRP Publication 129. Ann. ICRP **44**(1) (2015).

7. ICRP. *International Commission on Radiological Protection. Recommendations of the International Commission on Radiological Protection*. ICRP Publication 87 (Oxford: Pergamon Press) (2001).

8. Sarma, A., Heilbrun, M. E., Conner, K. E., Stevens, S. M., Woller, S. C. and Elliott, C. G. *Radiation and chest CT scan examinations: what do we know?* Chest J. **142**(3), 750–760 (2012).

9. Carmichael, A., Sami, A. and Dixon, J. *Breast cancer risk among the survivors of atomic bomb and patients exposed to therapeutic ionizing radiation*. Eur. J. Surg. Oncol. **29**, 475–479 (2003).

10. Yilmaz, M. H., Albayram, S., Yaşar, D., Ozer, H., Adaletli, I., Selçuk, D., Akman, C. and Altuğ, A. *Female breast radiation exposure during thorax multidetector computed tomography and the effectiveness of bismuth breast shield to reduce breast radiation dose*. J. Comput. Assist. Tomogr. **31**, 138–142 (2007).

11. International Commission on Radiation Protection (ICRP). *Recommendations of the International Commission on Radiological Protection*. ICRP Publication 60. (Oxford, UK: Pergamon Press) (1991).

12. ICRP. *2007 International Commission on Radiological Protection. Recommendations of the International Commission on Radiological Protection*. ICRP Publication 103. (Oxford: Pergamon Press) (2007).

13. Tokunaga, M., Land, C., Yamamoto, T., Asano, M., Tokuoka, S., Ezaki, H. and Nishimori, I. *Incidence of female breast cancer among atomic bomb survivors, Hiroshima and Nagasaki, 1950–1980*. Radiat. Res. **112**, 243–272 (2007).

14. HALL, E. J., Phil, D. and BRENNER, D. J. *Cancer risks from diagnostic radiology*. Br. J. Radiol. **81**, 362–378 (2008).

15. McNitt-Gray, M. F. *AAPM/RSNA Physics tutorial for residents: topics in CT. Radiation dose in CT*. Radiographics **22**, 1541–1553 (2002).

16. Deak, P. D., Smal, Y. and Kalender, W. A. *Multisection CT protocols: sex- and age-specific conversion factors used to determine effective dose from dose length product*. Radiology **257**, 158–166 (2010).

17. Jarry, G., DeMarco, J. J., Beifuss, U., Cagnon, C. H. and McNitt-Gray, M. F. *A Monte Carlo-based method to estimate radiation dose from spiral CT: from phantom testing to patient-specific models*. Phys. Med. Biol. **48**, 2645–2663 (2003).

18. Damilakis, J., Perisinakis, K., Tzedakis, A., Papadakis, A. E. and Karantanas, A. *Radiation dose to the conceptus from multidetector CT during early gestation: a method that allows for variations in maternal body size and conceptus position*. Radiology **257**, 483–489 (2010).

19. Tzedakis, A., Damilakis, J., Perisinakis, K., Stratakis, J. and Gourtsoyiannis, N. *The effect of z overscanning on patient effective dose from multidetector helical computed tomography examinations*. Med. Phys. **32**, 1621–1629 (2005).

20. Mazonakis, M., Tzedakis, A., Damilakis, J. and Gourtsoyiannis, N. *Thyroid dose from common head and neck CT examinations in children: is there an excess risk for thyroid cancer induction?* Eur. Radiol. **17**, 1352–1357 (2007).

21. Hendrick, R. E. *Radiation doses and cancer risks from breast imaging studies*. Radiology **257**(1), 246–253 (2010).

22. Saltybaeva, N., Jafari, M. E., Hupfer, M. and Kalender, W. A. *Estimates of effective dose for CT scans of the lower extremities*. Radiology **273**(1), 153–159 (2014).

23. Martin, C. J. *Effective dose: how should it be applied to medical exposures?* Br. J. Radiol. **80**(956), 639–647 (2010).

24. Ding, A., Gao, Y., Liu, H., Caracappa, P. F., Long, D. J., Bolch, W. E., Liu, B. and Xu, X. G. *VirtualDose: a software for reporting organ doses from CT for adult and pediatric patients*. Phys. Med. Biol. **60**, 5601–5625 (2015).

25. Virtual Phantoms, Inc. VirtualDose^{TM}: reduce medical CT radiation dose—increase patient safety. A Product of Virtual Phantoms, Inc. Product Data sheet (www.virtualphantoms.com).

26. BEIR VII Phase 2. Health Risks From Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase 2 (Washington, DC: The national Academies press) (2006).

27. Einstein, A. J., Henzlova, M. J. and Rajagopalan, S. *Estimating risk of cancer associated with radiation exposure from 64-slice computed tomography coronary angiography*. J Am Med Assoc **298**(3), 317–323 (2007) 10.1001/jama.298.3.317.

28. WHO. *2004: Obesity: preventing and managing the global epidemic*. WHO technical report series 894. (Geneva: World Health Organization) (2000).

29. Ridley, E. L. *CT Dose Reporting Challenged by Current Indicators*. January 27, 2012. Available on http://www.auntminnie.com/index.aspx?sec=sup_n&sub=pac&pag=dis&ItemID=98107Date (accessed 16 October 2016).

30. Angel, E. *et al*. *Dose to radiosensitive organs during routine chest CT: effects of tube current modulation*. Am. J. Roentgenol. **193**, 1340–1345 (2009) 10.2214/AJR.09.2886.

31. Tsai, H. Y., Tung, C. J., Yu, C. C. and Tyan, Y. S. *Survey of computed tomography scanners in Taiwan: dose descriptors, dose guidance levels, and effective doses*. Med. Phys. **34**(4), 1234–1243 (2007).

32. Origgi, D., Vigorito, S., Villa, G., Bellomi, M. and Tosi, G. *Survey of computed tomography techniques and absorbed dose in Italian hospitals: a comparison between two methods to estimate the dose-length product and the effective dose and to verify fulfilment of the diagnostic reference levels*. Eur. Radiol. **16**(1), 227–237 (2006).

33. Aldrich, J. E., Bilawich, A. M. and Mayo, J. R. *Radiation doses to patients receiving computed tomography examinations in British Columbia*. Can. Assoc. Radiol. J. **57**(2), 79–85 (2006).

34. Osei, E. K. and Darko, J. *A survey of organ equivalent and effective doses from diagnostic radiology procedures*. ISRN Radiol. **2013**, 204346 (2013) http://dx.doi.org/10.5402/2013/204346.

35. McCollough, C. H., Bushberg, J. T., Fletcher, J. G. and Eckel, L. J. *Answers to common questions about the use and safety of CT scans*. Mayo Clin. Proc. **90**(10), 1380–1392 (2015).

36. Smith-Bindman, R., Lipson, J., Marcus, R., Kim, K., Mahesh, M., Gould, R., Berrington de González, A. and Miglioretti, D. L. *Radiation dose associated with common computed tomography examinations and the associated lifetime attributable risk of cancer*. Arch. Intern. Med. **169**(22), 2078–2086 (2009) doi:10.1001/archinternmed.2009.427.

37. Brenner, D. and Huda, W. *Effective dose: a useful concept in diagnostic radiology*. Radiat. Prot. Dosim. **128**(4), 503–508 (2008) 10.1093/rpd/ncn056.

38. Hompson, D. E. *et al. Cancer incidence in atomic bomb survivors, Part II: solid tumors, 1958–1987*. Radiat. Res. **137**(2 Suppl), S17–S67 (1994).

39. Land, C. E., Tokunaga, M., Koyama, K., Soda, M., Preston, D. L., Nishimori, I. and Tokuoka, S. *Incidence of female breast cancer among atomic bomb survivors, Hiroshima and Nagasaki, 1950–1990*. Radiat. Res. **160**(6), 707–717 (2003).