Received:
3 February 2014

Revised:
27 June 2014

Accepted:
2 July 2014

doi: 10.1259/bjr.20140110

Cite this article as:

Tootell AK, Szczepura K, Hogg P. Comparison of effective dose and lifetime risk of cancer incidence of CT attenuation correction acquisitions and radiopharmaceutical administration for myocardial perfusion imaging. Br J Radiol 2014;87:20140110.

FULL PAPER

Comparison of effective dose and lifetime risk of cancer incidence of CT attenuation correction acquisitions and radiopharmaceutical administration for myocardial perfusion imaging

A K TOOTELL, BSc (Hons), MSc, K SZCZEPURA, BSc (Hons), MSc and P HOGG, FCR

The University of Salford, Directorate of Radiography, Salford, Greater Manchester, UK

Address correspondence to: Mr Andrew Tootell
E-mail: a.k.tootell@salford.ac.uk

Objective: To measure the organ dose and calculate effective dose from CT attenuation correction (CTAC) acquisitions from four commonly used gamma camera single photon emission CT/CT systems.

Methods: CTAC dosimetry data was collected using thermoluminescent dosimeters on GE Healthcare's Infinia™ Hawkeye™ (GE Healthcare, Buckinghamshire, UK) four- and single-slice systems, Siemens Symbia™ T6 (Siemens Healthcare, Erlangen, Germany) and the Philips Precedence (Philips Healthcare, Amsterdam, Netherlands). Organ and effective dose from the administration of ^{99m}Tc-tetrofosmin and ^{99m}Tc-sestamibi were calculated using International Commission of Radiological Protection reports 80 and 106. Using these data, the lifetime biological risk was calculated.

Results: The Siemens Symbia gave the lowest CTAC dose (1.8 mSv) followed by the GE Infinia Hawkeye single-slice (1.9 mSv), GE Infinia Hawkeye four-slice (2.5 mSv) and Philips Precedence v. 3.0. Doses were significantly lower

than the calculated doses from radiopharmaceutical administration (11 and 14 mSv for ^{99m}Tc-tetrofosmin and ^{99m}Tc-sestamibi, respectively). Overall lifetime biological risks were lower, which suggests that using CTAC data posed minimal risk to the patient. Comparison of data for breast tissue demonstrated a higher risk than that from the radiopharmaceutical administration.

Conclusion: CTAC doses were confirmed to be much lower than those from radiopharmaceutical administration. The localized nature of the CTAC exposure compared to the radiopharmaceutical biological distribution indicated dose and risk to the breast to be higher.

Advances in knowledge: This research proved that CTAC is a comparatively low-dose acquisition. However, it has been shown that there is increased risk for breast tissue especially in the younger patients. As per legislation, justification is required and CTAC should only be used in situations that demonstrate sufficient net benefit.

Single-photon emission CT (SPECT)/CT has become common place in clinical imaging, and a major role for CT is for the attenuation correction (AC) of SPECT data in myocardial perfusion imaging (MPI).^{1,2} The benefits of CT attenuation correction (CTAC) in MPI are well known and many national and international professional organizations recommend its use to improve SPECT MPI diagnostic accuracy.^{3,4} Associated with the CT acquisition is an additional radiation dose that is often considered to be low, yet very few articles quantify the dose and the associated risk.

Effective dose is a useful figure that allows for a comparison between different techniques and protocols to be made. However, it is widely recognized that the tissue weighting factors are averaged over both genders and all ages, and therefore assessment and comparison of risk for an individual patient or patient group is not advised.⁵⁻⁸ Lifetime

risk of cancer incidence, sometimes referred to as lifetime biological risk is a concept that has been suggested by a number of authors as an alternative to effective dose (*E*) to allow a comparison of risk from non-uniform dose distributions.^{5-7,9} Brenner⁵⁻⁷ is arguably the strongest advocate for a move to what he terms "effective risk" as it is argued that *E* is based on "questionable science" as the tissue-specific weighting factors used, although based on research, are established by committee decisions and do not take into account differing age and gender dependencies. Wall et al¹⁰ similarly state that *E* can and should play a role in radiation protection of radiation workers and members of the public and for the optimization of techniques involving changes in radiation quality.

The quality of the images generated by CTAC and the clinical evaluation of these to identify incidental extracardiac

findings has been discussed in the literature.^{11–13} Using phantom and human studies, it has been shown that CTAC data have the potential to allow a reporter to identify extracardiac pathology. The accuracy and confidence have been shown to vary with the protocols used. This study measured the organ dose and calculated the *E* from CTAC acquisitions from four different protocols. The protocols selected were those preset by manufacturers in four commonly used SPECT-CT scanners and were considered to be suitable to produce data of adequate quality to allow attenuation and scatter correction. The aim was to establish what differences in dose exist from the different protocols when the data produced are used for the same purpose. Using these data, the lifetime biological risk was calculated with a specific emphasis on the female breast. To contextualize these figures, organ, *E* and lifetime biological risks from the administration of radiopharmaceuticals (^{99m}Tc-tetrofosmin and ^{99m}Tc-sestamibi) were calculated from data contained in International Commission of Radiological Protection (ICRP) reports 80 and 106.^{14,15} Comparisons were also made to estimated doses using the dose-length product (DLP) and published normalized values of effective dose per DLP.¹⁶

METHODS AND MATERIALS

Organ dose (*H_T*) was measured using thermoluminescent dosimeters [TLD-100 (LiF); ThermoFisher Scientific™ Inc., Waltham, MA], and *E* was calculated from these values using the ICRP 103 weighting factors.¹⁷ TLDs were placed within critical organs in an adult CIRS ATOM® dosimetry phantom (model no. 701B; CIRS, Norfolk, VA). Four SPECT/CT systems were selected because of the variations in the CTAC protocols. The systems included GE Infinia™ Hawkeye™ (single slice), GE Infinia Hawkeye (four slice) (GE Healthcare, Buckinghamshire, UK), Siemens Symbia™ T6 (Siemens Healthcare, Erlangen, Germany) and Philips Precedence (Philips Healthcare, Amsterdam, Netherlands).

The CIRS ATOM dosimetry verification phantom is made up of the head and torso of an adult male. There are 39 contiguous slices containing differing density epoxy resin (representing bone, lung and soft tissue). The 701B is supplied with 5-mm pre-drilled holes spaced in a 30- × 30-mm matrix that are filled with tissue-equivalent plugs. Hole configuration had to be modified so that they aligned to specific internal organs. The modification was carried out by drilling additional holes as indicated in the phantom manufacturer's documentation for organ dosimetry.¹⁸

The location and range to be scanned were established by performing CT scan of the phantom thorax and the upper and lower limit of the left ventricle identified. The scan range was measured and found to be 12 cm. The upper and lower borders of the scan range were marked on the phantom using permanent ink. Radio-opaque markers were attached to the phantom to allow localization on the scan projection radiograph (SPR) on the Siemens and Philips systems. The GE systems do not acquire a SPR as the operator uses the emission data to plan the CTAC range. Using a zero refresh rate on these scanners' positioning monitors, a cobalt-57 source was placed on the marks for no more than 5 s to allow the scan range to be established. Using the reference activity of 3.7 MBq for the cobalt source, the dose from

this in 5 s at a distance of 1 cm in air would be 6.53×10^{-4} mGy. This value was considered to be negligible when calculating the dose from the TLDs in the phantom from the CTAC acquisitions.

TLDs (TLD-100™) (Thermo Scientific™, Erlangen, Germany) were cleaned and prepared in accordance with Tootell *et al.*¹⁹ TLDs were organized into batches that ensured that the percentage

Table 1. Number of thermoluminescent dosimeters (TLDs) used in critical organs

Organ	Number of TLDs
Adrenals	2
Bladder	16
Brain	11
Breast	2
Active bone marrow	85
Clavicle	20
Cranium	4
Cervical spine	2 ^a
Femora	4
Mandible	6 ^{b,c}
Pelvis	18
Ribs	18
Sternum	4
Thoraco-lumbar spine	9
Eyes ^d	2
Gallbladder	5
Heart	2
Intestine (small and large)	16
Colon	11
Small intestine	5
Kidneys	16
Liver	30
Lungs	36
Oesophagus	3
Pancreas	5
Prostate	3
Spleen	14
Stomach	11
Testes	2
Thyroid	10

^aTLDs located in the anterior of C2 and upper oesophagus were used to calculate extrathoracic organ dose.

^bTLDs located in the left and right lingula of the mandible and in the left and right of the sublingual fossa were used to calculate salivary gland organ dose.

^cTLDs located in the left and right lingula of the mandible were used to calculate oral mucosa organ dose.

^dNot included in effective dose calculations.

variation of each batch was between 1.8% and 2.2%. This was carried out by annealing and exposing all the TLDs to a uniform exposure of 120 kV and 20 mAs using a standard X-ray unit (Wolverson Arcoma, Willenhall, UK). The TLDs were ranked in order of response and organized into five batches. Each batch was calibrated using the same general radiography unit at beam energies equivalent to those of CTAC protocols using a calibrated Unfors Mult-O-Meter (Unfors RaySafe, Billdal, Sweden).

The TLDs were placed in a bespoke shielded case for transportation to the nuclear medicine departments involved in the study to prevent exposure to background radiation and any sources of radiation in the nuclear medicine departments. These TLDs were placed in the phantom in critical organs identified in ICRP 103 and the manufacturer user guide of the phantom to allow organ dose to be measured^{17,18,20} (Table 1).

A total of five TLDs remained with the phantom except during imaging for background radiation correction. CTAC imaging was performed using the standard manufacturer protocols for MPI AC (Table 2).

Three CTAC exposures were performed on each SPECT-CT system to allow a cumulative dose on the TLDs to be acquired. CT dose index volume and DLP data were recorded to be used for dose calculation and comparison to measured doses. Reading of the TLDs was carried out using a Harshaw 3500 manual TLDTM reader (Thermo Electron Corporation, Reading, UK) and WinRems software (Saint-Gobain Crystals & Detectors, Wermelskirchen, Germany). TLD readings were corrected for background and an average value for each TLD calculated. Organ doses were calculated and then used to calculate *E* and lifetime biological risk using the equations shown in Figure 1. The conversion coefficient for CT chest imaging was applied to the DLP readings and the resulting dosimetry compared to the measured readings.¹⁶

Active bone marrow dose was calculated using data on bone marrow distribution from Christy.²¹ According to statistics, ischaemic heart disease affects a larger proportion of the population of males over 55 years and females over 65 years.²² The maximum age considered by Christy is 40 years, therefore these data were used in the equation for calculating the equivalent dose to active bone marrow.

Values for r_T used in this study are tabulated in the Health Protection Agency report HPA-CRCE-028 for 11 cancers of high-risk organs over age ranges, 0–9; 10–19; 20–29 etc. up to 90–99 years.¹⁰ Cancers of other radiosensitive organs share a collective risk estimate. This study followed the method described by Li et al⁹ by applying this value to a weighted average dose of other radiosensitive organs (Figure 2).

Other organs included the salivary glands, brain, heart, kidney, gallbladder, spleen, pancreas, adrenal glands, thymus, small intestine, extrathoracic region and oral mucosa. Data collection using TLDs for lymph nodes, muscle, bone surface and skin was not performed as they are large organs/systems and it was deemed these would contribute very little to the overall *E* and lifetime biological risk calculations as only a small proportion of the tissue would be exposed during the imaging process and their exclusion would have negligible effect. The weighting for the remaining organs was averaged over those organs where dose was measured.²³

Organ and *E* dose for the radiopharmaceutical administration were calculated using data provided in ICRP report 80, report 106, diagnostic reference levels indicated in the Administration of Radioactive Substances Advisory Committee's publication and guidance published by the British Nuclear Medicine Society and adopted by the British Cardiac Society and the British Nuclear Cardiology Society.^{15,24–26} The total dose and risks for a stress and rest procedure using a total 1600 MBq of ^{99m}Tc-

Table 2. Protocols used for attenuation correction for myocardial perfusion imaging

Scanner	Scout view	Axial/helical	Tube potential (kV)	Tube current (mA)	Rotation	Slice thickness	Pitch	Automatic exposure/dose modulation
GE Infinia TM Hawkeye TM (single slice)	No	Axial	140	2.5	30 s per rotation (214° exposure)	10 mm	NA	NA
GE Infinia Hawkeye (four slice)	No	Helical	140	2.5	30 s per rotation (214° exposure)	5 mm	1.9 mm per rotation	NA
Siemens Symbia TM T6	Yes	Helical	130	20	0.6 s	3 mm	0.938	Automatic exposure control and dose modulation
Philips Precedence 16	Yes	Helical	120	30	1.5 s	5 mm	0.938	NA

NA, not applicable.

GE InfiniaTM HawkeyeTM was obtained from GE Healthcare, Buckinghamshire, UK; Philips Precedence from Philips Healthcare, Amsterdam, Netherlands; and Siemens SymbiaTM T6 from Siemens Healthcare, Erlangen, Germany.

Figure 1. Equations for (a) organ dose, (b) active bone marrow dose, (c) effective dose and (d) lifetime biological risk.¹⁸ ICRP, International Commission of Radiological Protection; TLD, thermoluminescent dosimeter.

a)

$$H_T = \frac{1}{n} \sum_j^n D_{i,j}$$

Where

H_T = equivalent organ dose
 j = 1,...,n, the number of TLDs in organ i .

b)

$$D_{abm} = \sum_k A_k \cdot D_k$$

Where

D_{abm} = Dose to active bone marrow
 A_k = proportion of active bone marrow described by Cristy²¹ ($\sum A_k = 1$)

c)

$$E = \sum_T W_T \cdot H_T$$

Where

E = effective dose to the entire body
 W_T = tissue weighting factor of tissue (T) defined by ICRP 103²⁰
 H_T = equivalent dose absorbed by tissue (T)

d)

$$R = \sum_T r_T \cdot H_T$$

Where

R = lifetime biological risk (defined as the generic lifetime radiation-attributable cancer risk)
 r_T = lifetime radiation-attributable organ-specific cancer risk estimates (per unit equivalent dose to tissue T)
 H_T = equivalent dose absorbed by tissue (T)

tetrofosmin and ^{99m}Tc -sestamibi were compared with the additional dose and risk from the CTAC acquisitions performed using parameters described in Table 2. Data for lifetime biological risk incidence were obtained from Wall et al.¹⁰

RESULTS

Table 3 shows the dose effective dose for a single CTAC acquisition of the four protocols used in the study.

Table 4 shows the comparison in E measured using TLD and E calculated using the DLP.

E and organ dose for the lung, oesophagus, colon, liver and stomach from the administration of ^{99m}Tc -tetrofosmin and

^{99m}Tc -sestamibi are shown in Table 4, and two CTAC acquisitions (performed for both rest and stress protocol) are shown in Table 5.

Following the method described by Wall et al,¹⁰ conversion to lifetime cancer risk per million (10^6) was performed and are shown in Table 6.

Consideration was given to the risk to the breast from radiopharmaceutical administration and CTAC acquisition. The phantom used in the study was male and no additional breast tissue was added, however, the acquired data allowed for a comparison of the risks within the context of this study.

DISCUSSION

Comparison of E_{DLP} and E_{TLD} showed significant differences in the two values with E_{DLP} being consistently lower. This agrees with the published literature.^{27–29} However, the average percentage difference between the two is 54.2%, which far exceeds figures quoted by Groves et al²⁷ of 18% and Hurwitz et al²⁹ of 25%. Criticisms of k state that the factors are based on old technology and old data; they are based on several scanners that were in use circa 1990 and the tissue-weighting factors used in their calculation are from ICRP 60.^{16,30,31} There are also a number of assumptions made that would increase the error in

Figure 2. Equivalent dose to other organs defined in International Commission of Radiological Protection 103.¹⁷

$$H_{\text{other}} = \frac{\sum_{\text{other organs}} w_T \cdot H_T}{\sum_{\text{other organs}} w_T}$$

Table 3. Organ and effective doses for a single CTAC acquisition measured using thermoluminescent dosimeters

Organ	Dose (mSv)			
	GE Infinia™ Hawkeye™ (single slice)	GE Infinia Hawkeye (four slice)	Siemens Symbia™ T6	Philips Precedence
Brain	0.0	0.0	0.1	0.1
Salivary glands	0.0	0.0	0.1	0.2
Thyroid	0.1	0.3	0.8	0.4
Oesophagus	1.3	1.9	1.2	2.3
Lungs	1.8	2.7	1.5	2.8
Breast	3.5	3.3	2.0	4.1
Liver	1.3	2.4	1.3	2.4
Stomach	0.5	1.2	0.9	1.5
Colon	0.0	0.1	0.2	0.2
Bladder	0.0	0.0	0.2	0.2
Testes	0.0	0.0	0.1	0.2
Active (red) bone marrow	0.6	0.6	0.9	0.9
Remainder	0.1	0.1	0.1	0.1
Effective dose	1.0	1.2	0.9	1.5

GE Infinia™ Hawkeye™ was obtained from GE Healthcare, Buckinghamshire, UK; Siemens Symbia™ T6 from Siemens Healthcare, Erlangen, Germany; and Philips Precedence from Philips Healthcare, Amsterdam, Netherlands.

the calculated effective dose. For example, the patient is assumed to be standard and, as noted by McCollough et al³² this standard patient is a little thin by today's standards (nominal body mass of 70 kg). Possible sources of error were considered and additional quality checks were performed on the TLDs. The batches were checked for uniformity and were found to be within the 2% level established before the experiment commenced at higher and lower doses of X-radiation. The images acquired as part of the CTAC exposure were also compared, and it was clear that the same region of the phantom was exposed each time. Whether the cited criticisms of k are the main contribution to these differences is unclear from this research.

Comparing E of the CTAC acquisitions to those from the administration of the radiopharmaceuticals, it can be seen that these figures are smaller but acquisition of AC data using CT does contribute additional dose to the patient. From this research, this is in the magnitude of 7.3–27.3%. Comparison of CTAC to the “typical effective dose” for a CT chest of 6.6 mSv supports the popular opinion that CTAC is a low-dose CT procedure.¹⁰

Consideration of risk again highlights large differences between the radiopharmaceutical and CTAC acquisition. When considered with the reported benefits of CTAC in improving the sensitivity and

Table 4. Effective dose using dose-length product (DLP) $\times k$ [conversion coefficient (mSv mGy⁻¹ cm)] where $k = 0.017$ ¹⁶

System protocol	CTDI _{vol} (mGy)	DLP (mGy cm)	Calculated effective dose (E_{DLP}) (mSv)	Measured effective dose (E_{TLD}) (mSv)	Percentage difference (%)
GE Infinia™ Hawkeye™ (single slice)	4.11	49	0.83	1.0	13.5
GE Infinia Hawkeye (four slice)	3.90	46	0.78	1.2	46.3
Siemens Symbia™ T6	1.75	21	0.36	0.9	85.7
Philips Precedence	3.50	42	0.71	1.5	71.5

CTDI_{vol}, CT dose index volume; TLD, thermoluminescent dosimeter.

Philips Precedence was obtained from Philips Healthcare, Amsterdam, Netherlands; GE Infinia™ Hawkeye™ from GE Healthcare, Buckinghamshire, UK; and Siemens Symbia™ T6 from Siemens Healthcare, Erlangen, Germany.

Table 5. Equivalent and effective doses following administration of radiopharmaceuticals for a rest/stress procedure and two CTAC acquisitions

Organ	Dose (mSv)					
	^{99m} Tc-tetrofosmin	^{99m} Tc-sestamibi	GE Infinia™ Hawkeye™ (single slice)	GE Infinia Hawkeye (four slice)	Siemens Symbia™ T6	Philips Precedence
Lung	5.1	7.1	3.6	5.4	3.1	5.5
Oesophagus	5.3	6.5	2.5	3.8	2.4	5.6
Colon	28.8	34.0	0.2	0.2	0.6	0.5
Liver	5.3	16.0	2.6	4.7	2.7	4.9
Stomach	7.4	10.0	1.1	2.4	1.7	3.1
Breast	3.7	5.7	7.1	6.6	4.1	8.2
<i>E</i> (mSv)	11	13.3	1.9	2.5	1.8	3.0

CTAC, CT attenuation correction; *E*, effective dose.

Philips Precedence was obtained from Philips Healthcare, Amsterdam, Netherlands; GE Infinia™ Hawkeye™ from GE Healthcare, Buckinghamshire, UK; and Siemens Symbia™ T6 from Siemens Healthcare, Erlangen, Germany.

specificity, it can be said that the reported benefits of attenuation and scatter correction using CT benefits do outweigh the risks.^{33–35}

A comparison of doses from the CTAC acquisitions showed some interesting findings. The protocol from the Siemens Symbia T6 gave the lowest *E*; this was significantly different to the protocols from the Philips Precedence and GE Hawkeye 4 slice systems (paired *t*-test, *p* < 0.05). However, statistical comparison of the protocols from the Symbia T6 to the GE Infinia Hawkeye single slice showed no statistical difference (paired *t*-test, *p* = 0.37). The Siemens Symbia T6 CT component is a higher specification system that has been shown to produce diagnostic quality CT images, so it would be expected that *E* would be higher.¹² Close examination of the imaging parameters in Table 2 does highlight two interesting features, including the use of automatic exposure control and dose modulation during the acquisition. This technology (referred to as CARE Dose4D)

manipulates the tube current in two ways. First, the tube current is varied based on the attenuation data acquired as part of the SPR. Second, attenuation in the patient is measured in real-time during the helical acquisition, where the mA is modulated to equalize the photon flux reaching the detectors during the scan. The aim of both these techniques is to keep noise levels consistent throughout the scan to allow for anatomical variations in attenuation, hence optimizing image quality and patient dose.

The GE systems have a low-specification CT component with many of the exposure parameters being fixed. At first glance, it could be assumed that with a tube current of 2.5 mA, the dose from CTAC acquisitions would be significantly lower than that of the Siemens, which has a tube current of 20 mA. However, taking the rotation time into account, the effective mAs of each slice is much higher. Calculations using the milliamp (mA) and rotation time and the angle of rotation illustrate that an effective

Table 6. Total risk (per million) from radiopharmaceutical and CTAC acquisitions using diagnostic reference levels and manufacturer protocols

Examination	Risk (per 10 ⁶)			
	Age at exposure (years)			
	40–49	50–59	60–69	70–79
^{99m} Tc-tetrofosmin	525	386	244	130
^{99m} Tc-sestamibi	608	447	284	152
CTAC GE Infinia™ Hawkeye™ (single slice)	63	52	39	24
CTAC GE Infinia Hawkeye (four slice)	101	83	61	37
CTAC Siemens Symbia™ T6	80	63	45	27
CTAC Philips Precedence	103	86	64	40

CTAC, CT attenuation correction.

Philips Precedence was obtained from Philips Healthcare, Amsterdam, Netherlands; GE Infinia™ Hawkeye™ from GE Healthcare, Buckinghamshire, UK; and Siemens Symbia™ T6 from Siemens Healthcare, Erlangen, Germany.

Table 7. Risk to breast (per million) from radiopharmaceutical and CTAC acquisitions using diagnostic reference levels and manufacturer protocols

Examination	Risk (per 10 ⁶)			
	Age at exposure (years)			
	40–49	50–59	60–69	70–79
^{99m} Tc-tetrofosmin	31	31	8	3
^{99m} Tc-sestamibi	48	48	12	5
CTAC GE Infinia TM Hawkeye TM (single slice)	60	60	15	6
CTAC GE Infinia Hawkeye (four slice)	55	55	14	5
CTAC Siemens Symbia TM T6	34	34	9	3
CTAC Philips Precedence	69	69	17	6

Philips Precedence was obtained from Philips Healthcare, Amsterdam, Netherlands; GE InfiniaTM HawkeyeTM from GE Healthcare, Buckinghamshire, UK; and Siemens SymbiaTM T6 from Siemens Healthcare, Erlangen, Germany.

milliamp seconds (mAs) of 44.6 is used for each slice in these acquisitions. Performing a *t*-test between the two GE systems together illustrates a statistically significant difference in dose ($p = 0.0002$), with the four-slice system giving the higher dose. Reasons for this could be owing to the method of acquisition as the four-slice system acquires data helically rather than axially.

The protocol used by the Phillips Precedence gave the highest *E* of the four systems. The Phillips Precedence is a 16-slice “full diagnostic” system, but as can be seen in Table 2, parameters used are significantly lower than those that would be used in diagnostic CT imaging. The opportunity for further dose reduction should be recognized by the operator and options for dose optimization on an individual patient basis utilized. The authors recognize that the imaging parameters used are set by the manufacturer, and a departmental process of optimization may have the potential to further reduce *E*. Manipulation of parameters such as mA, rotation time, pitch and/or acquisition method (helical or axial) have the potential to reduce dose while ensuring adequate data quality.

The phantom used in this study is representative of an adult male phantom, and therefore risk and calculations of *E* are specific to this gender. Dose to breast and risk calculations were carried out and are shown in Table 7. However, it is recognized that the risk to the female breast is likely to be different from the quoted figures because of the absence of additional breast tissue that would be present in the female phantom but as a comparison within the

context of this study, some interesting results were found. This comparison highlights that although the overall lifetime biological risks associated with the CTAC exposure are much lower, organ-specific risks may be comparable or higher. For example, the addition of a CTAC using the Philips Precedence protocol to a ^{99m}Tc-tetrofosmin stress and rest study in a 40–49 year old increases the risk to the breast from 31 per million to 100 per million.

CONCLUSION

The authors recognize that local optimization of administered radioactivity and CT imaging parameters should be performed and actual values for *E* and risk will vary accordingly. However, as a comparison exercise, this study provides information on the associated risks of performing CTAC. On comparison to doses and risks from the administration of radiopharmaceuticals, the CTAC poses a small increase in risk especially to the older population. However, it has been shown that consideration should be given to risks to individual organs, and in this case, practitioners should be aware of the increased risk to breast tissue especially in the younger patients. As per legislation, justification is required and CTAC should only be used in situations that demonstrate sufficient net benefit to the patient.

ACKNOWLEDGMENTS

Research was undertaken as part of the University of Salford's (Salford, UK) research programme. No funds were applied for as part of the research but equipment and material were provided by the Directorate of Radiography.

REFERENCES

- Hendel RC, Corbett JR, Cullom SJ, DePuey EG, Garcia EV, Bateman TM. The value and practice of attenuation correction for myocardial perfusion SPECT imaging: a joint position statement from the American Society of Nuclear Cardiology and the Society of Nuclear Medicine. *J Nucl Med* 2002; **43**: 273–80.
- Hesse B, Lindhardt TB, Acampa W, Anagnostopoulos C, Ballinger J, Bax JJ, et al. EANM/ESC guidelines for radionuclide imaging of cardiac function. *Eur J Nucl Med Mol Imaging* 2008; **35**: 851–85.
- Garcia TB. *Introduction to 12-lead ECG: the art of interpretation*. Jones & Bartlett Learning: Boston, MA; 2011.

4. Heller GV, Links J, Bateman TM, Ziffer JA, Ficaró E, Cohen MC, et al. American Society of Nuclear Cardiology and Society of Nuclear Medicine joint position statement: attenuation correction of myocardial perfusion SPECT scintigraphy. *J Nucl Cardiol* 2004; **11**: 229–30.
5. Brenner DJ. Effective dose: a flawed concept that could and should be replaced. *Br J Radiol* 2008; **81**: 521–3. doi: [10.1259/bjr/22942198](https://doi.org/10.1259/bjr/22942198)
6. Brenner DJ. *Effective dose—a flawed concept that could and should be replaced, International Commission on Radiological Protection*. Washington, DC: The National Academies Press; 2011.
7. Brenner DJ. We can do better than effective dose for estimating or comparing low-dose radiation risks. *Ann ICRP* 2012; **41**: 124–8. doi: [10.1016/j.icrp.2012.07.001](https://doi.org/10.1016/j.icrp.2012.07.001)
8. Ortiz P. The use of effective dose in medicine. In: *The 2nd International Symposium on the System of Radiological Protection*. United Arab Emirates: ICRP, 2013.
9. Li X, Samei E, Segars WP, Sturgeon GM, Colsher JG, Frush DP. Patient-specific radiation dose and cancer risk for pediatric chest CT. *Radiology* 2011; **259**: 862–74. doi: [10.1148/radiol.11101900](https://doi.org/10.1148/radiol.11101900)
10. Wall BF, Haylock R, Jansen JTM, Hillier MC, Hart D, Shrimpton PC. *Radiation risks from medical X-ray examinations as a function of the age and sex of the patient. Report HPA-crce-028*. Chilton, UK: Health Protection Agency; 2011.
11. Thompson J, Hogg P, Higham S, Manning D. Accurate localization of incidental findings on the computed tomography attenuation correction image: the influence of tube current variation. *Nucl Med Commun* 2013; **34**: 180–4.
12. Thompson JD, Hogg P, Manning DJ, Szczepura K, Chakraborty DP. A free-response evaluation determining value in the computed tomography attenuation correction image for revealing pulmonary incidental findings: a phantom study. *Acad Radiol* 2014; **21**: 538–45.
13. Tootell A, Vinjamuri S, Elias M, Hogg P. Clinical evaluation of the computed tomography attenuation correction map for myocardial perfusion imaging: the potential for incidental pathology detection. *Nucl Med Commun* 2012; **33**: 1122–6.
14. ICRP. Radiation dose to patients from radiopharmaceuticals (Addendum to ICRP Publication 53). ICRP Publication 80. *Ann ICRP* 1998; **28**.
15. ICRP. Radiation dose to patients from radiopharmaceuticals (Addendum 3 to ICRP Publication 53). ICRP Publication 106. *Ann ICRP* 2008; **38**: 1–97.
16. European Commission. European Commission and EUR 16262 EN, European guidelines for quality criteria for computed tomography. Luxembourg: 1999.
17. ICRP. The 2007 Recommendations of the ICRP. ICRP Publication 103. *Ann ICRP* 2007; **37**: 1–332.
18. CIRS tissue simulation and phantom technology. *Adult male phantom model number 701-D appendix 5*. Norfolk, VA: CIRS Inc.; 2010.
19. Tootell A, Szczepura K, Hogg P. Optimising the number of thermoluminescent dosimeters required for the measurement of effective dose for computed tomography attenuation correction data in SPECT/CT myocardial perfusion imaging. *Radiography* 2013; **19**: 42–7.
20. CIRS tissue simulation and phantom technology. Dosimetry Verification Phantoms Model 701-706 Data Sheet. 2012. [Cited 22 July 2014.] Available from: http://www.cirsinc.com/file/Products/701_706/701_706_DS.pdf
21. Cristy M. Active bone marrow distribution as a function of age in humans. *Phys Med Biol* 1981; **26**: 389–400.
22. Townsend NWK, Bhatnagar P, Smolina K, Nichols M, Leal J, Luengo-Fernandez R, et al. *Coronary Heart Disease Statistics 2012 Edition*. London, UK: British Heart Foundation; 2012.
23. Brady Z, Ramanauskas F, Cain TM, Johnston PN. Assessment of paediatric CT dose indicators for the purpose of optimisation. *Br J Radiol* 2012; **85**: 1488–98. doi: [10.1259/bjr/28015185](https://doi.org/10.1259/bjr/28015185)
24. ARSAC. *Notes for guidance on the clinical administration of radiopharmaceuticals and use of sealed radioactive sources*. Health Protection Agency for the Administration of Radioactive Substances Advisory Committee. Oxford, UK: 2006.
25. Arumugam PH, Reyes M, Sabharwal E, Tonge N, Underwood C SR. Procedure guidelines for radionuclide myocardial perfusion imaging with single-photon emission computed tomography (SPECT). 2012; Adopted by the British Cardiac Society, the British Nuclear Cardiology Society, and the British Nuclear Medicine Society. [Cited 22 July 2014.] Available from: http://www.bnms.org.uk/images/stories/Procedures_and_Guidelines/MPSP_procedure_guidelines_Final_12.pdf
26. ICRP. Diagnostic reference levels in medical imaging: review and additional advice. *Ann ICRP* 2001; **31**: 33–52.
27. Groves AM, Owen KE, Courtney HM, Yates SJ, Goldstone KE, Blake GM, et al. 16-detector multislice CT: dosimetry estimation by TLD measurement compared with Monte Carlo simulation. *Br J Radiol* 2004; **77**: 662–5.
28. Hashemi-Malayeri BJ, Williams JR. A practical approach for the assessment of patient doses from CT examinations. 2003. [Cited 22 July 2014.] Available from: www.dundee.ac.uk/medphys/documents/hashemi.pdf
29. Hurwitz LM, Reiman RE, Yoshizumi TT, Goodman PC, Toncheva G, Nguyen G, et al. Radiation dose from contemporary cardiothoracic multidetector CT protocols with an anthropomorphic female phantom: implications for cancer induction. *Radiology* 2007; **245**: 742–50.
30. ICRP. 1990 Recommendations of the ICRP. ICRP Publication 60. *Ann ICRP* 1991; **21**: 1–201.
31. McNitt-Gray M. *Assessing radiation dose: how to do it right, in 2011 AAPM CT dose summit*. Denver, CO: The American Association of Physicists in Medicine; 2011.
32. McCollough CH, Leng S, Yu L, Cody DD, Boone JM, McNitt-Gray MF. CT dose index and patient dose: they are not the same thing. *Radiology* 2011; **259**: 311–16. doi: [10.1148/radiol.11101800](https://doi.org/10.1148/radiol.11101800)
33. Dorbala S, Di Carli MF, Delbeke D, Abbara S, DePuey EG, Dilsizian V, et al., SNMMI/ASNC/SCCT guideline for cardiac SPECT/CT and PET/CT 1.0. *J Nucl Med* 2013; **54**: 1485–507. doi: [10.2967/jnumed.112.105155](https://doi.org/10.2967/jnumed.112.105155)
34. Giubbini RM, Gabanelli S, Lucchini S, Merli G, Puta E, Rodella C, et al. The value of attenuation correction by hybrid SPECT/CT imaging on infarct size quantification in male patients with previous inferior myocardial infarct. *Nucl Med Commun* 2011; **32**: 1026–32. doi: [10.1097/MNM.0b013e32834b4575](https://doi.org/10.1097/MNM.0b013e32834b4575)
35. Ou X, Jiang L, Huang R, Li F, Zhao Z, Li L. Computed tomography attenuation correction improves the risk stratification accuracy of myocardial perfusion imaging. *Nucl Med Commun* 2013; **34**: 495–500. doi: [10.1097/MNM.0b013e328360053a](https://doi.org/10.1097/MNM.0b013e328360053a)