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Evaluation of the radiation dose exposure and associated cancer risks in patients having preoperative parathyroid localization

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ABSTRACT

OBJECTIVE The study aimed to evaluate the total effective and organ absorbed radiation doses associated with three- and four-phase parathyroid computed tomography (CT) and sestamibi scans used for the preoperative localisation of parathyroid adenomas in a cohort of patients with primary hyperparathyroidism at a single institution. We aimed to assess the risk of cancer incidence for the organs demonstrating the highest absorbed doses for the different imaging techniques, and more specifically determine the risk for our cohort of patients.

METHODS Fifty patients with primary hyperparathyroidism had both multiphase CT and sestamibi scans. The Imaging Performance Assessment of CT Scanners (ImPACT) calculator was used to estimate the patient-effective and organ-absorbed radiations doses for all the CT examinations. For sestamibi scans, the US Nuclear Regulatory Commission NUREG/CR-6345 publication was used to estimate the dose for each patient. The attributable risks of cancer were calculated using the Health Protection Agency HPA-CRCE-028 publication.

RESULTS The mean patient total effective doses were 15.9% ± 2.8 mSv, 20.2% ± 2.8 mSv and 5.6 ± 0.24 mSv for three-phase CT, four-phase CT and sestamibi examinations, respectively. In our cohort, the highest attributable lifetime risk was for lung cancer (0.03%) after multiphase CT. This compared with a tenfold lower risk for thyroid cancer (0.003%). After sestamibi, the highest risk was for colon cancer (0.06%).

CONCLUSIONS Multiphase CT is associated with a higher radiation dose and thus a higher potential risk of cancer, but this risk is low in the older population that constituted the majority of our cohort.

KEYWORDS
4D CT – Primary hyperparathyroidism – parathyroidectomy

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Introduction

The surgical management of primary hyperparathyroidism (PHPT) has undergone significant changes over the last 20 years.[1] Minimally invasive parathyroidectomy has replaced the more traditional bilateral neck exploration as the standard of care for the treatment of PHPT. Refinements in imaging allowing for more accurate preoperative localisation have been critical to this minimally invasive approach.[2] Sestamibi-technetium-99m scintigraphy with or without single photon emission computed tomography (SPECT) in combination with ultrasonography is commonly used to localise parathyroid adenomas responsible for PHPT.[3] However, the specificity of sestamibi scans has been shown to be significantly reduced in the presence of thyroid nodules and lymphadenopathy.[4] Sensitivity is also reduced in multigland disease and with parathyroid hyperplasia.

Four-dimensional computed tomography (4D CT) is a relatively new imaging modality used for the preoperative localisation of parathyroid adenomas in patients with PHPT.[5] The technique uses standard three-dimensional CT imaging with the added 'fourth dimension' of the characteristic changes in enhancement of a parathyroid adenoma over time. Thus, a single study provides not only detailed anatomical information but also functional information based on the changes in perfusion over time.

One drawback of using 4D CT for preoperative parathyroid localisation is the relatively high radiation dose given to the patient in comparison with the more traditional localisation techniques of sestamibi and ultrasonography. This is due to the four phases being used for the CT: precontrast, arterial, venous and delayed venous. Several studies have investigated using three or two phases instead of four to reduce the radiation dose.[6,7–10] Only one published study to

date has evaluated both the patient-effective dose of radiation as well as the specific organ-absorbed doses for 4D CT.[11] This study also compared the radiation doses between 4D CT and sestamibi with single-photon emission CT (SPECT) imaging. It reported that the highest absorbed organ dose for 4D CT was seen in the thyroid, whereas for sestamibi imaging this was seen in the colon. The authors described a standardised protocol for both imaging modalities from which the results were obtained and did not look at a specific cohort of patients.

This study evaluates the total effective dose of radiation and the specific organ absorbed doses for both three- and four-phase CT, as well as sestamibi imaging, used for the preoperative localisation of parathyroid adenomas in a cohort of patients with PHPT at a single institution. We aimed to assess the risk of cancer incidence for the organs demonstrating the highest absorbed doses for the two imaging modalities, and more specifically to determine the risk for our cohort of patients.

Materials and Methods

Between August 2011 and April 2014, 50 patients had both multiphase CT and sestamibi scans with or without SPECT for the preoperative localisation of parathyroid adenomas for biochemically confirmed PHPT; 35 patients had four-phase CT scans and 15 had three-phase CT scans.

CT imaging was performed with a 64-slice CT scanner (GE Lightspeed VCT, General Electric Healthcare, WI, USA). The patient was positioned supine with a standard head rest. Imaging was performed from the angle of the mandible to the tracheal bifurcation. Unenhanced pre- and post-contrast imaging was obtained following the injection of 100ml of non-ionic iodinated contrast (Iohexol 300, Omnipaque, GE Healthcare), at a rate of 5ml/second via a pressure injector. For four-phase scans, arterial, venous and delayed venous images were obtained at 15, 65 and 100 seconds after contrast injection. For three-phase scans, the delayed venous images were omitted. The scanning parameters were 120 kV, 0.5 seconds of rotation time, 0.984 helical pitch and full-detector beam collimation of 40mm, with tube current dose modulation. The scan acquisition was at 1.25mm section thickness, with axial, sagittal and coronal 1.25mm reformations subsequently generated.

Sestamibi scans used an injection of 600–700 MBq of ^{99m}TC sestamibi. Planar imaging was obtained at 5 minutes, 20 minutes and 2 hours after injection, all with a 5-minute acquisition. At 2 hours, SPECT of the neck is also performed, 40 seconds in 64 steps.

The CT examination patient-effective and organ-absorbed radiation doses were calculated from the models described in the International Commission on Radiological Protection (IRCP) publication 103, using the Imaging Performance Assessment of CT Scanners (ImPACT) calculator, version 1.0.4.[12] This spreadsheet is a tool for calculating estimated patient organ-absorbed and total effective radiation doses from CT scanner examinations. It makes use of the National Radiological Protection Board (NRPB) Monte Carlo dose data sets produced in report SR250.[13] SR250 provides normalised organ dose data for irradiation of a mathematical phantom by a range of CT scanners. Student's two-tailed *t*-test was used to determine the level of statistical significance in the total effective dose difference between three- and four-phase CT examinations.

The patient-effective and organ-absorbed radiation doses for the sestamibi scans were derived from the US Nuclear Regulatory Commission NUREG/CR-6345 publication.[14] This document contains radiation dose estimates for a number of radiopharmaceuticals commonly used in nuclear medicine. Dose estimates are calculated using the Medical Internal Radiation Dose (MIRD) technique. Both of these methods for calculating patient effective and organ absorbed radiation doses from CT and sestamibi scan examinations have been used in a previous published study.[9] Both techniques were used to calculate radiation doses for each individual patient in our cohort.

The lifetime risks of radiation induced cancers to each patient as a function of age at exposure and sex were calculated using the Health Protection Agency HPA-CRCE-028 publication.[15] These risks are estimated on the basis of the risk models described in IRCP publication 103, together with typical organ doses for a range of common x-ray examinations derived by Monte Carlo calculation from patient dose data obtained in national surveys of UK radiology practice. These risks were calculated to be applied to the European American population only.

Results

Table 1 summarises the age distribution of our cohort of patients. Ninety percent of our patients were female and the mean age was 67 years (range 32–88 years). The mean age of the 35 patients who had four-phase CT examinations was 69 years (range 43–88 years) and 62 years (range 32–82 years) for the 15 patients having three phase CT examinations. The age distribution of patients with PHPT from the

Table 1 Age distribution in study cohort and in British Association of Endocrine and Thyroid Surgeons (BAETS) National Audit Report[16]

Age (years)	Ipswich Hospital		BAETS	
	Patients (*n*)	%	Patients (*n*)	%
< 21	0	0	56	0.8
21–30	0	0	194	2.7
31–40	2	4	403	5.7
41–50	4	8	887	12.5
51–60	7	14	1672	23.6
61–70	15	30	1984	28
71–80	14	28	1528	21.6
> 80	8	16	349	4.9
Total	50		7073	

British Association of Endocrine and Thyroid Surgeons (BAETS) fourth national audit report is also shown for comparison.[16] The majority of patients in both groups are over the age of 50, although our cohort had approximately 18% more patients over the age of 70.

The total effective radiation doses with three-phase CT, four-phase CT and sestamibi imaging were 15.9 ± 2.8 mSv, 20.2 ± 2.8 mSv and 5.6 ± 0.24 mSv, respectively (Table 2). Three-phase CT had a significantly lower effective dose than four-phase CT ($P < 0.0001$). This compares with a dose of 2.7 mSv of radiation a year for the average person living in the UK.[17] The highest estimated organ absorbed radiation doses were seen in the thyroid for CT (182.3 ± 22 mGy) and in the colon for sestamibi imaging (54.8 ± 2.5 mGy). The thyroid radiation dose for sestamibi imaging was only 1.39 mGy and the colon dose for CT was 0 mGy. Other organs with relatively high absorbed doses included the thymus, oesophagus, salivary glands and lungs for CT, and the bladder for sestamibi imaging.

Using data from the HPA-CRCE-028 publication, the lifetime attributable risk for thyroid cancer incidence after three- and four-phase CT examinations was calculated according to the age at exposure for a population of one million male and female patients (Table 3). The calculated lifetime risk for thyroid cancer in a female patient between the ages of 60 years and 69 years exposed to a four-phase CT

Table 2 Total effective and organ-absorbed radiation doses estimated for three- and four-phase computed tomography and colon cancer incidence after sestamibi imaging

Organ	Absorbed dose (mGy)								
	Three-phase CT			Four-phase CT			Sestamibi		
	Mean	± SD	Median	Mean	± SD	Median	Mean	± SD	Median
Adrenals	0.96	± 0.21	1	1.15	± 0.31	1	2.71	± 0.12	2.7
Bladder	0		0	0		0	23.3	± 1	23.1
Bone surfaces	47.9	± 6.9	44	61.6	± 6	62.5	3.65	± 0.16	3.6
Brain	36.2	± 8.2	32	45.8	± 8.7	47.5	1.13	± 0.05	1.1
Breasts	3.5	± 1.1	3.3	4.31	± 1.82	3.7	1.07	± 0.05	1.1
Colon	0		0	0		0	54.8	± 2.5	54.2
Gallbladder	0.35	± 0.1	0.3	0.4	± 0.12	0.4	11.3	± 0.5	11.2
Stomach	0.55	± 0.16	0.5	0.65	± 0.2	0.6	3.28	± 0.15	3.2
Small intestine	0		0	0		0	17	± 0.8	16.8
Heart	5.45	± 1.7	5	6.47	± 2.32	5.7	2.77	± 0.12	2.7
Kidneys	0.25	± 0.07	0.2	0.27	± 0.11	0.2	11.3	± 0.5	11.2
Liver	0.93	± 0.26	0.9	1.15	± 0.34	1	3.21	± 0.14	3.2
Lungs	23.1	± 5.7	22.2	27.7	± 6.8	25.9	1.51	± 0.07	1.5
Muscles	14.8	± 2.1	13.8	19.1	± 1.9	18.9	2.33	± 0.11	2.3
Oesophagus	38.2	± 17.6	33.4	41.9	± 22.3	32.5	1.45	± 0.06	1.4
Ovaries	0		0	0		0	8.8	± 0.4	8.7
Pancreas	0.81	± 0.25	0.8	0.98	± 0.32	0.9	3.15	± 0.14	3.1
Salivary glands	36.2	± 8.2	32	45.8	± 8.7	47.5	1.39	± 0.06	1.4
Red marrow	16	± 2.5	16.3	20.4	± 2.2	20	2.84	± 0.13	2.8
Skin	15.9	± 2.3	14.8	20.6	± 1.9	20.3	1.2	± 0.05	1.2
Spleen	0.77	± 0.21	0.8	0.96	± 0.25	0.9	3.28	± 0.15	3.2
Testes	0		0	0		0	2.2	± 0.1	2.2
Thymus	38.2	± 17.6	33.4	41.9	± 22.3	32.5	1.45	± 0.06	1.4
Thyroid	136.4	± 16.2	128.5	182.3	± 22	177	1.39	± 0.06	1.4
Uterus	0		0	0		0	7.56	± 0.34	7.5
Total effective dose (mSv)	15.9	± 2.8	15.4	20.2	± 2.8	20.1	5.6	± 0.24	5.6

CT, computed tomography; SD, standard deviation

examination was approximately 0.002%. For a female patient in the 30–39 year age group, the risk was approximately 0.02%.

For sestamibi scans the estimated lifetime attributable risk for colon cancer incidence (Table 4) was calculated. This showed that for a female patient in the 60–69 year age group, the calculated risk was approximately 0.008% for colon cancer. In the 30–39 year age group, this risk was approximately 0.02%.

We also calculated the estimated lifetime attributable risk for cancer incidence in eight different organs for three- and four-phase CT and sestamibi scans for our cohort of patients (Table 5). These calculations take into account both the age and sex distribution of our group and show the actual risk for a patient presenting to our hospital for surgery for PHPT. The highest risk from CT examinations was found for the lung and oesophagus, while for sestamibi imaging this was for the colon and bladder. For comparison, the crude cancer incidence in the UK for each of the organs is also shown.[18] Compared with the UK cancer incidence, our estimated attributable risk from four-phase CT scans was approximately 22% of the UK incidence of lung cancer. For oesophageal cancer, this risk was approximately 45% and for thyroid cancer it was approximately 31%. For sestamibi imaging, the estimated attributable risk in our cohort was approximately 11% of the UK incidence for colon cancer and approximately 16% for bladder cancer.

Table 3 Lifetime attributable risk of thyroid cancer after three- and four-phase parathyroid computed tomography (CT)

Age at exposure (years)	Cases per 1,000,000 people exposed (*n*)			
	Three-phase CT		Four-phase CT	
	Male	Female	Male	Female
0–9	246	1255	328	1677
10–19	136	709	182	948
20–29	68	355	91	474
30–39	41	177	55	237
40–49	14	82	18	109
50–59	14	27	18	36
60–69	0	14	0	18
70–79	0	0	0	0

Table 4 Lifetime attributable risk of colon cancer after sestamibi imaging

Age at exposure (years)	Cases per 1,000,000 people exposed (*n*)	
	Male	Female
0–9	817	400
10–19	669	323
20–29	537	263
30–39	433	208
40–49	328	159
50–59	235	115
60–69	137	76
70–79	66	38

Discussion

The incidence of PHPT in the general population is between 0.1% and 0.3%, with the majority of cases resulting from a solitary parathyroid adenoma.[2,3] Surgical excision of these parathyroid adenomas is the only cure. Accurate preoperative localisation is essential for targeted, minimally invasive parathyroidectomy. Compared with traditional bilateral neck exploration, this approach is associated with lower morbidity, due to decreased operative time and less dissection.

4D CT has been reported to provide increased sensitivity and specificity compared with sestamibi with SPECT in detecting parathyroid adenomas.[5,6,19] The technique provides excellent anatomic detail for preoperative localisation, as well as aiding the differentiation of adenomas from thyroid nodules and lymph nodes. In addition to being used when other imaging modalities have not been able to localise parathyroid adenomas, it has been used to improve preoperative localisation in the reoperative setting.[20]

The current study compared two different parathyroid CT protocols, three- and four-phase, with sestamibi scans in terms of the total effective radiation dose and the organ absorbed radiation doses for a cohort of patients presenting to our hospital for surgery for PHPT. We showed that there were significant differences in the total effective radiation doses, with four-phase CT scans being associated with the highest dose (20.2 mSv) and sestamibi imaging with the lowest dose (5.6mSv). Previous reported effective radiation doses for four phase or 4D CT have ranged from 5.56 mSv to 26.4 mSv.[6,11,19,21] These differences in radiation dose highlight the variation in protocols for parathyroid 4D CT imaging between institutions. Our results demonstrated that there was a significant reduction in the total effective radiation dose using three-phase CT scans compared with four-phase CT scans (15.9 vs 20.2 mSV, $P < 0.0001$).

The highest organ-absorbed radiation doses with parathyroid CT and sestamibi scans were seen in the thyroid and colon, respectively. We have also reported relatively high absorbed doses in the thymus, lungs and oesophagus for CT examinations and the bladder for sestamibi scans. This is consistent with a previous study reporting organ absorbed radiation doses from these two imaging modalities used for preoperative localisation in PHPT.[11]

The absorbed radiation dose for each individual organ is the main determinant of the potential risk of carcinogenesis in the specific organs. This risk of cancer incidence is associated with the age at exposure. The age distribution of the

Table 5 Lifetime attributable risks of cancer incidence after three- and four-phase computed tomography (CT) and sestamibi imaging in study cohort and UK cancer incidence

Organ	Cases per 1,000,000 people exposed (*n*)				
	CT		Sestamibi	UK incidence of cancer	
	Three-phase	Four-phase		Male	Female
Thyroid	28	19	0.2	30	60
Lung	268	307	17.5	770	610
Colon	0	0	100	460	410
Bladder	0	0	55	240	90
Red bone marrow	57	61	9	250	110
Oesophagus	87	122	3	180	90
Stomach	1	2	7	150	80
Breast	11	13	3	10	1550
Ovary	0	0	6	–	220

cohort of patients in this study has a higher proportion of patients over the age of 60 years compared with the BAETS national audit for PHPT patients (74% vs 54.5%).[16] Our cohort did not include anyone below the age of 30 years. As a result, the estimated risks of cancer incidence calculated for our population after CT and sestamibi imaging will not necessarily reflect the potential risks at other institutions with a different age distribution of patients. Interestingly, a recent publication examining the changes in the number of parathyroidectomy operations in England and Wales between 2000 and 2010 highlighted a doubling of operations in the 60–74 and 75 years and over age groups over the decade, suggesting an increasing age for the population presenting to surgeons for PHPT.[22]

Our results show that for thyroid and colon cancer, this risk decreases with increasing age. This is of particular significance as our study has examined the radiation exposure in a cohort of patients with a mean age of 67 years. The only previous report about radiation exposure from parathyroid imaging has highlighted the fact that the risk of thyroid and colon cancer is highest if the exposure is at a young age and that these risks are significantly reduced with age.[11] The study concluded that, because of this risk, caution should be exercised when investigating young people with PHPT, particularly in the case of thyroid cancer risk and 4D CT. These younger age groups, in particular ≤ 30 years, are not represented in our cohort and constitute only 3.5% of PHPT patients in the BAETS national audit.[18]

For our cohort of patients, we have estimated the lifetime attributable risk for cancer incidence after PHPT investigation in eight different organs, taking into account the age and sex distribution. This has shown that, of all the organs exposed, the risk of lung cancer is highest for three- and four-phase CT (approximately 0.03%) and the risk of colon cancer is highest for sestamibi scans (approximately 0.01%). The risk of thyroid cancer after CT was approximately 0.003%; tenfold lower than that for lung cancer. Thus, the overall risk from CT examinations to investigate PHPT is low in our cohort, particularly with reference to thyroid cancer. This risk would probably be outweighed by the benefit provided by the examinations in improved accuracy of preoperative localisation and the reduced morbidity associated with minimally invasive parathyroidectomy.

One important note of caution when estimating the risk of cancer induced by medical radiation is the potential uncertainty associated with these calculations. This has been reported in particular for the dose range up to 100 mSv.[23] These uncertainties have been highlighted by medical physicists in response to concerns that medically essential examinations may not be undertaken because of the associated radiation exposure risks.

Several studies have investigated using three or two phases for CT examinations instead of the four originally described.[6,7–10] These authors have reported equivalent diagnostic accuracy in localising parathyroid adenomas but with the added benefit of reducing the dose of radiation imparted to the patients. We have also demonstrated a significantly lower total effective radiation dose from three-phase CT examinations, which is, as a result, associated with lower risks for lung and thyroid cancer compared with four-phase imaging. Protocols for parathyroid CT examinations should try to minimise the radiation dose to reduce the associated risks of cancer without compromising diagnostic accuracy. Techniques to achieve this could include a reduction in the number of phases and considering altering scan parameters. An optimised protocol must balance the need for radiation dose reduction with the effects these changes may have on the detail and noise of the images obtained.

Conclusion

Four-phase parathyroid CT (4D CT) is associated with a significantly higher total effective radiation dose than three-phase CT and sestamibi scans when used for preoperative localisation. Three- and four-phase CT is potentially associated with a significantly higher attributable risk of lung cancer compared with sestamibi imaging, although the risk is low. The risk of thyroid cancer after CT is potentially significant in younger patients but is low in our cohort, due to their older age. Because of the increased risks of cancer associated with higher radiation doses, any effort to reduce the dose imparted from CT would lead to a reduction in the risk. Clinical judgement should be used in assessing these risks in individual patients in relation to the potential benefits of accurate preoperative localisation of parathyroid adenomas before minimally invasive parathyroidectomy.

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References

1. Sosa JA, Udelsman R. Minimally invasive parathyroidectomy. *Surg Oncol* 2003; **12(2)**: 125–134.
2. Harris R, Ryu H, Vu T *et al*. Modern approach to surgical intervention of the thyroid and parathyroid glands. *Semin Ultrasound CT MRI* 2012; **33**: 115–122.
3. Rodgers SE, Lew JI, Solórzano CC. Primary hyperparathyroidism. *Curr Opin Oncol* 2008; **20(1)**: 52–58.
4. Palestro CJ, Tomas MB, Tronco GG. Radionuclide imaging of the parathyroid glands. *Semin Nucl Med* 2005; **35(4)**: 266-76.
5. Rodgers SE, Hunter GJ, Hamberg LM *et al*. Improved preoperative planning for directed parathyroidectomy with 4-dimensional computed tomography. *Surgery* 2006; **140(6)**: 932–940.
6. Brown SJ, Lee JC, Christie J *et al*. Four-dimensional computed tomography for parathyroid localization: a new imaging modality. *ANZ J Surg* 2015 **85(6)**: 483–487.
7. Campbell MJ, Sicuro P, Alseidi A *et al*. Two-phase (low-dose) computed tomography is as effective as 4D-CT for identifying enlarged parathyroid glands. *Int J Surg* 2015; **14**: 80–84.
8. Raghavan P, Durst CR, Ornan DA *et al*. Dynamic CT for parathyroid disease: are multiple phases necessary? *AJNR Am J Neuroradiol* 2014; **35(10)**: 1,959–1,964.
9. Noureldine SI, Aygun N, Walden MJ *et al*. Multiphase computed tomography for localization of parathyroid disease in patients with primary hyperparathyroidism: How many phases do we really need? *Surgery* 2014; **156(6)**: 1,300–1,306.
10. Kutler DI, Moquete R, Kazam E *et al*. Parathyroid localization with modified 4D-computed tomography and ultrasonography for patients with primary hyperparathyroidism. *Laryngoscope* 2011; **121(6)**: 1,219–1,224.
11. Mahajan A, Starker LF, Ghita M *et al*. Parathyroid four-dimensional computed tomography: evaluation of radiation dose exposure during preoperative localization of parathyroid tumors in primary hyperparathyroidism. *World J Surg* 2012; **36(6)**: 1,335–1,339.
12. ImPACT's CT dosimetry tool: CT dosimetry version 1.0.4. impactscan.org. http://www.impactscan.org/ctdosimetry.htm (cited December 2016).
13. Shrimpton PC, Jones DG. Normalized organ doses for x-ray computed tomography calculated using Monte Carlo Techniques. *Radiat Prot Dosimetry* 1993; **49(1–3)**: 241–243.
14. Stabin MG, Stubbs JB, Toohey RE. *Radiation Dose Estimated for Radiopharmaceuticals* (NUREG/CR-6345). Washington, DC: US Nuclear Regulatory Commission; 1996.
15. Wall BF, Haylock R, Jansen JTM *et al*. *Radiation Risks for Medical X-Ray Examinations as a Function of the Age and Sex of the Patient* (HPA-CRCE-028). Didcot: Health Protection Agency; 2011.
16. British Association of Endocrine and Thyroid Surgeons. *Fourth National Audit Report*. Henley-on-Thames: Dendrite Clinical Systems; 2012.
17. Public Health England. *Ionising Radiation: Dose Comparisons*. London: Public Health England; 2011.
18. Cancer statistics for the UK. Cancer Research UK. http://www.cancerresearchuk.org/health-professional/cancer-statistics (cited December 2016).
19. Starker LF, Mahajan A, Björklund P *et al*. 4D parathyroid CT as the initial localization study for patients with de novo primary hyperparathyroidism. *Ann Surg Oncol* 2011; **18(6)**: 1,723–1,728.
20. Mortenson MM, Evans DB, Lee JE *et al*. Parathyroid exploration in the reoperative neck: improved preoperative localization with 4D-computed tomography. *J Am Coll Surg* 2008; **206(5)**: 888–895.
21. Madorin CA, Owen R, Coakley B *et al*. Comparison of radiation exposure and cost between dynamic computed tomography and sestamibi scintigraphy for preoperative localization of parathyroid lesions. *JAMA Surg* 2013; **148(6)**: 500–503.
22. Evans LM, Owens D, Scott-Coombes DM *et al*. A decade of change in the uptake of parathyroidectomy in England and Wales. *Ann R Coll Surg Engl* 2014; **96(5)**: 339–342.
23. Hendee WR. Policy statement of the international organization for medical physics. *Radiology* 2013; **267(2)**: 326–327.