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Cardiac Imaging

Comparison of Radiation Doses From Multislice Computed Tomography Coronary Angiography and Conventional Diagnostic Angiography

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OBJECTIVES The aim of this study was to quantify and compare effective doses from conventional angiography and multislice computed tomography (MSCT) coronary angiography using a 16-slice scanner.

BACKGROUND Multislice computed tomography is now a viable modality for cardiac imaging. However, for any diagnostic use of ionizing radiation, the risk to the patient must be considered and justified.

METHODS Multislice computed tomography angiography and conventional angiography were used to assess 180 patients with suspected coronary artery disease. Estimates of effective dose were derived from exposure data recorded for each patient examination. For each modality, a comparable calculation technique was used, based on Monte Carlo modeling of the standard Cristy phantom.

RESULTS In a subset of 91 directly comparable patients the mean effective dose for MSCT coronary angiography was 14.7 mSv (SD 2.2) and that for conventional angiography was 5.6 mSv (SD 3.6). A significant difference in effective dose was seen between the two protocols.

CONCLUSIONS The mean effective dose for MSCT coronary angiography was significantly higher than that for conventional angiography. As MSCT cardiac scanners become increasingly available, operators must be aware of the radiation dose and the factors that affect it. (J Am Coll Cardiol 2006;47:1840–5) © 2006 by the American College of Cardiology Foundation

Coronary artery disease is a common and major cause of premature death (1). Invasive coronary angiography is currently the "gold standard" investigation to detect obstructive coronary artery lesions but carries a small risk of serious complications (2). Recent developments in multislice computed tomography (MSCT) technology have enabled the detection of coronary artery disease noninvasively (3–7), and the introduction of 16-slice scanners (8,9) has improved accuracy.

Radiation dose levels in diagnostic conventional coronary angiography (CCA) are well known (10,11). Less is known about radiation doses for cardiac MSCT in the clinical setting. Coronary imaging with four-slice MSCT may give larger radiation doses than either conventional angiography or electron-beam computed tomography (CT) (12). Electrocardiogram-controlled tube current modulation has the potential to reduce patient dose in cardiac MSCT protocols (13,14). However, the advent of 16-slice scanners, and more recently 64-slice scanners, has brought increased use of MSCT in the diagnosis of coronary artery disease with little data on the accompanying radiation doses.

We compare the effective doses for a large series of patients investigated for coronary artery disease using both 16-slice CT coronary angiography and CCA. Radiation dosimetry is complex and can only estimate dose based on information about the radiographic procedure and an anatomic model used to represent the patient. We use the same anatomic model for both conventional and MSCT coronary angiography (CA), allowing a direct comparison between these techniques.

METHODS

Patient population. Patients presenting consecutively to our university hospital with suspected coronary artery disease who required in-patient CCA were recruited beforehand to undergo MSCT coronary angiography during the same hospital admission. Exclusion criteria were based on technical factors that made the patient unsuitable for MSCT coronary angiography. These were non-sinus rhythm, intolerance of beta-blockade, inability to lie flat, inability to perform a 20-s breath hold, cardiac prostheses, abnormal renal function (serum creatinine over 130 mmol/l), or an allergy to contrast media.

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Abbreviations and Acronyms

CABG = coronary artery bypass graft
CCA = conventional coronary angiography
CT = computed tomography
CTDI = computed tomography dose index
DAP = dose-area product
DLP = dose-length product
MSCT = multislice computed tomography

The study was fully approved by the local hospital ethics committee. All patients recruited during the study period from April 2003 to August 2004 were included in the evaluation.

MSCT coronary angiography protocol. Informed consent was obtained from each patient. Patients' heart rates were assessed 1 h before scanning, and if their heart rate was above 65 beats/min, 50 to 100 mg of oral metoprolol tartrate (Berk Pharmaceuticals, Eastbourne, United Kingdom) was administered.

Patients were scanned on a Sensation 16 (Siemens, Forchheim, Germany) with retrospective electrocardiogram-gated reconstruction. The scan sequence was a topogram, calcium-scoring scan, test bolus scan, and coronary angiogram.

The MSCT coronary angiography initially used 12 detectors (software Version 60A) (group 1), then 16 detectors once this became available (software Version 70A) (group 2). Scan parameters are listed in Table 1.

The test bolus scan was performed at the level of the pulmonary trunk. Sequential scans were performed every 2 s after administration of the test bolus (20 ml Iomeron 400 [Bracco, Milan, Italy] at 4 ml/s) until peak opacification in the ascending aorta was achieved.

The angiogram covered from the pulmonary trunk to just below the base of the heart. Patients with known coronary artery bypass graft (CABG) were scanned from the sternoclavicular joint with their arms cradled above their head. All scans were performed in a cranial to caudal direction. The timing of the main injection of contrast medium (105 ml Iomeron 400 at 4 ml/s) was determined by the test bolus data.

MSCT radiation dose. Many different dose indicators are used to describe medical exposures. The computed tomography dose index (CTDI) represents the radiation dose within a single slice under controlled conditions.

The CTDI may be measured free in air or within a cylindrical acrylic phantom to represent dose within the body. The CTDIw is a weighted average of CTDI values within a phantom and may be multiplied by the scan length and corrected for spiral pitch to give the dose-length product (DLP). The CTDIw and DLP are broadly indicative of patient dose and are often displayed on the scanner console (15).

To maximize accuracy, we measured CTDI in air using a Radcal 2025 electrometer and 3 cm^3 pencil ionization chamber (Radcal Corp., Monrovia, California) with a traceable calibration (Physikalisch-Technische Bundesanstalt [PTB], Berlin, Germany).

MSCT effective dose. The calculation of effective dose in MSCT is an approximation based on a number of factors. The CTDI is modified to take into account the best estimate of dose absorbed by the patient; achieved using a number of models or conversion factors. These are designed to reproduce the absorption characteristics of a "typical" patient as calculated using the established phantoms of recognized radiation dosimetry organizations. We used the basic conversion established by the National Radiological Protection Board (NRPB) in the United Kingdom from measured values of CTDI in air (16).

The NRPB used Monte Carlo modeling to estimate organ doses within an anthropomorphic geometrical phantom based on that of Cristy (17). The Imaging Performance Assessment of CT Scanners (ImPACT) group (London, United Kingdom) has matched a large range of contemporary CT scanners to the most appropriate NRPB data sets. Effective doses for MSCT were estimated using the ImPACT dosimetry calculator.

CCA technique. Experienced operators performed all conventional angiograms during routine sessions. Femoral access was used in the majority of cases. A standard sequence of projections was used, with variations according to need. Most patients (84%) also had a ventriculogram. Where a diagnostic procedure progressed to intervention, only the

Table 1. Multislice Computed Tomography Scan Parameters

	Calcium Scoring Protocols		Coronary Angiography Protocols	
	Group 1	Group 2	Group 1	Group 2
Effective mAs*	133	133 (maximum)	500	550
Set kVp	120	120	120	120
Slice width collimation (mm)	12 × 1.5	12 × 1.5	12 × 0.75	16 × 0.75
Table feed per rotation (mm)	5.7	5.7	2.8	3.4
Rotation time (s)	0.42	0.42	0.42	0.42
$CTDI_{vol}$ (mGy)	9.6	9.6 (maximum)	42.0	42.9
Overscan (mm)	36	36	18	24
Prospective ECG gating	No	Yes	No	No

*Effective mAs is a Siemens term that means the mA per rotation divided by pitch.
CTDI = computed tomography dose index; ECG = electrocardiogram.

Table 2. Patient Characteristics

	Group 1	Group 2
No. of patients	51	40
Male:female	31:20	27:13
Mean age (yrs)	64 (11)	60 (10)
Mean weight (kg)	78.9 (15.9)	85.1 (16.8)
Mean height (cm)	168 (10)	170 (9)
Mean body mass index (kg/m^2)	27.8 (4.6)	29.3 (5.2)
Mean heart rate (beats/min)	60 (10)	61 (7)

Data presented as mean (standard deviation).

diagnostic part of the procedure was included in the radiation dose estimate.

Three Siemens cardiac catheterization units were used: an Axiom Artis FC single-plane, an Axiom Artis BC biplane, and an older HiCor single-plane unit. Both Axiom units used automatic selection of additional copper filtration (from 0 to 0.9 mm). The HiCor unit was used with a fixed 0.2-mm copper filter.

CCA radiation dose. The Axiom study report for each procedure gave the projection, field size, kVp, additional filtration, and dose-area product (DAP) for each acquisition, plus the DAP for each plane for fluoroscopy. Only DAP was available from the HiCor unit, so patients were preferentially assigned to the Axiom units, depending on availability and clinical urgency.

The DAP takes into account the intensity, duration, and area of the X-ray beam and is measured by an integral device each time an exposure is made. We checked the calibration of each DAP meter using a Radcal 9010 electrometer and 90X5-6 ionization chamber with a traceable calibration (PTB). The DAP was corrected for attenuation by the couch and mattress where appropriate.

CCA effective dose. A PC-based X-ray Monte Carlo program (18) was used to estimate effective doses from conventional angiography (Radiation and Nuclear Safety Agency, Helsinki, Finland). This software is more flexible than the NRPB conversion factors used in previous studies. Like that used to estimate MSCT doses, it is based on the Cristy model. Although it can be adjusted to reflect patients of other weights and heights, this was not done, because the CT dose estimate used a standard-sized patient.

The geometry for each projection was described by field size, angulation (right-left and cranial-caudal), and focus-skin distance. The study report indicated which field was used for each run. Actual field dimensions were measured using conventional X-ray film for each nominal field size, assuming no further collimation. We assumed that the focus-image intensifier distance was 105 cm and that the patient was 5 cm from the image intensifier face.

We assumed that the fluoroscopy geometry matched that of the acquisitions. For cases that proceeded to intervention, the contribution from fluoroscopy was included in proportion to the duration of the diagnostic part of the procedure.

Statistics. Differences between parameters for the two patient groups were tested by unpaired *t* tests at the 95% confidence level (two-tailed). We assumed equal variances.

RESULTS

Patient population. Of 180 patients, 176 had a cardiac MSCT (four patients withdrew before MSCT). Because 11 patients were part of an initial test phase of cardiac MSCT protocols and incomplete data was recorded for another 12 patients, effective doses were available for coronary MSCT for 153 patients.

A further 62 patients had incomplete data for CCA, mainly where the HiCor unit was used owing to clinical urgency, and insufficient information was available to calculate effective dose accurately. Consequently 91 patients had effective dose measurements from both MSCT and conventional coronary angiography for direct comparison. The characteristics of this population are detailed in Table 2.

Effective dose from cardiac MSCT. For the 91 directly comparable patients the mean effective dose for MSCT coronary angiography (including test bolus) was 14.7 mSv (SD 2.2). This increased significantly ($p = 0.016$; two tailed) from a mean of 14.2 mSv (SD 2.0) when using 12 detectors (group 1; $n = 51$) to 15.3 mSv (SD 2.2) when using all 16 detectors (group 2; $n = 40$). There was no significant difference in scan length between the two groups, indicating that the difference is due to increased effective mA. Results are listed in Table 3.

The scan field was increased to image all recorded grafts for patients with previous CABG ($n = 14$). This increased the mean scan length from 149 mm for non-CABG patients to 206 mm for CABG patients. The mean effective dose for MSCT coronary angiography was a third higher for patients with a prior CABG: 19.4 mSv compared with 14.3 mSv for non-CABG patients.

Effective dose from CCA. For the directly comparable patients the mean DAP for CCA was 27.6 Gy·cm^2, and the mean effective dose was 5.6 mSv. There was no significant difference in DAP or fluoroscopy time between the directly comparable patients and those excluded due to incomplete data. Dose data are shown in Table 4. Figure 1 compares

Table 3. Effective Dose from Multislice Computed Tomography Coronary Angiography

	Group 1 (12 Detectors)	Group 2 (16 Detectors)	p Value
Mean effective dose from test bolus scans (mSv)	0.70 (0.21)	0.84 (0.38)	0.022
Mean scan length (mm)	151 (20)	156 (20)	0.217
Mean DLP (mGy·cm)	642 (83)	685 (85)	0.019
Mean effective dose (mSv)	13.5 (2.0)	14.5 (2.2)	0.033
Mean effective dose including test bolus (mSv)	14.2 (2.0)	15.3 (2.2)	0.016

Data presented as mean (standard deviation) with p values from a two-tailed *t* test used to test for a significant difference.
DLP = dose-length product.

Table 4. Effective Dose from Conventional Coronary Angiography

	Group 1	Group 2	All Patients	p Value
Mean no. of acquisitions	12.8 (2.3)	12.2 (3.7)	12.5 (3.0)	0.330
Mean fluoroscopy time (min)	4.5 (3.0)	4.0 (2.3)	4.3 (2.7)	0.732
Mean DAP (Gy·cm^2)	27.9 (15.1)	27.3 (16.1)	27.6 (15.5)	0.842
Mean effective dose (mSv)	5.8 (3.7)	5.4 (3.4)	5.6 (3.6)	0.674

Data presented as mean (standard deviation) with p values from a two-tailed *t* test used to test for a significant difference.
DAP = dose-area product.

the effective doses for coronary angiograms using both techniques.

The mean effective dose for CABG patients (n = 7) was 7.3 mSv and that for non-CABG patients was 5.8 mSv. The CABG sample size was too small to make a meaningful comparison.

DISCUSSION

Our study demonstrates that MSCT coronary angiography on a 16-slice scanner gives a significantly higher effective dose than CCA when evaluating patients with suspected coronary artery disease.

Values such as CTDI and DAP do not allow comparison between different imaging modalities. Effective dose takes into account the amount of radiation absorbed in different organs and tissues, the relative biologic effectiveness of the radiation used, and the differing radiosensitivities of each organ and tissue. It can therefore be used to compare different imaging modalities. We directly compared the effective dose for coronary angiography using two different techniques, which had not been performed in a patient population before.

In comparing dose estimates, differences in scanner type and scan protocol are key factors to consider. Initial dose estimates for MSCT coronary angiography using four-slice scanners were lower than our data. Those estimates used phantom measurements (12) and a DLP method (19) on a small series of patients, unlike our larger patient cohort in a real clinical setting. We found a higher effective dose than studies (14,20) assessing 16-slice CT angiography, because our average clinical scan length was longer than the scan lengths used in those phantom studies.

When we moved from 12 to 16 detectors, the radiation dose increased in proportion to the manufacturer's recommended effective mAs. This does not predict what will happen for greater numbers of detectors, because various factors influence radiation exposure, including the geometric efficiency of the beam and the resultant overscan. Bolus tracking may reduce radiation exposure, but as the test bolus scan contributed 5% to overall dose, this reduction is likely to be small.

Clearly our results refer to the protocols in place at the time of the study. Fixed exposure settings were used for all patients. Ideally, operators should optimize protocols to achieve adequate image quality for different-sized patients

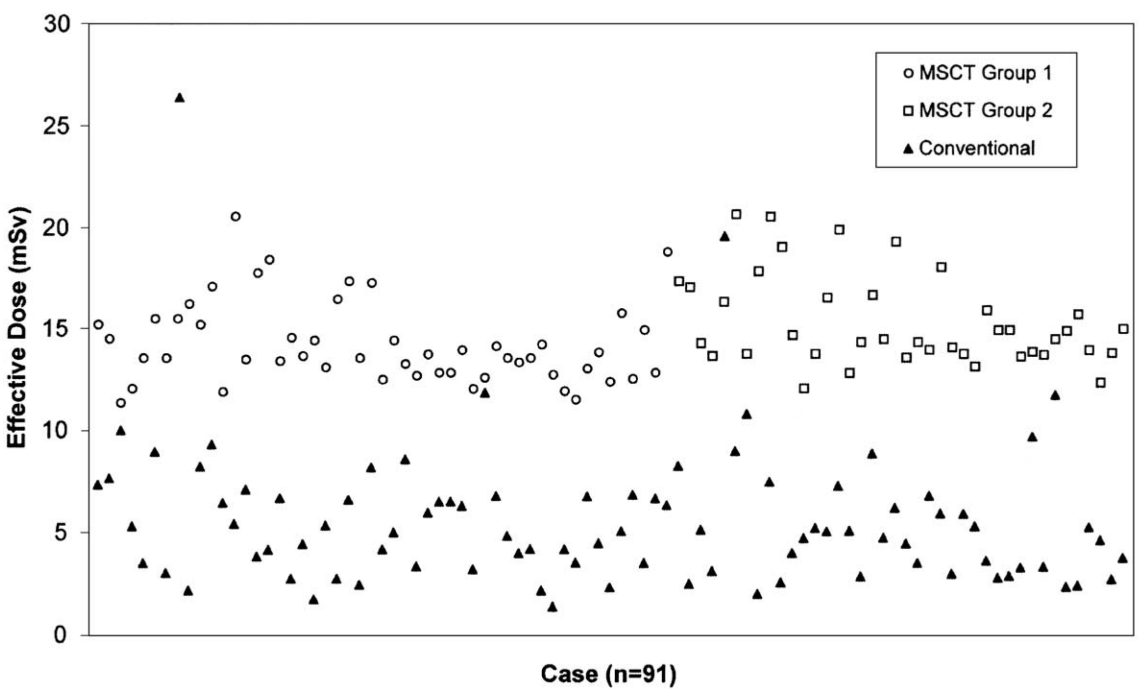

Figure 1. Effective doses from multislice computed tomography (MSCT) and conventional coronary angiography.

and should be aware of the impact this will have on patient dose.

Patients also had a calcium-scoring scan using 12 detectors, which covered from the carina to just below the base of the heart (mean scan length 182 mm). For the directly comparable patients, the mean effective dose was 4.1 mSv for group 1, but only 2.6 mSv for group 2 when electrocardiogram-controlled tube current modulation was used. The effective dose from the topogram is small, typically in the range of 0.1 to 0.2 mSv.

Our population, studied in a modern cardiac catheterization laboratory, gave similar DAP values to those in the literature for diagnostic angiography (21). Our estimates of effective doses were also similar to those from other studies. However, our use of the Monte Carlo program allowed us to better model the geometries and beam characteristics used for individual patients.

The International Commission on Radiological Protection has estimated the additional lifetime risk of fatal cancer as approximately 1 in 20,000 per mSv for the whole population (22). Although this risk is lower for the geriatric population generally investigated for coronary artery disease, significant reductions in risk will only be seen in patients in their 70s and 80s. Our subjects had an average age of 63 years.

A coronary CT angiogram with an effective dose of 14.7 mSv has a risk of inducing a fatal cancer of 1 in 1,400. Conventional coronary angiography (5.6 mSv) has a risk of 1 in 3,600, and a calcium-scoring scan (2.6 mSv) a risk of 1 in 7,700. To put this in context, a typical effective dose for a rest-stress myocardial single photon emission CT scan using technetium-99m is 8 mSv and that for a myocardial scan using thallium-201 is 18 mSv (23).

Coronary CT gives a higher risk of cancer than conventional angiography, although it is without the invasive mortality and morbidity risks. Radiation-induced skin injuries have been reported for interventional procedures carried out under fluoroscopic guidance (24,25); the risk of skin injury is greater when long or multiple procedures are carried out. Diagnostic procedures are unlikely to result in skin injury, and a comparison of skin doses from conventional angiography and MSCT is beyond the scope of this paper. Risks from contrast administration are inherent to both imaging techniques.

Study limitations. The anatomic model used to calculate effective dose will influence accuracy. Patient-specific dosimetry is not generally available for MSCT. Therefore, calculations do not allow for individual variation in weight, height, or gender but are based on a "standard" hermaphrodite adult with a weight of 71 kg and height of 174 cm. Our population was shorter and heavier than this model, reflecting the overweight population investigated for coronary artery disease. Fluoroscopy systems automatically adjust the amount of radiation delivered for body size, whereas current cardiac CT protocols do not offer this facility.

Conclusions. Coronary CT delivers a relatively high radiation dose for a purely diagnostic procedure. It also delivers a significantly higher effective dose than conventional angiography to patients being investigated for coronary artery disease. With the increasing availability of MSCT cardiac scanners, operators must be aware of the radiation dose, and the factors that affect it, for both clinical and research protocols.

As the clinical role of noninvasive CT coronary angiography develops, clinicians should remember that the use of ionizing radiation in medical exposures should be both justified and optimized. Further work is needed to determine optimal scan protocols. Future studies, using the next generation of CT scanners with 64 or more detectors, must provide information on their radiation exposure when evaluating the clinical use of cardiac CT.

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REFERENCES

1. American Heart Association. Heart Disease and Stroke Statistics—2004 Update. Dallas, TX: American Heart Association, 2003.
2. de Bono D, The Joint Audit Committee of the British Cardiac Society and Royal College of Physicians of London. Complications of diagnostic cardiac catheterisation: results from 34,041 patients in the United Kingdom confidential enquiry into cardiac catheter complications. Br Heart J 1993;70:297–300.
3. Ohnesorge B, Flohr T, Becker C, et al. Cardiac imaging by means of electrocardiographically gated multisection spiral CT: initial experience. Radiology 2000;217:564–71.
4. Becker CR, Kleffel T, Crispin A, et al. Coronary artery calcium measurement: agreement of multirow detector and electron beam CT. Am J Roentgenol 2001;176:1295–8.
5. Kopp AF, Ohnesorge B, Becker C, et al. Reproducibility and accuracy of coronary calcium measurements with multi-detector row versus electron-beam CT. Radiology 2002;225:113–9.
6. Achenbach S, Ulzheimer S, Baum U, et al. Noninvasive coronary angiography by retrospectively ECG-gated multislice spiral CT. Circulation 2000;102:2823–8.
7. Kopp AF, Schroeder S, Kuettner A, et al. Non-invasive coronary angiography with high resolution multidetector-row computed tomography. Results in 102 patients. Eur Heart J 2002;23:1714–25.
8. Ropers D, Baum U, Pohle K, et al. Detection of coronary artery stenoses with thin-slice multi-detector row spiral computed tomography and multiplanar reconstruction. Circulation 2003;107:664–6.
9. Nieman K, Cademartiri F, Lemos PA, et al. Reliable noninvasive coronary angiography with fast submillimeter multislice spiral computed tomography. Circulation 2002;106:2051–4.
10. Wilde P, Pitcher EM, Slack K. Radiation hazards for the patient in cardiological procedures. Heart 2001;85:127–30.
11. Neofotistou V, Vano E, Padovani R, et al. Preliminary reference levels in interventional cardiology. Eur Radiol 2003;13;2259–63.
12. Hunold P, Vogt FM, Schmermund A, et al. Radiation exposure during cardiac CT: effective doses at multi-detector row CT and electron-beam CT. Radiology 2003;226:145–52.
13. Jakobs TF, Becker CR, Ohnesorge B, et al. Multislice helical CT of the heart with retrospective ECG gating: reduction of radiation

exposure by ECG-controlled tube current modulation. Eur Radiol 2002;12:1081–6.
14. Flohr TG, Schoepf UJ, Kuettner A, et al. Advances in cardiac imaging with 16-section CT systems. Acad Radiol 2003;10:386–401.
15. Managing patient dose in computed tomography. ICRP Publication 87. Ann ICRP 2000;30.
16. Jones DG, Shrimpton PC. Survey of CT Practice in the UK. Part 3: Normalised Organ Doses Calculated Using Monte Carlo Techniques. NRPB-R250. London: Her Majesty's Stationary Office, 1991.
17. Cristy M. Mathematical Phantoms Representing Children of Various Ages for Use in Estimates of Internal Dose. NUREG/CR-1159, ORNL/NUREG/TM-367. Oak Ridge, TN: Oak Ridge National Laboratory, 1980.
18. Tapiovaara M, Lakkisto M, Servomaa A. A PC-Based Monte Carlo Program for calculating Patient Doses in Medical X-Ray Examinations. STUK-A139. Helsinki: Radiation and Nuclear Safety Agency, 1997.
19. McCollough CH. Patient dose in cardiac computed tomography. Herz 2003;28:1–6.
20. Poll LW, Cohnen M, Pump H, et al. Radiation exposure in cardiac multislice CT with a 4- and a 16-row detector scanner. Presented at: European Congress of Radiology (ECR); Vienna, Austria: March 2003.
21. Hart D, Hillier MC, Wall BF. Doses to Patients from Medical X-Ray Examinations in the UK—2000 Review. NRPB-W14. London: National Radiological Protection Board, 2002.
22. 1990 recommendations of the International Commission on Radiological Protection. ICRP Publication 60. Ann ICRP 1990;21.
23. Administration of Radioactive Substances Advisory Committee. Notes for Guidance on the Clinical Administration of Radiopharmaceuticals and Use of Sealed Radioactive Sources. Appendix I. Available at: http://www.advisorybodies.doh.gov.uk/arsac/nfgdec1998.pdf. Accessed March 21, 2006.
24. Avoidance of radiation injuries from medical interventional procedures. ICRP Publication 85. Ann ICRP 2000;30.
25. Aerts A, Decraene T, van den Orrrd JJ, et al. Chronic radiodermatitis following percutaneous coronary interventions: a report of two cases. J Eur Acad Dermatol Venereol 2003;17:340–3.