

Radiation exposure from Chest CT: Issues and Strategies

Concerns have been raised over alleged overuse of CT scanning and inappropriate selection of scanning methods, all of which expose patients to unnecessary radiation. Thus, it is important to identify clinical situations in which techniques with lower radiation dose such as plain radiography or no radiation such as MRI and occasionally ultrasonography can be chosen over CT scanning. This article proposes the arguments for radiation dose reduction in CT scanning of the chest and discusses recommended practices and studies that address means of reducing radiation exposure associated with CT scanning of the chest.

Key Words : Tomography, X-ray Computed; CT; Chest; Radiation Dosage

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INTRODUCTION

Increased utilization of CT to answer a plethora of clinical questions has resulted in increasing radiation exposure associated with CT scanning, thereby emphasizing the requirement for appropriate strategies to optimize and reduce existing levels of radiation exposure. Recent recognition of expanded use of CT scanning has raised serious concerns over the magnitude of radiation exposure to the population. Subsequently, it has been recommended that CT radiation dose can be reduced using various strategies (1-3). Recommended strategies for radiation dose reduction include: educating referring physicians and radiologists about the magnitude of the problem, adopting guidelines for legitimate indications for CT scanning to avoid overuse and optimizing techniques of CT scanning. This article highlights the basis for growing concerns regarding radiation dose associated with CT scanning of chest and outlines strategies for CT radiation dose reduction based on various clinical studies and published reports.

RISKS ASSOCIATED WITH CT RADIATION EXPOSURE

The fundamental parameter for describing the effects of radiation in a tissue or organ is the absorbed dose. Absorbed radiation dose is the energy deposited in the tissue by the radiation beam passing through it. Risks associated with radiation exposure are largely determined by absorbed radiation

dose. These risks may fall into two main categories, namely deterministic or stochastic effects. The deterministic effects result in cell death and are best quantified by radiation dose received by the specified organ. Each organ has a threshold level, beyond which the radiation effects to healthy tissue generally occur and increase in proportion to increasing absorbed dose (4-6). Deterministic effects are usually manifested soon after exposure. Examples of such effects include skin reddening, swelling or burns, hematologic depression, sterility and cataracts. The deterministic effects occur when a minimum threshold dose is received and their severity is based on increasing exposure. These effects are rarely seen with diagnostic radiological studies including CT scanning, as radiation doses do not reach the threshold level for deterministic effects (7, 8). Therefore, the main risks to the patient are due to stochastic effects, which can result in the induction of cancer in the subjects and genetic effects in the offspring of the irradiated subjects. In contradiction to deterministic effects, stochastic effects have no threshold level of exposure and any amount of exposure may cause the effect. Indeed, stochastic effects are those, which are not categorized by their severity but by their incidence. Based on the probability of occurrence, an example of a stochastic effect would be cancer. In reference to radiation-induced stochastic effects, latent period is defined as the length of time that elapses between a radiation exposure and provable biological effects. The latent period is longer than 30 year for most cancers except for leukemia, which may have a much shorter latent period (two years). The goal of all radiation based diagnostic techniques must be to

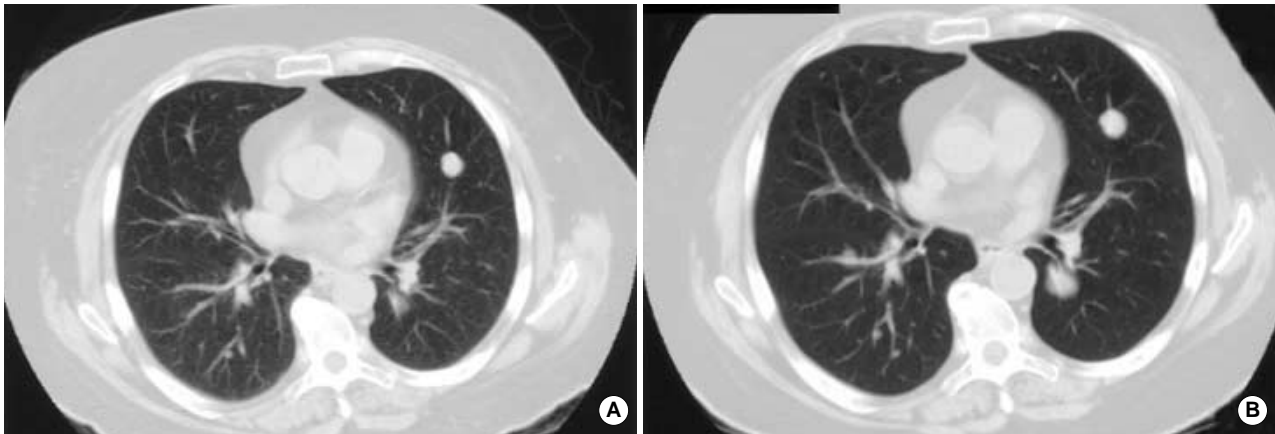


Fig. 1. Low radiation dose images can also give diagnostic quality images. Transverse CT images reveal multiple metastatic nodules in a 64-yr-old man with colon cancer who underwent a standard radiation dose CT (224 mAs) (A) and follow-up CT with 50% reduction in radiation dose (112 mAs) (B).

eliminate deterministic effects of radiation and reduce the incidence of stochastic effects.

The knowledge of stochastic risks of cancer from radiation comes mostly from the reported outcomes of radiation exposure in the survivors of the Hiroshima and Nagasaki nuclear explosions. Many publications from bodies including the European Commission's Radiation Protection Actions Committee (EUR16262), United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), International Council of Radiation Protection (ICRP) and American College of Radiology (ACR) have recently raised serious concerns about the increasing radiation exposure from CT and its potential risks, particularly to the young population (1-4). In the United States, the National Institute of Environmental Health Sciences (NIEHS), an institute of National Institute of Health is evaluating X-ray radiation for possible listing as a carcinogen on basis of the evidence of carcinogenicity in humans reported by the International Agency for Research on Cancer (IARC) (9). The IARC has classified X-rays and gamma rays as carcinogenic to humans on the basis of sufficient evidence for carcinogenicity (9).

A typical thoracic CT scan can give a radiation dose equivalent to 50-450 pairs (posterior-anterior and lateral views) of chest radiographs, depending on the CT scan protocol being utilized (10). Effective radiation dose equivalent for chest radiography in two views ranges from 0.06 to 0.25 milli-Sieverts (mSv). Corresponding doses with CT using conventional examination parameters are 3-27 mSv, and 0.3-0.55 mSv using low radiation dose CT settings (11). The International Commission of Radiological Protection (ICRP) in a publication from 1990 suggested that low level of radiation exposure could result in cancer (11, 12). The risk of radiation-induced cancer is estimated to be higher in infants and children and lower in the elderly. The scientific basis for many of these projections is weak and has been extrapolated from studies of the effects of higher radiation exposure (gamma rays from atomic

explosion), which are greater than doses received in diagnostic radiography. The estimation of risk associated with radiation dose assumes a linear relationship exists between radiation dose and subsequent risk of development of cancer.

CT Dose Index (CTDI-measured in milliGray or mGy) and dose length product (DLP measured in milliGray. Centimeter or mGy.cm) are the major CT radiation dose indicators, which are displayed on the CT planning console and give an estimate of absorbed dose. The European Guidelines on Quality Criteria for Computed Tomography (EUR 16262) have described region-specific normalized effective dose that can be multiplied with the DLP to obtain broad estimates of effective dose (measured in milli-Sievert or mSv). Alternatively, effective dose for a particular scanning technique can also be estimated with the help of mathematical anthropomorphic phantom using Monte Carlo techniques (EUR 16262).

CT RADIATION DOSE REDUCTION: ISSUES AND SPECIFIC STRATEGIES

All CT scanners comprise an X-ray tube that generates an X-ray beam during scanning. Radiation exposure to the patients from CT scanning is determined by the characteristics of the X-ray beam, which depends upon the parameters being used for CT scanning. Although reducing scanning parameters such as X-ray tube current and scan time reduces radiation exposure, they also affect the diagnostic quality of images generated during the study, especially if scanning parameters are not adjusted carefully (13, 14). Consequently, whereas low radiation dose CT images can provide diagnostic results, they may not be as esthetically pleasing as the standard radiation dose images. However, both radiologists and referring physicians should realize that the aim of CT scanning is to obtain diagnostic quality images with lowest possible radiation exposure and not "pretty pictures" at the

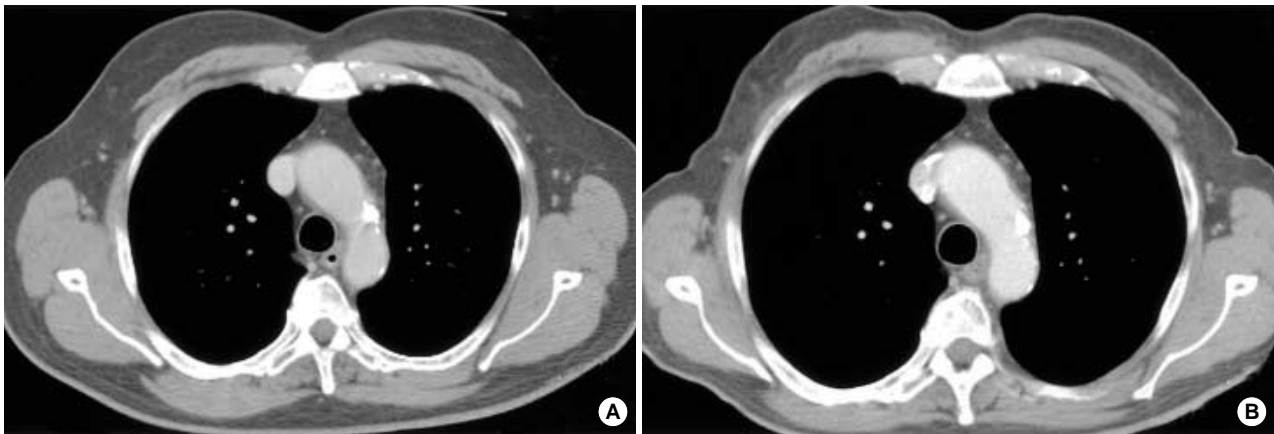


Fig. 2. Technology can aid in radiation dose reduction. Transverse CT image (224 mAs) (A) of a 44-yr-old man with chronic cough acquired with conventional scanning technique is similar to CT image (112 mAs) (B) acquired with automatic tube current modulation technique (at 50% reduction in radiation dose) in terms of diagnostic quality.

cost of greater radiation than actually needed for the study (Fig. 1) (13, 14). This is a difficult task as there is a noticeable lack of guidelines regarding details of standard scanning technique that should be used for obtaining a routine CT scan of chest (15-18).

The pace of technologic development in CT technology was highlighted in the 2003 Annual Meeting of the Radiological Society of North America in Chicago, Illinois, United States, with simultaneous unveiling of 32-, 40- and 64-slice multislice CT scanners by different vendors. Indeed, in addition to the scanning technique, radiation dose associated with CT scanning is also affected by the type of scanner such as single-slice or multislice CT. If appropriate scanning protocols are not used radiation dose associated with multislice CT scanners can be substantially greater than with single-slice CT scanners. In multislice CT scanners, radiation dose efficiency (proportion of X-ray beam passing through the patient and X-ray beam used by the scanner to generate cross-sectional CT images) improves with increase in the number of simultaneously acquired slices from 4 to 8 or 16 slices.

In view of limited recommendations and heterogeneity of scanning practices, referring physicians should be aware of CT radiation issues and contribute positively to efforts dedicated to radiation dose reduction. Many centers perform a CT scan of the chest with the same radiation exposure as the abdomen, although diagnostic quality CT of the chest can be acquired at lower radiation exposure than abdominal examinations because of lower radiation absorption in the lungs. Prasad et al. (17) have documented that chest CT image quality obtained with modification of CT scanning parameters is acceptable for evaluating normal anatomic structures with 50% reduced radiation dose. With helical CT scanning, it is also possible to enhance the speed of an exam to reduce the radiation exposure time and therefore the exposure levels (17). Regardless of the fact that faster helical CT scanners can now perform the entire torso scanning in a single breath-hold, it

is important to restrict scanning to the area of diagnostic concern, as each "extra" image and "added" scan entails "extra" radiation exposure to the patient.

Reduction in radiation dose does not justify the performance of an incomplete or suboptimal study, which may delay diagnosis or necessitate repeat examination to confirm the diagnosis. CT examinations should be limited to carefully identified indications with elimination of inappropriate requests for CT scanning. Referring physicians and radiologists should review prior imaging examinations of the patient to determine whether they answer the clinical query or a follow-up CT scan is necessary to address clinical issues. Whereas in a busy department, this may seem to be impractical, this strategy will avoid an unnecessary scan and result in a much needed triage of all patients with selection for alternative imaging when appropriate. If possible, acquisition of CT images in multiple phases such as pre-contrast phase, dynamic and delayed phases of contrast enhancement must be avoided, except when essential to diagnosis. While a justified exam must never be denied, all attempts must be made to avoid unnecessary scans. Follow-up CT exams should be judiciously spaced to answer the specific clinical concerns of the individual patient. Indeed, no CT examination should be repeated without clinical justification and should always be limited to the area of pathology under request. Physicians should regard "CT over-referrals" as unacceptable as "under-referrals."

Radiologists as well as the referring physicians must emphasize that CT protocols be tailored to reduce radiation exposure and adjusted depending on patient's age (pediatric versus adult) and size. For instance, children must never be evaluated with techniques used to scan adult patients. Referring physicians must insist that radiologists and technologists reduce radiation exposure for children. Donnelly et al. (19) have recommended use of reduced radiation dose CT scanning of chest in children weighing 20-140 lbs. Similarly, Lucaya et al. (20) have reported no significant loss of diagnostic information

with a low radiation dose (20% of standard radiation dose exam) CT technique for all indications in CT scanning of the chest. Wildberger *et al.* (21) have investigated the feasibility of optimizing radiation exposure based on body weight and documented mean reduction of radiation exposure of 45% compared with the standard technique.

Protection of radiosensitive organs like breasts, eye lenses, thyroid and gonads is especially relevant in pediatric patients and young adults, as these parts frequently lie in the pathways of X-ray beam (3, 22). In CT examinations where these structures are included in the field of examination without being the organs of clinical concern, some form of radioprotective shielding should be employed. Hopper *et al.* (23) have evaluated a bismuth radioprotective brassiere constructed for radiation dose savings to the breast during diagnostic thoracic CT scanning. With the use of bismuth shielding, there was an average radiation dose saving of 57% to the breast from CT scanning of the chest. Similarly, during CT scanning of chest, the thyroid shield can result in radiation dose savings to the thyroid gland of 74.2% (24).

CT RADIATION DOSE: RECOMMENDATIONS FOR CHEST SCANNING

Several investigators have described clinical situations where low radiation dose CT scanning must be performed (25-38). These include:

Routine Chest CT and follow-up exams

Many CT scan centers use "fixed" scanning parameters, irrespective of patient size, which results in greater radiation exposure to "smaller patients." Indeed in a recent study, Huda *et al.* (25) have documented that current CT scanning techniques used to perform chest CT examinations are not adjusted according to patient size and result in relatively high radiation doses, which could be reduced by modulating scanning techniques based on patient size. Low radiation dose CT has been reported to be as effective as standard radiation dose scans in demonstrating pathologic findings in the lung and mediastinum (Fig. 1) (26). Therefore, low radiation dose CT should be considered as a viable alternative to standard radiation dose CT, especially in young patients with benign disease and for follow-up exams (27, 28).

High resolution CT (HRCT) of the chest

Radiation dose associated with HRCT of chest is much higher than a routine chest scan. Even with reduced radiation dose scanning technique, the radiation dose of HRCT can exceed the radiation dose of a chest radiography by 100 times (29). Therefore, HRCT should be restricted to carefully selected indications such as investigation of suspected interstitial lung disease, airspace diseases and in immunocompromised patients with acute parenchymal abnormalities, where dif-

ferential diagnosis or a specific diagnosis can be made. HRCT images, acquired with significantly reduced radiation, can yield anatomic information equivalent to that obtained with standard dose CT scans in the majority of patients, without significant loss of image quality (30). Mayo *et al.* (31) have reported that combining 1.5-mm slice thickness at 20-mm interval with low radiation dose scans, an acceptable quality of HRCT can be obtained with radiation dose equivalent to that of a single chest radiograph. Interestingly, a study has compared low radiation dose thin-section CT, chest radiography, and conventional radiation dose thin-section CT in patients with chronic infiltrative lung disease and healthy control subject (32). The study reported that correct first-choice diagnosis was made more often with either CT technique than with radiography ($p < .02$). Zwirowich *et al.* (30) have reported that the low radiation dose and higher radiation dose CT studies are equivalent in the evaluation of vessels, lobar and segmental bronchi, and anatomy of secondary pulmonary lobules, and in characterizing the extent and distribution of reticulation, honeycomb cysts, and thickened interlobular septa. Studies have shown that in infants, a purely reticular pattern is rarely observed, whereas pulmonary diseases associated with overinflation are relatively frequent (29). Indeed, investigation of diseases associated with air-trapping with paired inspiratory-expiratory CT examination can provide the required information without the need for HRCT scanning and the associated greater radiation exposure. Due to the increased radiation dose, indications for pediatric pulmonary HRCT must be limited to selected cases and decided in consultation between the radiologists and the pediatricians, taking into account the pretest probability of commoner airway diseases versus less common parenchymal diseases. Studies have reported that diagnostic HRCT scans can be obtained in infants and children with 80% radiation dose saving in comparison to conventional high resolution scans (33).

Screening for lung cancer

Because of its high sensitivity for detecting small pulmonary nodules, which are the most common early manifestation of lung cancer, CT scanning of the chest fulfills most requirements of a good screening test (34). Arguments for recommending lung cancer screening with low radiation dose CT are based on the assumption that detection of a high proportion of small resectable lung cancers in the population will reduce the associated mortality, by precipitating surgical resection at an early stage (27). Promising results have been shown with significantly reduced radiation exposure in CT examinations performed for lung cancer screening (27, 35, 36). CT scans for screening purposes must be performed at lowest possible radiation dose.

Asbestos-related pleural lesions

For detection of benign asbestos-related pleural plaques and thickening, low radiation dose HRCT can give equiva-

lent results with significant reduction in radiation dose, in comparison to scans performed with standard radiation exposure (37).

Work up of hemoptysis

Patients with hemoptysis and less than two risk factors for malignancy (male, >40 yr old, >40 pack-year smoking history) and negative chest radiography can be followed with observation (38-40). On the other hand, in patients with either two or more risk factors for malignancy or persistent or recurrent hemoptysis, CT scanning and bronchoscopy are complementary examinations.

Pulmonary metastases

Although, CT scan of the chest is commonly used for assessing pulmonary metastases, it is worthwhile to remember circumstances where it might not add information that alters patient management. For instance, in subjects with low stage (T1) renal cell carcinoma with normal chest radiograph, a CT scan is not essential (41). Similarly, if chest radiograph demonstrates multiple nodules, CT is not necessary unless required for follow-up of systemic therapy. In subjects with testicular cancer and negative abdominal CT exam, chest CT scanning may not increase detection of metastases as compared with the chest radiography (42).

Detection of pulmonary nodule

Low radiation dose CT scan can be performed for detection and assessment of contours of pulmonary nodules (43). Low radiation dose scanning with 90% less radiation exposure, has been documented to have a high sensitivity in the detection of pulmonary nodules with accurate characterization of lesion margins (spicules) and the size of the nodules (43). In another experimental and clinical study with single-slice helical CT scanners, Diederich et al. (44) documented that pulmonary nodules measuring more than 5 mm can be detected reliably by low radiation dose CT scanning.

CT guided biopsy and drainage

In patients undergoing CT guided biopsies of chest, Ranavel et al. (45) have reported that differences in image quality for images acquired with lower radiation dose CT scanning did not significantly impact on the performance of the procedure and additional radiation exposure could not be justified. As image quality is usually not as critical as for diagnostic studies, in CT guided biopsies and drainage, referring physicians and radiologists should insist on use of minimum radiation exposure during CT guided procedures.

ALTERNATIVE TECHNIQUES FOR IMAGING THE CHEST

Many recent advances in CT technologies, which address

the issue of radiation optimization while maintaining image quality, are also facilitating acquisition of satisfactory images with reduced radiation exposure to patients (46-55). These include pre-patient collimation of X-ray beam, efficient X-ray filters, improved detector geometry, automatic tube current modulation (Fig. 2) and noise reduction filters. However, alternative cross-sectional imaging studies such as ultrasound and MRI should be used when they have equal diagnostic capability as an optimally performed CT examination.

Although MRI of the lung is compromised by many factors such as motion artifacts from respiration and pulsations, it offers unique advantages that include lack of radiation, higher contrast resolution, and a broad range of functional information (56). In recent years, MRI techniques have evolved considerably and have found significant applications in thoracic diseases for evaluation of the heart, major vessels, mediastinum, lung hila, musculoskeletal anatomy and neurovascular structures of the mediastinum (57). Evolution of magnetic resonance angiography using gadolinium-based contrast agents offers a promising technique for the diagnosis of acute and chronic pulmonary embolism (58). In addition, MRI has emerged as an ideal imaging technique for assessing acquired diseases of the aorta such as aortic dissection, intramural hematoma and aneurysm. It also offers a radiation-free method of imaging congenital pathology of the aorta, including aortic arch anomalies and co-arcuation (59). In pediatric chest, MRI has been reported to be more useful than other imaging modalities in evaluation of the bony thorax and mediastinum, particularly in defining the extent of the lesions and can replace CT in selected cases in the pediatric chest (60).

Functional investigation of the lungs with MRI comprising pulmonary perfusion (with contrast agents, MR angiography) and ventilation (with inhaled hyperpolarized noble gases and fluorinated gases) has been reported. Initial reports suggest that MRI of lung ventilation is more sensitive in the detection of ventilation defects than scintigraphy, CT or pulmonary function tests (61). In comparison with CT scanning, MRI provides equivalent information and, in some cases, superior detection and evaluation of the spread of pleural diseases. MRI is also useful in distinguishing malignant from benign pleural disease (62). In addition, MRI and CT have been reported to have nearly equivalent diagnostic accuracy in staging malignant pleural mesothelioma (63). MRI has also been reported to be an ideal method for visualizing diaphragmatic lesions (64). Indeed, MRI can replace CT for evaluation of certain chest conditions and physicians and radiologists must define situations where these alternative techniques such as MRI and ultrasound can provide equivalent or better information without radiation exposure.

Although there is a need for improved MRI techniques to protect patients from injuries caused by the occult presence of ferromagnetic foreign bodies or implants, in absence of these foreign bodies and implants, no scientific study has shown a health hazard associated with magnetic field exposure. At

present, there is no evidence for hazards associated with cumulative exposure to these magnetic fields.

Although role of ultrasonography in chest is limited by the inability of ultrasound waves to penetrate air-filled structures and thoracic cage bones, recent studies have confirmed that ultrasonography can be a useful diagnostic tool for various diseases of the chest (65). Palpable nodules at the chest wall (e.g. lymph nodes) and rib fractures can be characterized by ultrasonography (66). Foremost applications of ultrasonography in chest include ultrasound-guided transthoracic biopsy and catheter placement, evaluation of pleural pathology notably pleural effusion and differentiation of pleural fluid from solid masses. Ultrasonography offers the simplest and most sensitive technique to detect and measure pleural fluid as well as pericardial effusions (67). In addition, it provides useful assessment of diaphragmatic masses and peridiaphragmatic masses and fluid collections. Ultrasound guided transthoracic biopsy of masses abutting the chest wall is an effective and safe alternative to CT scanning, without associated radiation exposure (68). It allows biopsy of chest wall lesions as well as parenchymal, pleural and mediastinal lesions abutting the chest wall. Accurate needle placement, shorter procedure time, and performance in debilitated and less cooperative patients are important advantages of ultrasound guided biopsy. Transesophageal endoscopic ultrasound-guided fine needle aspiration of mediastinal lesions can obviate the need for more invasive diagnostic studies such as thoracotomy (69). In addition, echocardiography is indispensable for the assessment of congenital and acquired heart diseases.

CONCLUSIONS

In summary, recent statistics suggest a marked increase in the utilization of CT scanning and associated radiation exposure to the patient population. There is a general consensus that the current levels of CT radiation dose may be associated with increased risk of cancer. Ease of availability and "ready-made" information from CT scanning must not substitute a thorough clinical examination of all patients referred for a radiation-based examination such as CT. Although CT provides useful information, referring physicians should be aware of the associated radiation risk and need for judicious use, the possibility of reducing radiation dose and choice of alternative imaging technique for solving the clinical queries related to their patients.

REFERENCES

1. EUR 16262 Commission of the European Community. *European guidelines on quality criteria for computed tomography. Report EUR 16262 EN, 1999.*
2. UNSCEAR 2000. *The United Nations Scientific Committee on the Effects of Atomic Radiation. Health Phys 2000; 79: 314.*
3. Tack Group on Control of Radiation Dose in Computed Tomography. *Managing patient dose in Computed Tomography. A report of the International Commission on Radiological Protection. Ann ICRP 2000; 30: 7-45.*
4. Gray JE. *Safety (risk) of diagnostic radiology exposures. In: Janower ML, Linton OW, Eds. Radiation risk: a primer. Reston, VA: American College of Radiology 1996: 15-7.*
5. Wagner LK, Eifel PJ, Geise RA. *Potential biological effects following high X-ray dose interventional procedures. J Vasc Interv Radiol 1994; 5: 71-84.*
6. Huda W, Peters KR. *Radiation-induced temporary epilation after a neuroradiologically guided embolization procedure. Radiology 1994; 193: 642-4.*
7. Koenig TR, Wolff D, Mettler FA, Wagner LK. *Skin injuries from fluoroscopically guided procedures: part 1, characteristics of radiation injury. AJR Am J Roentgenol 2001; 177: 3-11.*
8. Koenig TR, Mettler FA, Wagner LK. *Skin injuries from fluoroscopically guided procedures: part 2, review of 73 cases and recommendations for minimizing dose delivered to patient. AJR Am J Roentgenol 2001; 177: 13-20.*
9. IARC Monographs on the evaluation of carcinogenic risk to humans. *Ionizing radiation, part 1: X- and gamma (γ)-radiation, and neutrons. International Agency for Research on Cancer (IARC), Lyons, France. Vol. 75, 2000.*
10. Diederich S, Lenzen H. *Radiation exposure associated with imaging of the chest: comparison of different radiographic and computed tomography techniques. Cancer 2000; 89 (Suppl 11): 2457-60.*
11. ICRP. *Recommendations of the International Commission on Radiological Protection (Publication 60). Oxford: Pergamon Press 1991.*
12. Wiest PW, Locken JA, Heintz PH, Mettler FA Jr. *CT scanning: a major source of radiation exposure. Semin Ultrasound CT MR 2002; 23: 402-10.*
13. Kalra MK, Prasad S, Saini S, Blake MA, Varghese J, Halpern EF, Thrall JH, Rhea JT. *Clinical Comparison of Standard-Dose and 50% Reduced-Dose Abdominal CT: Effect on Image Quality. AJR Am J Roentgenol 2002; 179: 1101-6.*
14. Slovis TL. *CT and computed radiography: The pictures are great, but is the radiation dose greater than required? AJR Am J Roentgenol 2002; 179: 39-41.*
15. Karabulut N, Martin DR, Yang M, Tallaksen RJ. *MR Imaging of the Chest using a Contrast-enhanced breath-hold modified three-dimensional Gradient-Echo technique: comparison with two-dimensional Gradient-Echo technique and multidetector CT. AJR Am J Roentgenol 2002; 179: 1225-33.*
16. Johkoh T, Muller NL, Nakamura H. *Multidetector spiral high-resolution computed tomography of the lungs: distribution of findings on coronal image reconstructions. J Thorac Imaging 2002; 17: 291-305.*
17. Prasad SR, Wittram C, Shepard JA, McLoud T, Rhea J. *Standard-dose and 50%-reduced-dose chest CT: comparing the effect on image quality. AJR Am J Roentgenol 2002; 179: 461-5.*
18. Prokop M. *Optimizing dosage in thoracic computerized tomography. Radiologie 2001; 41: 269-78.*
19. Donnelly LF, Emery KH, Brody AS, Laor T, Gylys-Morin VM, Anton

- CG, Thomas SR, Frush DP. *Minimizing Radiation Dose for Pediatric Body Applications of Single-Detector Helical CT: Strategies at a Large Children's Hospital*. *AJR Am J Roentgenol* 2001; 176: 303-6.
20. Lucaya J, Piqueras J, Garcia-Pena P, Enriquez G, Garcia-Macias M, Sotil J. *Low-dose high-resolution CT of the chest in children and young adults: dose, cooperation, artifact incidence, and image quality*. *AJR Am J Roentgenol* 2000; 175: 985-92.
 21. Wildberger JE, Mahnken AH, Schmitz-Rode T, Flohr T, Stargardt A, Haage P, Schaller S, Gunther RW. *Individually adapted examination protocols for reduction of radiation exposure in chest CT*. *Invest Radiol* 2001; 36: 604-11.
 22. Hidajat N, Schroder RJ, Vogl T, Schedel H, Felix R. *The efficacy of lead shielding in patient dosage reduction in computed tomography*. *Rofo Fortschr Geb Rontgenstr Neuen Bildgeb Verfahr* 1996; 165: 462-5.
 23. Hopper KD, King SH, Lobell ME, TenHave TR, Weaver JS. *The breast: in-plane x-ray protection during diagnostic thoracic CT--shielding with bismuth radioprotective garments*. *Radiology* 1997; 205: 853-8.
 24. Hopper KD. *Orbital, thyroid, and breast superficial radiation shielding for patients undergoing diagnostic CT*. *Semin Ultrasound CT MR* 2002; 23: 423-7.
 25. Huda W, Scalzetti EM, Roskopf M. *Effective doses to patients undergoing thoracic computed tomography examinations*. *Med Phys* 2000; 27: 838-44.
 26. Takahashi M, Maguire WM, Ashtari M, Khan A, Papp Z, Alberico R, Campbell W, Eacobacci T, Herman PG. *Low-dose spiral computed tomography of the thorax: comparison with the standard-dose technique*. *Invest Radiol* 1998; 33: 68-73.
 27. Diederich S, Lenzen H, Puskas Z, Koch AT, Yelbuz TM, Eameri M, Roos N, Peters PE. *Low dose computerized tomography of the thorax. Experimental and clinical studies*. *Radiologe* 1996; 36: 475-82.
 28. Huda W, Ravenel JG, Scalzetti EM. *How do radiographic techniques affect image quality and patient doses in CT?* *Semin Ultrasound CT MR* 2002; 23: 411-22.
 29. Ambrosino MM, Genieser NB, Roche KJ, Kaul A, Lawrence RM. *Feasibility of high-resolution, low-dose chest CT in evaluating the pediatric chest*. *Pediatr Radiol* 1994; 24: 6-10.
 30. Zwirewich CV, Mayo JR, Muller NL. *Low-dose high-resolution CT of lung parenchyma*. *Radiology* 1991; 180: 413-7.
 31. Mayo JR, Jackson SA, Muller NL. *High-resolution CT of the chest: radiation dose*. *AJR Am J Roentgenol* 1993; 160: 479-81.
 32. Lee KS, Primack SL, Staples CA, Mayo JR, Aldrich JE, Muller NL. *Chronic infiltrative lung disease: comparison of diagnostic accuracies of radiography and low- and conventional-dose thin-section CT*. *Radiology* 1994; 191: 669-73.
 33. Reuter M, Oppermann HC, Ankermann T, Biederer J, Heller M. *High-resolution computed tomography of the lungs in pediatric patients*. *Rofo Fortschr Geb Rontgenstr Neuen Bildgeb Verfahr* 2002; 174: 684-95.
 34. Diederich S, Wormanns D, Heindel W. *Low-dose CT: new tool for screening lung cancer?* *Eur Radiol* 2001; 11: 1916-24.
 35. Oguchi K, Sone S, Kiyono K, Takashima S, Maruyama Y, Hasegawa M, Feng L. *Optimal tube current for lung cancer screening with low-dose spiral CT*. *Acta Radiol* 2000; 41: 352-6.
 36. Kaneko M, Kusumoto M, Kobayashi T, Moriyama N, Naruke T, Ohmatsu H, Kakinuma R, Eguchi K, Nishiyama H, Matsui E. *Computed tomography screening for lung carcinoma in Japan*. *Cancer* 2000; 89: 2485-8.
 37. Michel JL, Reynier C, Avy G, Bard JJ, Gabrillargues D, Catilina P. *An assessment of low-dose high resolution CT in the detection of benign asbestos-related pleural abnormalities*. *J Radiol* 2001; 82: 922-3.
 38. Lederle FA, Nichol KL, Parenti CM. *Bronchoscopy to evaluate hemoptysis in older men with nonsuspicious chest roentgenograms*. *Chest* 1989; 95: 1043-7.
 39. Haponik EF, Britt EJ, Smith PL, Bleecker ER. *Computed chest tomography in the evaluation of hemoptysis. Impact on diagnosis and treatment*. *Chest* 1987; 91: 80-5.
 40. Set PA, Flower CD, Smith IE, Chan AP, Twentyman OP, Shneerson JM. *Hemoptysis: comparative study of the role of CT and fiberoptic bronchoscopy*. *Radiology* 1993; 189: 677-80.
 41. Lim DJ, Carter MF. *Computerized tomography in the preoperative staging for pulmonary metastases in patients with renal cell carcinoma*. *J Urol* 1993; 150: 1112-4.
 42. See WA, Hoxie L. *Chest staging in testis cancer patients: imaging modality selection based upon risk assessment as determined by abdominal computerized tomography scan results*. *J Urol* 1993; 150: 874-8.
 43. Gartenschlager M, Schweden F, Gast K, Westermeier T, Kauczor H, von Zitzewitz H, Thelen M. *Pulmonary nodules: detection with low-dose vs conventional-dose spiral CT*. *Eur Radiol* 1998; 8: 609-14.
 44. Diederich S, Lenzen H, Windmann R, Puskas Z, Yelbuz TM, Henneken S, Klaiber T, Eameri M, Roos N, Peters PE. *Pulmonary nodules: experimental and clinical studies at low-dose CT*. *Radiology* 1999; 213: 289-98.
 45. Ravenel JG, Scalzetti EM, Huda W, Garrisi W. *Radiation exposure and image quality in chest CT examinations*. *AJR Am J Roentgenol* 2001; 177: 279-84.
 46. Toth TL, Bromberg NB, Pan TS, Rabe J, Woloschek SJ, Li J, Seidenschneider GE. *A dose reduction x-ray beam positioning system for high-speed multislice CT scanners*. *Med Phys* 2000; 27: 2659-68.
 47. Fox SH, Toth T. *Dose reduction on GE CT scanners*. *Pediatr Radiol* 2002; 32: 718-23.
 48. Kachelriess M, Watzke O, Kalender WA. *Generalized multi-dimensional adaptive filtering for conventional and spiral single-slice, multi-slice, and cone-beam CT*. *Med Phys* 2001; 28: 475-90.
 49. Greess H, Wolf H, Baum U, Lell M, Pirkl M, Kalender W, Bautz WA. *Dose reduction in computed tomography by attenuation-based on-line modulation of tube current: evaluation of six anatomical regions*. *Eur Radiol* 2000; 10: 391-4.
 50. Itoh S, Koyama S, Ikeda M, Ozaki M, Sawaki A, Iwano S, Ishigaki T. *Further reduction of radiation dose in helical CT for lung cancer screening using small tube current and a newly designed filter*. *J Thorac Imaging* 2001; 16: 81-8.
 51. Kalra MK, Wittram C, Maher MM, Sharma A, Avinash GB, Karau K, Toth TL, Halpern E, Saini S, Shepard JA. *Can Noise Reduction Filters Improve Low Radiation Dose Chest CT Images? - pilot*

- study. *Radiology* 2003; 228: 257-64.
52. Kalra MK, Maher MM, Sahani DV, Blake MA, Hahn PF, Avinash GB, Toth TL, Halpern E, Saini S. *Low-dose CT of the abdomen: Evaluation of image improvement with use of noise reduction filters- pilot study. Radiology* 2003; 228: 251-6.
 53. Kalra MK, Maher MM, Lucey BC, Blake M, Karau K, Saini S. *Lesion detection on reduced radiation dose CT images processed with noise reduction filters (abstract). Radiology* 2002; 645.
 54. Frush DP, Slack CC, Hollingsworth CL, Bisset GS, Donnelly LF, Hsieh J, Lavin-Wensell T, Mayo JR. *Computer-simulated radiation dose reduction for abdominal multidetector CT of pediatric patients. AJR Am J Roentgenol* 2002; 179: 1107-13.
 55. Mayo JR, Whittall KP, Leung AN, Hartman TE, Park CS, Primack SL, Chambers GK, Limkeman MK, Toth TL, Fox SH. *Simulated dose reduction in conventional chest CT: validation study. Radiology* 1997; 202: 453-7.
 56. Kersjes W, Mayer E, Buchenroth M, Schunk K, Fouda N, Cagil H. *Diagnosis of pulmonary metastases with turbo-SE MR imaging. Eur Radiol* 1997; 7: 1190-4.
 57. Thompson BH, Stanford W. *MR imaging of pulmonary and mediastinal malignancies. Magn Reson Imaging Clin N Am* 2000; 8: 729-39.
 58. Muller NL. *Computed tomography and magnetic resonance imaging: past, present and future. Eur Respir J Suppl* 2002; 35: 3s-12.
 59. Fattori R, Nienaber CA. *MRI of acute and chronic aortic pathology: pre-operative and postoperative evaluation. J Magn Reson Imaging* 1999; 10: 741-50.
 60. Kangarloo H. *Chest MRI in children. Radiol Clin North Am* 1988; 26: 263-75.
 61. Kauczor HU, Heussel CP, Schreiber WG, Kreitner KF. *New developments in MRI of the thorax. Radiologe* 2001; 41: 279-87.
 62. Luo L, Hierholzer J, Bittner RC, Chen J, Huang L. *Magnetic resonance imaging in distinguishing malignant from benign pleural disease. Chin Med J (Engl)* 2001; 114: 645-9.
 63. Heelan RT, Rusch VW, Begg CB, Panicek DM, Caravelli JF, Eisen C. *Staging of malignant pleural mesothelioma: comparison of CT and MR imaging. AJR Am J Roentgenol* 1999; 172: 1039-47.
 64. Gavelli G, Canini R, Bertaccini P, Battista G, Bna C, Fattori R. *Traumatic injuries: imaging of thoracic injuries. Eur Radiol* 2002; 12: 1273-94.
 65. Yang PC. *Ultrasound-guided transthoracic biopsy of the chest. Radiol Clin North Am* 2000; 38: 323-43.
 66. Mathis G, Gehmacher O. *Lung and pleural ultrasound. Schweiz Rundsch Med Prax* 2001; 90: 681-6.
 67. Madan A, van Rooij WJ, Verpalen MC. *Sonographically guided needle biopsy in peripheral thoracic masses: results in 50 patients. Rofo Fortschr Geb Rontgenstr Neuen Bildgeb Verfahr* 1994; 160: 75-7.
 68. Sheth S, Hamper UM, Stanley DB, Wheeler JH, Smith PA. *US guidance for thoracic biopsy: a valuable alternative to CT. Radiology* 1999; 210: 721-6.
 69. Catalano MF, Rosenblatt ML, Chak A, Sivak MV Jr, Scheiman J, Gress F. *Endoscopic ultrasound-guided fine needle aspiration in the diagnosis of mediastinal masses of unknown origin. Am J Gastroenterol* 2002; 97: 2559-65.