JBR–BTR, 2010, 93: 15-19.

UPDATE

RADIATION DOSE OPTIMIZATION IN THORACIC IMAGING

D. Tack

Guidelines for reduction of CT radiation dose were introduced in 1997 and are now more than 12 years old. The process initiated by the European Regulatory authorities to reduce the excess of radiation from CT has however not produced the expected results. Reference diagnostic levels (DRL) from surveys are still twice as high as needed in most European countries and were not significantly reduced as compared to the initial European ones. Many factors may at least explain partially the lack of dose reduction. One of them is the complexity of the dose optimization process while maintaining image quality at a diagnostically acceptable level. Chest is an anatomical region where radiation dose could be substantially reduced because of high natural contrasts between structures, such as air in the lungs and fat in the mediastinum. In this article, the concept of CT radiation dose optimization and the factors that contribute to maintain global excess in radiation dose are reviewed and a brief summary of results from research in the field of chest CT radiation dose is given.

Key-words: Radiations, injurious effects – Lung, CT.

The overall increase in patient irradiation caused by the growing use of spiral- and multidetector-row CT (MDCT) is of particular relevance for thoracic imaging. The number of clinical indications for thoracic CT has steadily increased, and CT has become a first line imaging tool for diseases previously imaged with chest radiography, ventilation/perfusion scintigraphy, and pulmonary angiography (1). Moreover, the use of CT for screening purposes has raised the number of CT examinations performed in clinically asymptomatic patients (2). Finally, the relatively higher number of CT examinations performed in younger patients increases cumulative radiation in a population vulnerable to its potential long-term effects (3).

Although recent publications have addressed radiation-related topics in CT imaging of specific thoracic diseases (4-10), the approach of thoracic radiologists to the general issue of patient radiation and their strategies for dose reduction are not known. Such information, however, might help to focus and further enhance already ongoing efforts in this field (9, 11, 12). The aim of this article is to list and discuss the available solutions to optimize and reduce radiation dose in adult thoracic MDCT examinations.

Methods for dose reduction

Definitions

The term "s*tandard dose*" refers to the dose usually recommended by CT manufacturers and often used in routine practice but that could be substantially reduced – to an optimized dose level – without deleterious effect on image quality.

The term "optimized dose" should refer to a dose that provides adequate image quality but not with excessive radiation, and is the practical application of ALARA (As Low As Reasonably Achievable) principle.

The term "low dose" should be restricted to a CT delivered dose not higher than that delivered by a set of plain films investigating the considered condition. At low-dose, image quality is lower but diagnostic accuracy is preserved.

Optimization process is per definition a process that eliminates the excess of radiation that does not provide significant increase in image quality. Optimized dose level for a given examination is not known. It has to be defined for a standard human body that may de defined as weighting 70 to 74 kg. This optimized dose level depends on many factors and in particular on the CT technology. The more recent the CT is, the lower will be the required dose to provide adequate image quality. Because there is no large consensus on optimized dose levels the European Regulatory Authorities have developed an approach for dose reduction that is based on survey studies.

Survey studies

The unique strategy for reducing the collective radiation dose from diagnostic CT examinations proposed by the European Union in 1997 is based on surveys that intend to define a diagnostic reference level (DRL) corresponding to the 75th percentile of the observed doses for a given CT examination. The first historical survey was conducted in the United Kingdom on single detector-row scanners in the mid 1990ies and served as the European DRL in the entire European Union. The DRL is expressed either in weighted Computed Tomography Dose Index (CTDIw) serving as index of image quality or in dose-length product (DLP) expressed in mGy.cm serving as the indicator of the exposure per acquisition and or per examination in case of multiphasic procedure. The historical European DRL for chest CT was as high as 650 mGy.cm for one single acquisition. Several more recent s are listed in Table I. The corresponding effective dose (estimating the cancer risk) is calculated by multiplying the DLP by a conversion factor (0.017 mSv/mGy.cm) and is of 11 mSv. The lifetime risk of dying from a radiation induced cancer if exposed to 11 mSv is calculated by multiplying the effective dose expressed in Sievert (Sv) by 5%. For the European for Chest helical CT, DRL, this lifetime risk is of 1/1820 but could be substantially reduced (13, 14).

According to the European rules, any radiology department performing CT examinations with a dose higher than the DRL is expected to reduce this dose (13-15). Thus, after publication of a national survey, the collective dose from CT should decrease because the 25% highest dose values should be reduced. A

From: Department of Radiology, Clinique Louis Caty, Hôpital RHMS, Baudour, Belgium. *Address for correspondence*: Dr D. Tack MD, PhD, Clos du Mélèze, 17, B-1420 Braine-L'Alleud, Belgium. Email : denis.tack@skynet.be.

renewed survey should thus redefine a DRL lower than the original one and the process of dose reduction being repeated. First surveys conducted in the EU typically showed that a factor of 2 to 6 was observed between the dose level of a P75 and the one of a P25 (13). If a second survey is conducted within a reasonable short time interval after the first one, it is actually believed that the reference dose levels could decrease significantly and that the interval between DLP respectively corresponding to the P75 and the P25 could be reduced. Unfortunately, to the best of our knowledge, no EU member has yet performed such repeated surveys and all published national DRL are still very high, ranging from 430 mGy.cm in United Kingdom to 627 mGy.cm in Italy (13). In 2010, 12 years after publication of the EU 97/43 directive had been published, thus the goal of the survey strategy from the EU directive is by far not achieved.

Automatic exposure control systems

It is to note that most DRLDRL were obtained from surveys performed in the late 1990ies or in the early 2000. At that time, CT scanners were not equipped with automatic exposure control systems (AEC), also called tube current modulation device, because these systems were introduced only by 2002 (16). AEC are able to provide equalized image quality throughout the helical acquisition for all patients. Technical approach for AEC varies between manufacturers but all AEC systems are able to automatically adapt the dose to the patient's size, weight and/or absorption. Thus, AEC can reduce the dose in small patients but also increase the dose in obese patients. Before AEC were introduced, the concern about radiation dose was not as high as it is now. As a matter of fact, standard CT with the same very high dose was applied to all patients while providing satisfactory image quality. This means that standard CT delivered a radiation dose suited for obese patients and a significant excess in dose in all non obese patients. One can estimate that the mean amount of excess in radiation dose was at least 50% of the delivered one.

Since AEC systems are now widely used, there are two major problems concerning surveys: first, in order to take into account that AEC systems are widely used, surveys have to be focused on standard patients in order to get rid of the effect of distortion in weight distribution among participants. Second, new surveys suitable for modern MDCT scanners equipped with AEC should be urgently conducted in the entire Union in order to definitely abandon the historical DRLDRL that are approximately twice as high for standard patients and that suited obese patients only.

New reference values

Because of this urgent need in new DRLDRL, an electronic survey has been recently conducted among chest radiologists, members of thoracic scientific societies, around the world (14). This survey revealed that 60% of respondents acquire chest MDCT with DLP lower than 250 mGy.cm in a standard patient, more than 80% of them using the AEC device that equip their 8 to 64 MDCT (14). This DLP value may serve as new reference for thoracic MDCT scanning powered by AEC. Assuming that a chest MDCT covers a longitudinal (caudocranial) distance of 30 cm in a standard patient, the reference value (75th percentile) of a chest MDCT expressed in volume computed tomography dose index (CTDIvol) would be lower than 7.8 mGy (Table I). The median CTDIvol value would be around 6 mGy and the 25th percentile, usually presented as the goal for MDCT optimization, would be around 4.5 mGy (13). In addition, as explained hereafter, CT pulmonary angiography can be obtained with a higher vessel enhancement while using a lowered tube potential at 100 KV. With 100 KV, the CDTIvol is reduced by 30% as compared to 120 KV. The goal to achieve in terms of CTDIvol in a standard patient undergoing CT pulmonary angiography is thus equal or below 4 mGy. No doubt that the newest scanner generation with technical advances in dose reduction (new filters, new detectors, new reconstruction algorithms such as iterative reconstruction) will enable to reduce these values by 30 to 70% with equal or even higher image quality (Fig. 1).

Optimization

Optimization of a CT radiation dose consists of reducing the dose to the lowest possible level while maintaining image quality at an acceptable and comfortable level. Good competence in CT technique and in particular in the AEC system that is available is required. The key parameter to optimize is the index of image quality. This index is scanner (manufacturer) specific and usually difficult to manage. Additional parameters to manage may be the minimum and maximum tube current, the slice thickness, the rotation time, the pitch, and the reconstruction kernel. Very important parameter to set up as well is the tube potential. Optimization process may be facilitated by a simulator of the image that would be obtained with the preselected parameters (Toshiba Medical Systems). Optimization is part of the ALARA (As Low As Reasonably Achievable) concept and could be considered as part of normal daily practice in CT. On the other hand, optimization that consists in testing on patients could be considered as clinical research and may require authorization of a local ethical committee in addition to written patient informed consent. Up to now neither guideline nor rule is available regarding the appropriate methods for dose optimization and ALARA "behavior". In addition, as AEC systems are complex and usually not well known by CT users, the optimization process is practically very complex.

Many factors contribute to the absence of significant dose optimization in daily practice. First, as

Table I. — Reference diagnostic levels for helical CT of the chest in a standard patient

Source	DLP (mGy.cm)	CTDIvol (mGy)
EU 16262 1999 (SDCT)	650	22.0
Italy 2006: (MDCT)	627	21.0
France 2004 (MDCT)	500	16.0
Germany 2002 (SDCT-MDCT)	480	15.5
United Kingdom 2003 (MDCT)	442	14.7
Chest Radiologists (P60) – ref 14	250	8.0
Optimized RDL(P75)	210	7.0
Optimized median (P50)	**180**	**6.0**
CTPA (100 KV)	150	4.0

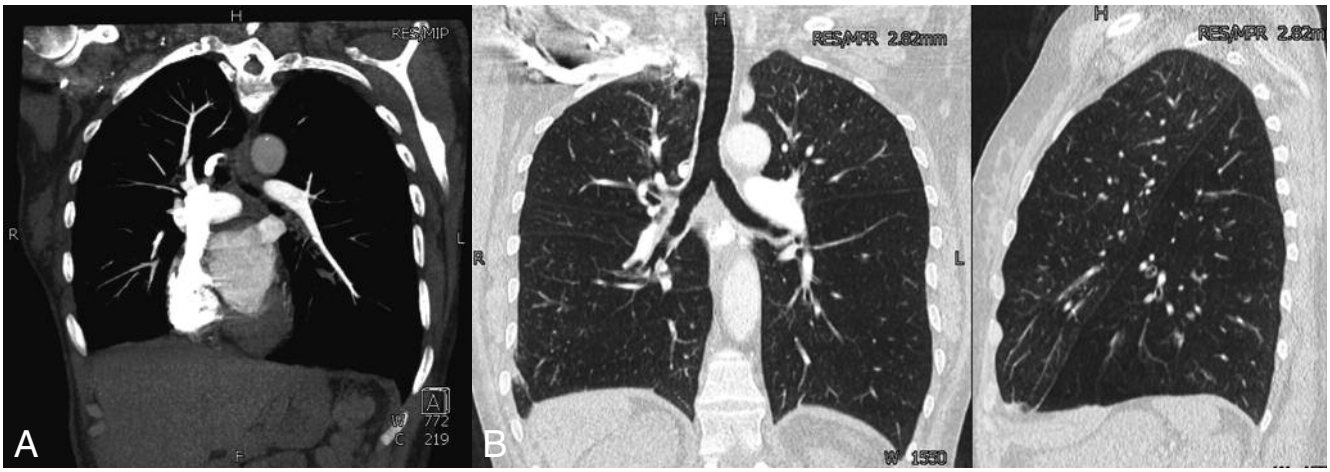

Fig.1. — Optimized MDCT pulmonary angiography with newest MDCT generation.
38 year-old female patient weighting 65 Kg, suspected of acute pulmonary embolism. 128 MDCT pulmonary acquisition performed at 100 KV and with tube current modulation (Care dose 4D® – Siemens Medical Systems, Forchheim, Germany). CTDI vol automatically reduced the mean mAs from 100 to 62. Mean CTDIvol for this acquisition was 2,46 mGy. Total DLP for this examination was 85 mGy.cm and the corresponding effective dose was 1,45 mSv. A. CTPA window showing excellent image quality and high vascular enhancement. B. Lung window settings showing excellent image quality as well.

explained here above, the regularity authorities do not provide radiologists with freshly renewed survey data. So DRL are high. Second, the European recommendation is to focus the attention on the third quartile of surveys (P75), but the concept of the 75th percentile is probably insufficient to significantly reduce collective dose. It has been advised (13) to focus on the first quartile (P25). The P25 could be used by CT centers as the goal to be reached, particularly with modern MDCT scanners. Third, there is no penalty for any CT center that would not reduce an excess in dose. Fourth, AEC are so complex and not sufficiently explained to CT users by manufacturers that radiologists may not feel confident or even may be completely unable to modifying the AEC parameters installed by the vendor on their CT (16). Fifth, radiologists fear to reduce the dose for many reasons, one of those being the absence of training in the use of optimized dose and in the setup of AEC systems. Sixth, hospital physicists who are familiar with dose measurements are not able to propose clinically relevant noise index levels that fit with all CT scanners, indications, and AEC systems. Seventh, the standard setups proposed by manufacturers are almost systematically too high by 40 to 50 % mainly because the manufacturers want to satisfy clients and because these clients (radiologists) usually want excellent image quality without any compromise. Finally, the way radiologists are educated in their universities could have a significant impact on what they are going to promote and use for their entire career. German radiologists are much friendlier with dose justification as are French and Belgian radiologists who usually give a much higher importance to the highest possible detection rate whatever the radiation risks, and to the most perfect image quality. This is at least what I have personally observed in a recent optimization process conducted in Luxemburg, a country where radiologists work who have been educated in France, Belgium and Germany.

Low-dose chest MDCT

Routine chest CT

The concept of reducing the radiation dose in chest CT was first introduced in by Naidich et al. (1990) who reduced the tube current on incremental 10-mm collimation CT, and demonstrated that with low tube current settings (i.e. 20 mAs), the image quality is sufficient for assessing the lung parenchyma. While these images are sufficient for assessing lung parenchyma, the increased noise results in marked degradation of the quality of images photographed with mediastinal window settings. Because of this, these authors recommended that such low-dose technique should be most suitable for children and for screening. As such, these recommendations have been implemented and further studied in lung cancer screening programs (17).

Similar dose reduction strategies have been applied to thin-section CT, in which no significant difference in lung parenchyma structures was detectable between low-dose (i.e. 40 mAs) and high-dose (i.e. 400 mAs) (18). Although the observed differences were not statistically significant, changes in ground-glass opacity were difficult to be assessed at low-dose CT because of the increased noise. Therefore, it was recommended that 200 mAs should be used for initial thin-section CT and lower doses (i.e., 40-100 mAs) for follow-up examinations.

The relationship between radiation exposure and image quality at mediastinal and pulmonary window settings has been evaluated on conventional 10-mm collimation CT images on a single model of CT scanner with mAs settings ranging from 20 to 400 mAs (19). Although this study showed a consistent increase in image quality with radiation dose, no difference in detection of mediastinal and lung abnormalities could be detected. These findings were confirmed on MDCT by Dinkel et al. (20) who showed that 90% reduction in dose compared

with standard-dose techniques was not associated with impaired detection of suspicious lesions of malignant lymphoma and extrapulmonary tumours.

In order to investigate the effect of dose reduction without scanning patients several times at several dose levels, it is now possible to use computed simulation of dose reduction by adding random noise to the image obtained at standard dose. In a validation trial, it has been shown that experienced chest radiologists were unable to distinguish CT images obtained with simulated reduced doses from those obtained with really reduced doses. This technique of simulated reduced doses allows investigators to determine the impact of dose reduction on diagnostic performances without exposing patients to additional radiations and/or several injections of iodinated contrast material.

CT pulmonary angiography

The simulated low-dose technique has been used to evaluate the effect of dose reduction on CT pulmonary angiography. A group of 21 individuals that showed at least one filling defect within a pulmonary artery were used to simulate CT pulmonary angiography with reduced radiation doses, at 60, 40, 20, and 10 mAs. This study showed that frequencies of positive and inconclusive results, branching order of the most distal artery with a filling defect were not changed when tube current-time product was reduced from 90 to 10 mAs. On the other hand, the quality of intravascular contrast enhancement decreased when the tube current-time product setting was lower than 40 mAs. This study suggests that the reduction of the tube-current time product setting to 40 mAs to achieve a reduced radiation dose at CT pulmonary angiography appears to be acceptable (21).

Sigal-Cinqualbre et al. have assessed the feasibility of low-kilo voltage in CT pulmonary angiography protocols and have evaluated the effect of such protocols on image quality (22). These authors have simultaneously reduced the tube potential and increased the mAs settings. They have shown that in patients weighting less than 75 kg, 80 kV (and 135 or 180 mAs respectively in patients weighting less than 60 or 75 kg) are sufficient to obtain the same image quality than in patients larger than 75 kg and scanned at 120 kV and 90 mAs. These results need to be confirmed and verified in other indications than CT pulmonary angiography, but this study has already suggested that reducing the tube potential could be a valid method, an alternative to decrease the mAs settings, to reduce the radiation dose. Since 2004, several studies have validated the used tube potential at 100 KV in patients up to 100 Kg (23). The dose reduction of 100 Kv acquisition is of 30% as compared to 120 KV. The recommended CTDIvol for standard patients undergoing CT pulmonary angiography is thus 30% lower than the one for a routine chest MDCT and should be as low as 4 mGy.

Air trapping and expiratory CT

By demonstrating air-trapping, expiratory thin-section CT is able to detect a disease before the functional tests. This makes this technique an essential part of the diagnosis of bronchiolitis of various origins. As expiratory CT is most often obtained after inspiratory CT, this additional acquisition exposes patients to supplementary radiation dose. This is of concern in patients with bronchiolitis, because they can often be young, and, despite their relatively favorable prognosis, have a high risk of recurrence resulting in repeated follow-up examinations and repeated exposure to CT radiation. In order to investigate the possible effect of dose reduction on the visual quantification of air trapping, we considered the "bronchiolitis obliterans syndrome" (BOS) after lung transplantation as a model for bronchiolitis (24). In this model, we applied the simulated low-dose technique on expiratory thin-section CT examinations in patients with possible BOS. In 27 lung transplant recipients, expiratory thin-section CT was performed at 140 kVp and 80 effective mAs. Dose reduction corresponding to 60, 40, and 20 effective mAs was simulated. This study showed that a simulated dose-equivalent of 25% of the standard dose, i.e. 20 mAs, had no substantial effect on the visual quantification of air trapping. Because its radiation dose approximated that of incremental thin-section CT with 10 mm section intervals performed with a standard dose, expiratory low-dose MDCT could be used in the assessment of air trapping in patients with suspected bronchiolitis. This model could be extended to other origins of bronchiolitis.

Conclusion

CT radiation dose optimization and reduction is a complex process that seems to stay motionless since years. Optimization behavior requires strong efforts and close cooperation between radiologists, manufacturers and regularity authorities for obtaining the significant results that have been originally expected from the European Directive 97/43. Chest is an appropriate body region for dose reduction and optimization because of its natural contrasts. Actual recommended CDTIvol for a standard patients undergoing helical chest CT is at 6 mGy whereas the corresponding DLP is at 180 mGy.cm. CTPA benefits from lowering tube potential from 120 to 100 KV and the corresponding typical CTDIvol is at 4 mGy whereby the DLP can be reduced to 120 mGy.cm in a standard patient. Newest MDCT generation should enable further dose reduction of 30 to 70%.

References

1. Mayo J.R., Aldrich J., Muller NL.: Radiation exposure at chest CT: a statement of the Fleischner Society. *Radiology*, 2003, 228: 15-21.
2. Brenner D.J.: Radiation risks potentially associated with low-dose CT screening of adult smokers for lung cancer. *Radiology*, 2004, 231: 440-445.
3. Brenner D.J., Hall E.J.: Computed tomography — an increasing source of radiation exposure. *N Engl J Med*, 2007, 357: 2277-2284.
4. Remy-Jardin M., Pistolesi M., Goodman L.R., et al.: Management of suspected acute pulmonary embolism in the era of CT angiography: a statement from the Fleischner Society. *Radiology*, 2007, 245: 315-329.
5. Bankier A.A., Schaefer-Prokop C., De Maertelaer V., et al.: Air trapping: comparison of standard-dose and simulated low-dose thin-section CT techniques. *Radiology*, 2007, 242: 898-906.
6. Heyer C.M., Mohr P.S., Lemburg S.P., Peters S.A., Nicolas V.: Image quality and radiation exposure at pulmonary CT angiography with 100- or 120-kVp protocol: prospective randomized study. *Radiology*, 2007, 245: 577-583.
7. Itoh S., Koyama S., Ikeda M., et al.: 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: 81-88.
8. Madani A., De Maertelaer V., Zanen J., Gevenois P.A.: Pulmonary emphysema: radiation dose and section thickness at multidetector CT quantification — comparison with macroscopic

and microscopic morphometry. *Radiology*, 2007, 243: 250-257.
9. Ravenel J.G., Scalzetti E.M., Huda W., Garrisi W.: Radiation exposure and image quality in chest CT examinations. *AJR*, 2001, 177: 279-284.
10. Szucs-Farkas Z., Kurmann L., Strautz T., Patak M.A., Vock P., Schindera S.T.: Patient exposure and image quality of low-dose pulmonary computed tomography angiography: comparison of 100- and 80-kVp protocols. *Invest Radiol*, 2008, 43: 871-876.
11. Kalra M.K., Maher M.M., Toth T.L., et al.: Strategies for CT radiation dose optimization. *Radiology*, 2004, 230: 619-628.
12. Mayo J.R., Kim K.I., MacDonald S.L., et al.: Reduced radiation dose helical chest CT: effect on reader evaluation of structures and lung findings. *Radiology*, 2004, 232: 749-756.
13. Stamm G.: Collective radiation dose from MDCT: critical review of surveys studies. In: Tack D., Gevenois P.A., eds. Radiation dose from adult and pediatric multidetector computed tomography. Berlin, Heidelberg, New York, Springer, 2007, 82-97.
14. Bankier A.A., Tack D., Ngo L., Boiselle, P.M.: 56. Dose Reduction in Thoracic CT: A Global Survey. RSNA 2009 Chicago. SSA04 29/11/2009.
15. Union E.-E.: European guidelines on quality criteria for computed tomography EUR 16262 EN.
16. Kalra M.K., Toth T.L.: Automatic exposure control in multidetector-row computed tomography. In: Tack D., Gevenois P.A., eds. Radiation dose from adult and pediatric multidetector computed tomography. Berlin, Heidelberg, New York, Springer, 2007, 117-128.
17. Henschke C.I., McCauley D.I., Yankelevitz D.F., et al.: Early Lung Cancer Action Project: overall design and findings from baseline screening. *Lancet*, 1999, 354: 99-105.
18. Zwirewich C.V., Mayo J.R., Müller N.L.: Low-dose high-resolution CT of lung parenchyma. *Radiology*, 1991, 180: 413-417.
19. Mayo J.R., Webb W.R., Gould R., et al.: High-resolution CT of the lungs: an optimal approach. *Radiology*, 1987, 163: 507-510.
20. Dinkel H.P., Sonnenschein M., Hoppe H., Vock P.: Low-dose multislice CT of the thorax in follow-up of malignant lymphoma and extrapulmonary primary tumors. *Eur Radiol*, 2003, 13: 1241-1249.
21. Tack D., De Maertelaer V., Petit W., Scillia P., Muller P., Suess C., Gevenois P.A.: Comparisons of Standard-Dose and Simulated Low-Dose Multi-Detector-Row CT Pulmonary Angiography. *Radiology*, 2005, 236: 318-325.
22. Sigal-Cinqualbre A.B., Hennequin R., Abada H.T., Chen X., Paul J.F.: Low-kilovoltage multidetector row chest CT in adults: feasability and effect on image quality and iodine dose. *Radiology*, 2004, 231: 169-174.
23. Schueller-Weidekamm C., Schaefer-Prokop C.M., Weber M., Herold C.J., Prokop M.: CT angiography of pulmonary arteries to detect pulmonary embolism: improvement of vascular enhancement with low kilovoltage settings. *Radiology*, 2006, 241: 899-907.
24. Bankier A.A., Schaefer-Prokop C., De Maertelaer V., Tack D., Jaksch P., Klepetko W., Gevenois P.A.: Air trapping: comparison of standard-dose and simulated low-dose thin-section CT techniques. *Radiology*, 2007, 242: 898-906.