Reduction of effective dose and organ dose to the eye lens in head MDCT using iterative image reconstruction and automatic tube current modulation

Pavel Ryska, Tomas Kvasnicka, Jiri Jandura, Ludovit Klzo, Jakub Grepl, Jan Zizka

Aims. To compare the effective and eye lens radiation dose in helical MDCT brain examinations using automatic tube current modulation in conjunction with either standard filtered back projection (FBP) technique or iterative reconstruction in image space (IRIS).

Methods. Of 400 adult brain MDCT examinations, 200 were performed using FBP and 200 using IRIS with the following parameters: tube voltage 120 kV, rotation period 1 second, pitch factor 0.55, automatic tube current modulation in both transverse and longitudinal planes with reference mAs 300 (FBP) and 200 (IRIS). Doses were calculated from CT dose index and dose length product values utilising ImPACT software; the organ dose to the lens was derived from the actual tube current-time product value applied to the lens. Image quality was assessed by two independent readers blinded to the type of image reconstruction technique.

Results. The average effective scan dose was 1.47±0.26 mSv (FBP) and 0.98±0.15 mSv (IRIS), respectively (33.3% decrease). The average organ dose to the eye lens decreased from 40.0±3.3 mGy (FBP) to 26.6±2.0 mGy (IRIS, 33.5% decrease). No significant change in diagnostic image quality was noted between IRIS and FBP scans (P=0.17).

Conclusion. Iterative reconstruction of cerebral MDCT examinations enables reduction of both effective and organ eye lens dose by one third without significant loss of image quality.

Key words: multidetector computed tomography, image reconstruction, radiation effects, eye lens, cataract

INTRODUCTION

Radiation doses resulting from medical exposure are steadily increasing in the population. In the United States, the medical radiation dose has already reached the average level of natural radiation background. Although computed tomography (CT) accounts for only about 15% of radiologic examinations in the United States, it delivers two thirds of the entire cumulative exposure from all radiologic studies. Diagnostic use of computed tomography may be responsible for up to 2% of all incident cancer cases in the United States nowadays.

In order to change this unfavourable trend resulting from the continuously increasing number of CT procedures performed worldwide, adoption of adequate precautions aimed at radiation dose reduction is of great importance. Among the most promising approaches seems to be the technique of iterative reconstruction (IR) of CT image. Interestingly, IR was already used on first generation CT scanners in the early 1970s. However, it was rapidly replaced by filtered back projection (FBP) which offered incomparably shorter reconstruction times. For the next three decades, IR continued to develop solely in the field of nuclear medicine. As emission tomography methods (SPECT, PET) deal with much less projection data but with increased proportion of noise than CT, image noise suppression emerged as the most desirable feature and long reconstruction times of IR were subsidiary.

Eventually, recent advancement in computer hardware and implementation of multi-core processors led to dramatic increase in computational power enabling reintroduction of IR to computed tomography in the very late 2000s. Despite still longer yet acceptable reconstruction times, IR proved its ability to significantly reduce image noise thus enabling radiation exposure reduction by tens of percent compared to standard FBP (ref.5,6).

The purpose of the study was to compare image characteristics, effective dose and organ dose to the eye lens in cerebral multidetector computed tomography (MDCT) using either standard FBP or iterative reconstruction in image space (IRIS). As all studies published have dealt with fixed tube current head MDCT protocols, this is, to our knowledge, the first study which evaluates the potential benefit of iterative reconstruction protocol combined with automatic tube current modulation. A brief review of the pertinent literature is included.

MATERIALS AND METHODS

A total of 400 non-emergency adult brain MDCT examinations were prospectively included in the study. Of these, 200 were reconstructed using standard FBP and, after image reconstruction software upgrade, 200 using IRIS. All scans were performed in accordance with local protocol on a single source MDCT scanner (Somatom
RESULTS

In terms of radiation dose, IRIS based protocols showed significant (P<0.001) radiation dose reduction when compared to standard FBP protocols. The average effective dose was 1.47 ± 0.26 mSv (FBP) and 0.98 ± 0.15 mSv (IRIS), respectively (33.3% decrease). The average organ dose to the eye lens decreased from 40.0 ± 3.3 mGy (FBP) to 26.6 ± 2.0 mGy (IRIS, 33.5% decrease). An overview of all evaluated radiation exposure parameters is summarized in Table 1.

Compared to numeric modelling of the organ dose by dedicated software, the results of direct thermoluminescent dosimetry showed lower organ dose values in both scan categories. The mean organ dose to the eye lens in FBP category was 40.0 mGy (calculated by ImPACT software) and 33.9 mGy (measured by TLD, i.e. 15% less). Respective results for IRIS category were 26.6 mGy (ImPACT) and 23.0 mGy (TLD, i.e. 14% less).

Quantitative analysis of image noise revealed slightly increased noise levels in the IRIS group. The median value of image noise was 3.9 for FBP (95% CI 3.9 – 4.0) and 4.2 for IRIS (95% CI 4.1 – 4.3), respectively. The difference was statistically significant (P<0.01).

Analysis of subjective image quality perception showed no significant difference (P=0.17) between groups of FBP scans (mean quality score = 2.12; median = 2) and IRIS scans (mean quality score of 2.17; median = 2). The vast majority of scans were rated with score 2 (standard noise, good diagnostic quality) in both FBP (88%) and IRIS (83%) categories. Of 400 scans, only one scan in FBP and one scan in IRIS group were rated with score 4 (high level noise, limited diagnostic quality). No scans rated with score 5 (unacceptable noise, non-diagnostic scan) were noted in either FBP or IRIS category. kappa reliability test showed substantial interobserver agreement with kappa = 0.76. For details see Table 2.

DISCUSSION

It is an unfavourable fact that despite unprecedented progress in medical technologies within the last few decades, medical radiation exposure continuously and progressively rises. Worldwide, there are an estimated 3.1 billion radiologic procedures, 0.5 billion dental exposures, and close to 40 million nuclear medicine procedures performed annually. The global average annual per-capita effective dose from medicine is about 0.6 mSv (of the total 3.0 mSv received from all natural sources) and has approximately doubled in the past 10-15 years.

Due to high availability of medical imaging and standards of medical care, the situation in well developed countries is – from the point of view of radiation safety – paradoxically worse. The average medical radiation ef-
The effective dose to the U.S. population showed an increase of 600% in a single generation, reaching the annual per-capita value of 3.0 mSv in 2006, i.e. exceeding the average annual exposure from natural background of 2.4 mSv (ref.7). From 1995 to 2007, the number of visits to U.S. emergency departments that included a CT examination increased from 2.7 million to 16.2 million, constituting an almost six-fold increase with an exponential growth rate of 16% per annum8.

It should be stressed that CT is by far the most significant contributor to the collective dose among all medical diagnostic procedures in developed countries. In the United States, CT accounts for one half (1.47 mSv) and nuclear medicine for one quarter (0.77 mSv) of the annual per capita effective dose received from all medical procedures (3.01 mSv). If the contribution of nuclear medicine studies is omitted, CT accounts for two thirds of the per capita effective dose from all radiologic procedures, including interventional ones (2.24 mSv annually) (ref.1,7).

Available data from other well developed (Level I) countries show that CT (0.87 mSv) accounts for approximately 44% of the effective dose from all medical procedures (2.00 mSv per person annually) (ref.9).

![Fig. 1. Comparison of normal head MDCT scans reconstructed with FBP in a 35-year-old male (A and B; CTDIvol = 34.03 mGy) and IRIS in a 46-year-old male (C and D; CTDIvol = 22.73 mGy). The differentiation between gray and white matter, sharpness of contours, and image noise are comparable. The image texture of IRIS scans (C and D) is slightly different, also known as “blotchy” appearance, however, the diagnostic value is fully comparable. The image quality was rated with score 2 in both cases by both reviewers.](image-url)
Although quantification of estimated cancer risk from CT scans is a controversial way of expressing the CT dose concerns, it has been estimated that between 0.7% and 2.0% of new cancer cases in the United States may be solely attributable to CT scanning\textsuperscript{3,10}. Based on the fact that there are approximately 1.5 million new cancer cases in the United States each year, CT might be the cause of 10,000 to 30,000 new cancers annually. Thus, the need for standardization, optimization, and stringent adherence to ALARA (“as low as reasonably achievable”) principles is of utmost importance. Nonetheless, even recent publications indicate that there is substantial variance of doses applied for the same types of CT procedures on different scanners and at different institutions as well as significant potential for reducing radiation dose in routine CT examinations\textsuperscript{11,12}. A multicentric study from California showed a great deal of variance with a 20-fold difference across effective doses applied at routine head MDCT scans among four institutions: median of 2 mSv with absolute range of 0.3 – 6 mSv (ref.\textsuperscript{11}).

In the past three decades, various dose reduction strategies have been implemented by CT scanner manufacturers such as automated tube current modulation, peak kilovoltage optimization, x-ray shutters for over-ranging, high pitch scanning, adaptive noise filtering, increasing detector efficiency and so forth\textsuperscript{13-15}. Although some of

Fig. 2. Scans of suboptimal / limited diagnostic quality acquired in the same 88-year-old female who entered the study twice. Both FBP (A and B; CTD\textsubscript{vol} = 33.70 mGy) and IRIS scans (C and D; CTD\textsubscript{vol} = 21.69 mGy) show increased image noise level, indistinct delineation between normal and altered white matter, and artificially increased attenuation at the interface between the skull and cerebral surface. In terms of image quality, the FBP scans (A and B) were rated 3 by both reviewers and IRIS scans (C and D) were rated 3 and 4 by respective reviewers. Still, the extent of chronic ischaemic changes including the lesion within the left anterior limb internal capsule can be appreciated in both scans.
these tools enabled dose savings of the order of tens of percent, the overall radiation load to the population has not begun to taper\textsuperscript{1,3}. This can be easily explained by the fact that all those radiation dose reduction measures still do not outweigh the rapidly growing number of CT procedures.

The most straightforward approach to lowering CT dose is an overall reduction of tube current and, if possible, of tube kilovoltage. Recently introduced techniques of iterative CT image reconstruction benefit from inherent low image noise levels and have already proved their ability to decrease radiation exposure by tens of percent compared to standard FBP (ref.5,6). Since 2009, multiple studies have confirmed the ability of IR to achieve robust image quality with up to 60\% dose reduction in abdominal, chest, cardiac, vascular, and colon MDCT studies\textsuperscript{5,6,16-24}.

Table 1. Comparison of radiation exposure parameters between groups of FBP and IRIS scans.

<table>
<thead>
<tr>
<th></th>
<th>FBP (n=200)</th>
<th>IRIS (n=200)</th>
<th>% reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTDI\textsubscript{vol} [mGy]</td>
<td>33.3 ± 2.1</td>
<td>22.4 ± 1.6</td>
<td>-32.7%</td>
</tr>
<tr>
<td>DLP [mGy.cm]</td>
<td>589.7 ± 64.2</td>
<td>396.2 ± 41.4</td>
<td>-32.8%</td>
</tr>
<tr>
<td>Effective dose [mSv]</td>
<td>1.47 ± 0.26</td>
<td>0.98 ± 0.15</td>
<td>-33.3%</td>
</tr>
<tr>
<td>Organ dose to the lens [mGy]</td>
<td>40.0 ± 3.3</td>
<td>26.6 ± 2.0</td>
<td>-33.5%</td>
</tr>
</tbody>
</table>

Values are expressed as mean ± standard deviation. FBP = filtered back projection; IRIS = iterative reconstruction in image space; CTDI\textsubscript{vol} = volume computed tomography dose index; DLP = dose length product.

Head CT examinations are of the most common of CT indications. In the United States, CT head scans represent the second most common indication for CT and constitute 28.4\% of all CT examinations, surpassed by only abdominal/pelvic CT studies with 31.7\% of the total\textsuperscript{1,7}. It is therefore surprising that much less attention has been attracted to the dose reducing potential of IR in head CT rather than in body CT examinations, notwithstanding the considerable radiosensitivity of the eye lens. This was also one of the major reasons why we decided to perform this study.

Only recently, first few papers on the use of IR in head MDCT have been published\textsuperscript{25-28}. Three of the four studies dealt with the use of adaptive statistical iterative reconstruction (ASIR). ASIR is not a pure iterative reconstruction technique as it utilizes FBP for calculating an initial image data set in order to speed up the reconstruction process. Then, iterative algorithms are applied to this data set in order to reduce image noise. In clinical practice, one can use variably blended images with individually adjusted ratios of FBP and ASIR techniques.

In the study of Ren et al.\textsuperscript{25}, forty patients received two complete non-helical brain MDCT studies in a single session, one using 300 mAs and one 200 mAs of fixed tube current – time product. No significant differences in image qualities were found between the FBP reconstruction technique with 300 mAs and 50\% ASIR blending with 200 mAs. Except for CTDI\textsubscript{vol} and DLP, no radiation dose parameters were evaluated. The major disadvantage of this study is the fact that all subjects underwent two complete CT head scans in one session thus contradicting the ALARA principles.

Kilic et al.\textsuperscript{26} retrospectively evaluated 149 adult non-helical head MDCT scans divided into two groups, standard (FBP) and low (ASIR) dose. They used a fixed blend of 70\% FBP and 30\% ASIR in the low dose group and achieved effective dose reduction of 31\% (1.6 mSv with ASIR) compared to standard dose group (2.3 mSv with FBP). The effective dose was estimated by multiplying DLP by a conversion factor of 0.0021. No significant difference in diagnostic acceptability and artifacts was noted between groups. For posterior fossa scanning, 140 kVp tube voltage was used which lead to high CTDI\textsubscript{vol} values in both standard dose (93.49 mGy) and low dose (69.14 mGy) groups, thus increasing the radiation load near/in the area of the eye lens. However, no eye lens dose calculations or measurements were provided.

Rapalino et al.\textsuperscript{27} compared 50 helical head MDCT scans reconstructed with FBP (120 kV; 175 mAs with fixed tube current, CTDI\textsubscript{vol} of 66.51 mGy) and 100 reduced-dose scans (120 kV; 140 mAs with fixed tube current; CTDI\textsubscript{vol} of 49.70 mGy) reconstructed at six predefined levels of ASIR blended with FBP. The effective dose was estimated by multiplying DLP by a conversion factor of 0.0021 and yielded 2.66 mSv for higher dose

Table 2. Results of qualitative image analysis for readers 1 and 2.

<table>
<thead>
<tr>
<th>Visual score</th>
<th>FBP (n=200)</th>
<th>IRIS (n=200)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reader 1</td>
<td>Reader 2</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>180</td>
<td>177</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>22</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>1</td>
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<td>5</td>
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<td>0</td>
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</tbody>
</table>

FBP = filtered back projection; IRIS = iterative reconstruction in image space. Visual scores: 1 = very low noise, optimal diagnostic quality; 2 = standard noise, good diagnostic quality; 3 = increased noise, diagnostic quality; 4 = high level noise, limited diagnostic quality; 5 = unacceptable noise, non-diagnostic scan.
induced cataract development. The threshold in absorbed dose for the lens of the eye from the International Commission on Radiological Protection is 500 mGy. In our study, the average organ dose to the eye lens (26.6 mGy) remained 19 times lower than this value.

All three studies dealt with blended FBP and IR techniques (ASIR). The only head MDCT study using a reconstruction algorithm based purely on IR techniques is the study of Korn et al., utilizing iterative reconstruction in image space (IRIS). Ninety consecutive patients were randomly assigned to undergo helical brain MDCT reconstructed with both FBP and IRIS, using either standard dose (320 mAs; CTDIvol 60.1 mGy), 15% (275 mAs; CTDIvol 51.8 mGy), or 30% dose reduction (225 mAs; CTDIvol 42.3 mGy). The effective dose which was estimated by multiplying DLP by a conversion factor of 0.0023 yielded 2.2 mSv, 1.8 mSv, and 1.5 mSv in respective categories. IR resulted in lower image noise and higher contrast-to-noise levels at all dose levels. Image quality and overall diagnostic acceptability were considered significantly lower at 30% dose reduction. Based on linear regression analysis, the authors state that standard contrast-to-noise levels may be obtained at about 20% dose reduction when IR is used.

None of these four IR based MDCT head studies utilized automatic tube current modulation in order to further reduce both intracranial signal-to-noise ratios, minor attenuation differences between grey and white matter, and shielding of brain tissue by the skull bones, head CT scans generally offer the first clinical observations of combined iterative reconstruction algorithm with automatic tube current modulation in order to fulfill ALARA objectives while maintaining acceptable image quality. Compared to European Commission Quality Criteria for MDCT, which set CTDIvol of 60 mGy as a reference standard for head scans, our FBP protocols alone offer 44% dose reduction against the standard of reference (CTDIvol of 60 versus 33.3 mGy). Further, if we add the synergic effect of the iterative reconstruction in image space, the resulting dose reduction yields 63% against the reference standard (CTDIvol of 60 versus 22.4 mGy).

Despite the fact that the eye lens was exposed to the primary beam virtually in all subjects of our study, the average organ dose to the eye lens (26.6 mGy) remained 19 times lower than the new strict threshold of 500 mGy for absorbed dose as stated by ICRP standards. These results are already comparable to average eye lens dose achieved in non-helical CT scans performed in tilted axial mode: 18.1 ± 7.6 mGy with automatic tube current modulation switched off and 15.6 ± 4.2 mGy with automatic tube current modulation switched on.

This is also the first study on patients in routine clinical settings, based on eye lens dose calculations in head MDCT protocols utilizing IR algorithms. Both effective and eye lens doses were calculated by a numerical model (ImPACT software). In a limited number of subjects, we attempted to calibrate the data acquired from a mathematical model using direct thermoluminescent dosimetry. The results of direct eye lens dose measurements were even 15% (FBP) or 14% (IRIS) lower than numerical simulations provided by the dedicated software. Considering the remarkably different ways of obtaining organ dose values between these two methods, the difference of the order of 15% seems rather low if we take into account the methodological disparity of the two approaches. The observed difference might be attributed to the fact that the eye lens exposure dramatically changes during the x-ray tube rotation: the eye lens is exposed to maximum dose input in a range of anteroposterior projections whereas in posteroanterior directions the x-ray beam is markedly attenuated by calvarium and skull base before it reaches the eye lens. This effect may show a great deal of interindividual variability due to unequal calvarium thickness, actual cut plane orientation (e.g. whether the plane containing the lens also includes the pyramids) and so forth. Therefore, it is virtually impossible to build a precise mathematical model for eye lens dose estimations. Nevertheless, our calculated and measured organ doses did not differ remarkably, thus suggesting clinically acceptable accuracy of the numerical model.

The achieved effective and organ doses in our study population are at the very low end of published ranges. Albeit undoubtedly beneficial from the radiation safety point of view, the study might have limitations, namely decreased image quality and the inferior diagnostic performance of such scans. Due to inherently unfavorable intracranial signal-to-noise ratios, minor attenuation differences between grey and white matter, and shielding of brain tissue by the skull bones, head CT scans generally require high-dose protocols set up for boosting contrast-to-noise ratios. For example, a classic neuroradiologic issue...
of acute ischaemia detection requires exceptional image quality in order to identify subtle differences in grey matter attenuation. On the contrary, the vast majority of non-urgent head CT scans are for much less demanding issues in terms of contrast-to-noise ratios, such as detection of space occupying lesions, lacunar infarctions, calcifications, acute haemorrhage, or assessment of ventricles/subarachnoid CSF spaces. The same applies to almost all follow-up CT studies. The protocols presented in our study were set up and used in non-emergency cases only. It should be mentioned that our institutional emergency head CT protocols are based on higher mAs settings and solely on FBP algorithms in order to reduce the reconstruction time to minimum.

Although there was a slight, yet statistically significant decrease in signal-to-noise ratios in IRIS scans, the analysis of subjective image quality perception showed no significant differences between FBP and IRIS groups. Of 400 scans, only two scans (0.5%) were rated as of limited diagnostic quality. It is debatable whether such degree of dose reduction might theoretically result in impaired diagnostic performance, however, this problem is beyond the scope of our study and will require future intraindividual comparative studies in large cohorts of patients. Nevertheless, 99.5% of scans were considered to be of adequate image quality and our reduced dose IRIS protocol became a routine non-emergency head CT protocol. Also, we have not encountered a clinical case of incorrect or incomplete CT diagnosis which might have been attributable to insufficient diagnostic value of these low dose head CT scans.

In conclusion, our results show that combination of dose reducing strategies, namely iterative image reconstruction and automatic tube current modulation, is capable of significant radiation dose reduction, particularly in terms of organ dose delivered to the eye lens which is several times more radiosensitive than previously thought. The synergic effect of both techniques allowed us to routinely obtain non-emergency helical head MDCT scans with only 37% of the radiation dose set as a reference standard for head scans. The average organ dose to the eye lens achieved with our protocol is already comparable to organ dose achieved in standard non-helical MDCT scans performed in tilted axial mode where the eye lens is not exposed to the primary beam.

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CONFLICT OF INTEREST STATEMENT

The authors state that there are no conflicts of interest regarding the publication of this article.

REFERENCES

7. Schauer DA, Linton OW. NCRP report no. 160, ionizing radiation exposure of the population of the United States, medical exposure: are we doing less with more, and is there a role for health physicists? Health Phys 2009;97:1-5.
20. Flicek KT, Hara AK, Silva AC, Wu Q, Peter MB, Johnson CD. Reducing the radiation dose for CT colonography using adaptive statisti-


