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The reliability of radiation dose display of a computed tomography scanner

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HIGHLIGHTS

- There is variation in the difference between the radiation dose reported by the CT scanner and actual measured dose.
- This variation is substantial and may differ from zero.
- To achieve more precise radiation dose data, especially in comparing studies, the average difference should be determined.
- A correction factor for radiation dose should be utilized for every scanner used in studies.

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ABSTRACT

Background: Internationally, the typical allowed difference between the measured radiation dose and dose reported by a computed tomography (CT) scanner is ±20 %. The objective is to describe a method in order to analyse this difference in a CT scanner in the Emergency Department of Kanta-Häme Central Hospital, and to calculate a correction factor for more comparable radiation dose values in further studies.
Methods: Ten intra-day radiation dose measurements were performed with undisturbed setting. Measurement reports on differences between measured and displayed dose were gathered from the vendor maintenance and supervising authority over a 12-year period. Additionally, two in-house measurements were made. A total of 18 datapoints were collected, with some differences in measurement settings. Data were also analysed against imaging parameters, ambient air pressure and time to identify trends or associations in the variation of the discrepancy.
Results: Measured doses were generally lower than displayed doses. Differences between displayed and measured doses varied between −3.46 and −0.10 %, with a mean of −1.26 % in the intra-day measurements, and between +4.65 and −17.3 %, with a mean of −7.53 % in the long-term data. There were no trends nor connections in the variations.
Conclusion: Since the acceptable difference between the radiation dose display and the measured dose is relevant, the average difference for every CT scanner should be determined before radiation dose studies, especially when comparing multiple scanners.

1. Introduction

The number of computed tomography (CT) examinations is continuously increasing globally although a recent downward trend has been recorded in some countries [1–3]. In the emergency department (ED) setting, steadily increasing CT utilization has been observed [2,4–6].

CT examination is based on ionizing radiation. Therefore, its dose-dependent effects may become detrimental. Acute health effects such as skin burns, or acute radiation syndrome occur when radiation dose exceeds certain levels. Although the risk of cancer depends on the radiation dose, even low doses may increase the risk of longer-term malignant effects [7].

Because of the potential negative health effects of ionizing radiation, it is important to acknowledge the radiation dose used during imaging

Abbreviations: KHCH, Kanta-Häme Central Hospital; STUK, Säteilyturvakeskus, radiation and nuclear safety authority; PMMA, polymethyl methacrylate.

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and minimize patient radiation exposure in CT imaging. The development in CT scanners has made the reduction of radiation dose possible [8,9]. On the other hand, the increasing use of CT leads to higher cumulative doses of ionizing radiation in population [10].

The supervising authority for equipment producing ionizing radiation in Finland is the Radiation and Nuclear Safety Authority (Säteilyturvakeskus, STUK). It approves and monitors the usage of CT scanners in healthcare in Finland [11]. In international guidelines a less than 20 % discrepancy in radiation dose reports compared to measurements made with phantoms is generally considered acceptable [12,13].

1.1. Variables

CT Dose Index (CTDI) describes the amount of radiation energy absorbed by the ionization chamber while acquiring a single slice [14]. It is calculated as the total radiation divided by the number of slices (Eq. (1)). It is usually determined as $CTDI_{100}$, in which the amount of radiation energy of a single slice is calculated as an average of the radiation absorbed by the ionization chamber while scanning the whole 100 mm length of the ionization chamber, regardless of the number of slices scanned (Eq. (2)). $CTDI_{100}$ takes into account the variation of the sum wave along the detector length [14,15].

Equation 1: CTDI

$$CTDI[\mathrm{mGy}] = \frac{1}{T}\int_{-\infty}^{\infty} D(z)dz \tag{1}$$

Equation 2: $CTDI_{100}$

$$CTDI_{100}[\mathrm{mGy}] = \frac{1}{T}\int_{-50\ mm}^{50\ mm} D(z)dz \tag{2}$$

CT scanners generally describe the radiation dose used during imaging with two different quantities. Volume Averaged CT Dose Index ($CTDI_{vol}$) is a standardized parameter describing the radiation output of the CT scanner within a single image slice, and Weighted Dose Length Product (DLP_w) takes into account the whole scan area [14,16].

While CTDI and $CTDI_{100}$ describe radiation dose during a single gantry rotation at a single point, $CTDI_{vol}$ is calculated using weighed average CTDI ($CTDI_w$) and a factor known as pitch, as explained later. $CTDI_w$ is calculated from $CTDI_{100}$ measurements made from the centre and periphery of the phantom, to account for variation in the radiation absorbed between peripheral and central regions of the slice (Eq. (3)) [14].

With modern helical multi-slice CT scanners, the scan areas of consequent rotations of the gantry usually overlap giving multiple scans from a particular area. This yields more data and thus improves the quality of the image, but also increases the radiation used to acquire a slice. To account for this overlap, the concept of a pitch is incorporated into the equation and $CTDI_{vol}$ is calculated. Pitch, as a non-unit factor, simply describes how much the bed moves in relation to the length of the detector array within a single rotation of the gantry. $CTDI_{vol}$ is calculated by dividing $CTDI_w$ by the pitch used (Eq. (4)) [14,16].

Equation 3: $CTDI_w$

$$CTDI_w[\mathrm{mGy}] = \frac{1}{3}CTDI_{100}^{center} + \frac{2}{3}CTDI_{100}^{periphery} \tag{3}$$

Equation 4: $CTDI_{vol}$

$$CTDI_{vol}[\mathrm{mGy}] = \frac{CTDI_w}{pitch} \tag{4}$$

$CTDI_{vol}$ provides information about the amount of radiation used to perform the study. Whereas CTDI, $CTDI_{100}$ and $CTDI_w$ describe the amount of radiation administered during one rotation of a gantry, $CTDI_{vol}$ describes the amount of radiation administered to obtain one slice of the image acquired. It is a useful index to track across patients and protocols for quality assurance purposes and can be used as a quantity to compare protocols across different practices and scanners when related variables, such as image quality, are also taken in account [16].

DLP_w is calculated from $CTDI_w$ by multiplying $CTDI_w$ value by the scan length. CT scanners typically report this value without the subscript w, i.e. DLP. DLP_w describes radiation administered in the whole scan (Eq. (5)) [14].

Equation 5: DLP_w

$$DLP_w\ [mGy{\cdot}cm] = CTDI_w{\cdot}\text{scan length} \tag{5}$$

CTDI values are reported as milliGrays (mGy) and DLP values as milliGray centimetres (mGy·cm).

The aim of this study was to develop a method to evaluate the accuracy of the radiation display dose reports of a CT scanner, and to determine the accuracy of the dose reports of the CT scanner and calculate a correction factor for later studies.

2. Materials and methods

The ED of Kanta-Häme Central Hospital (KHCH) has two CT scanners, Toshiba Aquilion 32 and Siemens Somatom Definition AS+, since 2007 and 2016 respectively. Up to September 2016, the Toshiba was the sole CT scanner in the ED. In 2019 Toshiba was replaced with another CT scanner. For both scanners, the calibration of the radiation display was made by the vendor at installation and has not been altered since. Since only a couple of radiation display accuracy measurements have so far been performed on the Somatom Definition AS+, the focus will only be on the data from the older (Toshiba) scanner in this article. Later, when enough follow-up data is gathered, the same methodology will be implemented to determine the accuracy of present scanners.

Ten intra-day consecutive measurement set was performed, and all radiation measurement reports (n = 18) over the course of twelve years were revisited: measurements made by the vendor services, by STUK and by KHCH personnel.

2.1. Measurement setting

A standardized CT radiation dose measurement device, a phantom, i.e. standard 15 cm long polymethyl methacrylate (PMMA) cylinder, 16 or 32 cm in diameter representing the head or torso respectively was used. A 100 mm long ionization chamber was placed in a fitting hole within the phantom to measure the radiation. The holes not currently in use were always filled with PMMA. Measurements were then taken from the centre of the phantom and 10 mm below the surface of the phantom (IEC 2001) [16]. All measurements revisited in this study were made with this kind of setting using a head phantom.

A series of ten consecutive DLP_w measurements, using head protocol were performed with the Toshiba CT-scanner using a calibrated 100 mm long acrylic (PMMA) pencil ion chamber (Radcal MOD10 × 5-3CT, calibration accuracy ±4 % using X-rays @ 150 kVp & 10.2 mm Al HVL) positioned within a standard head phantom. Two CT scans were performed for a single DLP_w measurement: $CTDI_{100}^{centre}$ and $CTDI_{100}^{periphery}$.

The phantom itself was centred into the CT bore using custom made straps and lasers, (Fig. 1). The use of straps was adopted from the STUK measurement protocol.

This configuration makes it possible to measure the DLP_w from longer segments as the phantom and the pencil ion chamber always stay in the middle of the bore, ignoring the patient table movement. Also, in this way, the radiation attenuation within the patient table will not affect the results. The ion chamber was connected to a UNIDOS electrometer (Radcal Model 9015) and the automatic air temperature and pressure compensation of the electrometer were used in the measurements.

A Total of ten DLP_w measurements were performed every half hour and the electrometer readings ($CTDI_{100}$ [mGy]) were converted into

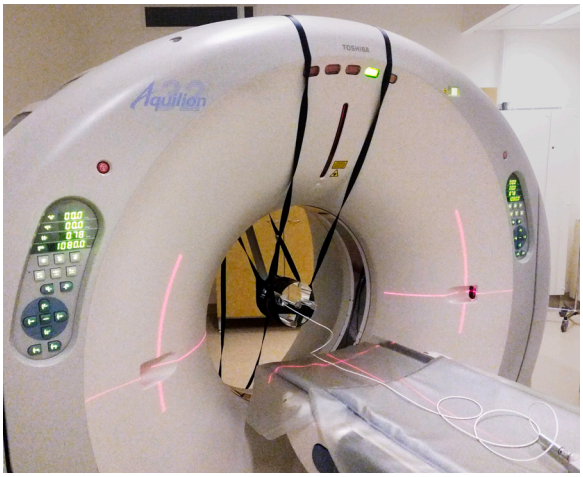

Fig. 1. The 16 cm head PMMA phantom in harness. Ionization chamber in a peripheral position.

DLP_w values using Eqs. (3) and (5). The radiation tube was heated before every measurement set, complying with standard imaging and measurement protocols. The imaging parameters used in these ten measurements are presented in Table 1.

After these ten measurements, all the reports from phantom control measurements made with head protocol on the CT scanners between the years 2007 and 2019 were acquired retrospectively. Most of the control measurements were performed by the vendor's maintenance services, Tromp Medical, previously Tosfin. STUK performed control measurements sporadically in 2007, 2013, and 2018. In addition to these control measurements by vendor maintenance and STUK, phantom measurements with KHCH staff were performed in 2017 and 2019.

From vendor maintenance, we had 13 data points, where measurement was done with head protocol. These measurements were made with a standard 16 cm diameter head phantom and fitting ionization chamber (Unfors Xi, uncertainty 5 % at reference point RQT9, 120 kV, 3.7 mm Al and 0.25 mm Cu) placed on the patient table. To eliminate the possible effect of the patient table on the radiation dose measured, the average of two $CTDI_{100}^{periphery}$ measurements, 180° apart was taken for $CTDI_w$ calculation. Imaging parameters varied between measurements.

STUK checked the Toshiba CT scanner three times with head protocol, using standard head phantom and fitting ionization chamber (Radcal 9015 with Radcal MOD 10 × 5-3CT, calibration accuracy ±4 % using X-rays @ 150 kVp & 10.2 mm Al HVL). The first of the three measurements was a measurement made after the introduction of the scanners for patient use. STUK had a setting with straps similar to that used in in-house measurements. Likewise, it took only one $CTDI_{100}^{periphery}$ measurement to calculate $CTDI_w$. However, STUK used different imaging parameters than were used in the ten consecutive measurement series.

The in-house measurements made in 2017 and 2019 followed the same protocol as STUK, with the difference of using the average of two $CTDI_{100}^{periphery}$ measurements to calculate $CTDI_w$. Excluding the scan length, parameters identical to those in the previous measurements made by STUK were used. All in-house measurements used the same equipment as was used in the ten consecutive measurement set described earlier.

Table 1
Imaging parameters used in 10 intra-day measurements.

Imaging parameter	Value
Voltage	120 kV
Current	300 mA
Scan time	7.5 s
Length of scan	100 mm

Identical scan parameters, 120 kV, 300 mA, rotation time 0.75 s, were used in 12 of the 18 measurements. Some parameter variation was reported between measurements, even with the same provider, even though all measurements were done with head protocol. All measurements were made with 120 kV voltage, reported current varied from 134 to 300 mA and reported rotation time from 0.5 to 1.00 s. Reported length of scan used in measurements varied from 10 to 217 mm and scan time from 4.73 to 15.5 s. Average DLP value was 550.26 mGy cm with SD of 208.16 mGy cm.

Also, air pressure data on the dates of the control measurements was gathered to ascertain whether some of the variation observed could be explained by insufficient adjustment for air pressure, assuming that ambient air pressure in CT rooms equals weather data from the nearest observation point. The Finnish Meteorological Institute has supplied free data on air pressure only since 2010. Since air temperature and humidity are controlled via acclimatization, weather reports cannot access relevant data concerning temperature or humidity, of which temperature is known to affect measurements while humidity does not [17]. Since this was a retrospective study, and ambient air pressure, temperature, or humidity was not recorded during control measurements, more precise data could not be accessed.

2.2. Statistical methods

The ten consecutive intra-day measurement set, and the long-term control data were independently tested for normality by visual inspection from histogram and Q-Q plots, the Kolmogorov-Smirnov test and the Shapiro-Wilk test.

The difference between measured and displayed dose in the set of ten consecutive measurements was analysed with a one-sample Wilcoxon test.

The long-term data of DLP values gathered from the scanner, including the mean result from the above-mentioned ten consecutive measurements, were analysed against time and different imaging parameters with visual inspection of correlation scatterplots and Pearson's correlation coefficient in an attempt to identify a trend in the variation change and to explain the causes of the variation. The difference between measured and displayed dose was also analysed with one-sample Wilcoxon test.

For the effect of air pressure, analyses were made by visual inspection of correlation scatterplots and Pearson's correlation coefficient between ambient air pressure and the difference between measured and displayed dose.

Statistical analysis was performed with SPSS. Results are presented as mean with standard deviation (SD) and the confidence interval of 95 % (CI 95 %). A p-value of 0.05 or less was considered statistically significant.

This study was approved by the Division of Medicine and Department of Emergency Medicine in Kanta-Häme Central Hospital. Due to the nature of the study, because no patient data, or any other personal data whatsoever was handled, approval by the Ethics Committee of Tampere University Hospital was not required.

3. Results

The ten consecutive intra-day measurement dataset was not considered normally distributed based on histogram and Q-Q plot although p-values for Kolmogorov-Smirnov and Shapiro-Wilk tests were 0.200 and 0.193 respectively, implying normal distribution. The long-term control dataset was considered normally distributed. Histogram and Q-Q plot showed relatively typical normal distribution and p-values for Kolmogorov-Smirnov and Shapiro-Wilk tests were 0.200 and 0.954 respectively.

In the ten consecutive intra-day measurement set, the measured

radiation doses were slightly lower than the doses reported by the device, on average 416.7 (SD ± 0) mGy cm vs. 422.2 (±4.2) mGy cm. The mean difference between measured and displayed dose was −1.26 (±1.04 %-points) (CI 95 %, −2.00 to +0.52 %). Difference from zero was significant ($p = 0.005$).

In the long-term control data, in all but one control measurement, the measured radiation dose was lower than the dose reported by the CT scanner. The difference between displayed and measured doses varied between −17.3 and 4.65 % with a mean of −7.52 % (±5.71 %-points) (CI 95 %: −10.4 to +4.68 %). The difference from zero was statistically significant ($p < 0.001$). The differences between measured and displayed doses from both sets are displayed in Fig. 2.

There was no trend against time in the development of the difference between the measured and displayed doses, nor any correlation against different imaging parameters. No correlations were apparent in any Scatterplots and Pearson's correlation coefficients for the difference against time was −0.004, for the difference against current −0.054, for the difference against the length of scan 0.258 and for the difference against the scan time 0.297. All correlations were considered non-significant. Also, there was no correlation between ambient air pressure and the difference observed between measured and displayed dose. Scatterplot did not show any correlation and Pearson's correlation coefficient was 0.231 (NS).

The correction factor to be used with radiation dose analysis in further studies is calculated by adding the mean difference to one. Thus, the correction factor for the older scanner is 1 + (−0.0752) = 0.9248.

4. Discussion

This study has shown that there was substantial variation between measured and displayed radiation doses. The variation was significantly lower in measurements made in one day with undisturbed setting than between measurements made on different occasions over the years. There was no trend within the annual variation. Since there was no trend, nor any discernible association with variation, the mean difference between measured and displayed doses can be used to describe the accuracy of the radiation display and a simple correction factor can be calculated to achieve more accurate radiation dose values.

The results are in line with those of an earlier report of discrepancies between measured and displayed doses [18]. Otherwise, reports of differences between displayed and measured doses have been rare. The factors causing variation and error have been reported. These factors can be divided into two groups. Firstly, there is variation due to the CT scanner itself and secondly, there is variation due to the measurement or external conditions. The radiation dose displayed by the CT scanner is calculated only from the imaging parameters. The production of x-rays is a stochastic process. Although factors like voltage, current, the material of the anode and filtering used largely determine the spectre of the radiation, the number of photons produced is not always identical and so there is variation in the spectre even when parameters are identical. In the second group, factors such as the differing technologies of CT scanners, differences between ionization chambers and their measurement accuracies, the placement of the measuring devices, the amount of scattered radiation missing the ionization chamber together with air pressure and temperature can affect the accuracy of the measurement [12,19].

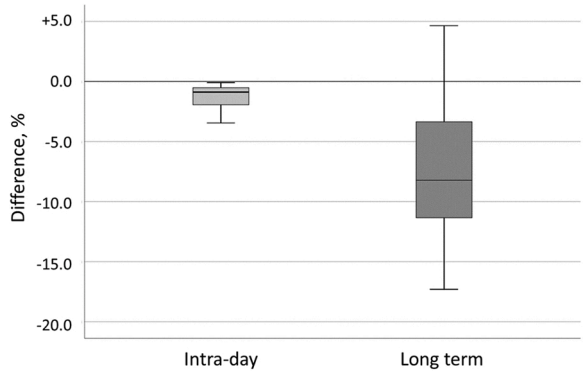

Fig. 2. Amount of difference between measured and displayed dose in intra-day and long-term measurements.

The placement of the measuring devices is always done with the help of lasers. The exact position and orientation of the phantom still vary between settings and this may affect the measurement result [12]. When the phantom is placed on the patient table, it moves during the scan, and the amount of scattering radiation reaching the ionization chamber is smaller at both extremes of the scan length than in the middle of the scan. When the phantom is suspended on straps, the ionization chamber is positioned in the same location throughout the whole measurement and thus the amount of scattering radiation missing the ionization chamber is constant and longer scan lengths can be utilized. In the data, all but vendor maintenance used straps to position the phantom to minimize variation caused by the measurement. This setting appears to be better than placing the phantom on a patient table. There seems to be a trend for less variation and on average smaller error in the data with strap settings than when the phantom is positioned on the patient table. However, the data is too small to enable a proper analysis and conclusions on this matter.

Air pressures and temperatures are accounted for either automatically by the measurement device or manually with correction factors. All the equipment in this study used automatic correction and there was no correlation between display error and air pressure.

The in-house set of ten consecutive measurements was performed without touching the setting between or during the measurements except for the placement of the ionization chamber. Further, the x-ray tube was heated according to an identical protocol for each measurement. Thus, the results describe more of the variation caused by the CT scanner than the variation caused by measurement.

Internationally, authorities monitoring medical radiation equipment typically allow the calibration of the radiation display to vary by 20 % [12,13,19]. This requirement was met in the data.

The extent of deviance permitted in radiation display calibration may significantly affect the results of radiation dose studies, even when it is within the range permitted. If the information about the accuracy of the radiation display is not included in the study, it is practically impossible to say how accurate the result is. This is the case especially when radiation dose data from more than one device is combined or compared. The present study shows that even when accessing longitudinal data from a single machine, the calibration is not constant day-to-day and may affect the results, depending on the setting. On the other hand, since there was no deterioration in the accuracy of the calibration as a function of time, nor any other trends, there is no need to adjust data correction beyond simple constant correction factor.

The strengths of this study are the in-house set of ten consecutive measurements, the use of repeated control measurements, made in a course of years, and a thorough investigation of factors possibly explaining the variation. Measurements done with undisturbed setting show that calibration measurements done within a short timespan do not register the whole variation possible. With the repeated measurements made in a course of years it is possible to investigate thoroughly the possible factors explaining the variation. In the absence of an obvious explanation for the majority of the variation, it can be assumed that these factors also affected the initial calibration of the radiation dose display, causing a systematic error in radiation dose reports. Hence, the utilization of a correction factor is justified.

A limitation of this study is that it was performed on only one CT scanner. Theoretically, it is possible that this kind of variation within dose measurements is typical only for this particular CT scanner. This is unlikely because monitoring authorities globally allow variation of this

magnitude and the national supervisor has never addressed the subject. Because of the amount of the data points, the analyses between different subgroups do not yield statistically significant results. Hence, the different methods of measurement cannot be evaluated, nor all explanatory factors accessed. Gathering more data would make it possible to calculate a more accurate correction factor. On the other hand, it would require significantly more frequent measurements, since the life cycle of a CT scanner is not long enough to provide substantially larger data with yearly measurements. A correction factor will be calculated for other CT scanners before conducting comparative radiation dose studies to see whether a similar variation is present. These corrected radiation doses will be used in further studies alongside with the doses reported by the CT machines.

5. Conclusion

This study has shown that the radiation dose reports of a CT scanner are not accurate and that there is a systematic error in the calibration of a radiation display of a CT scanner. In addition, a method for calculating a correction factor has been described. An individual correction factor should be implemented for each scanner prior to radiation dose analysis to ensure more precise radiation dose values. This is the case particularly when comparing more than one CT scanner. Although some margin of error persists, it is considerably smaller than without using correction factors since the systematic error is greatly reduced.

Ethical statement

This study was approved by the Division of Medicine and Department of Emergency Medicine in Kanta-Häme Central Hospital. Due to the nature of the study, because no patient data, or any other personal data whatsoever was handled, approval by the Ethics Committee of Tampere University Hospital was not required.

CRediT authorship contribution statement

Väinö Forss was responsible for study design, analysis of the data and most of the drafting. **Heikki Yli-Ollila** was responsible for study design, in-house measurements, drafting the article and supervision of the article. **Jussi Vatanen** was responsible for preliminary study design and drafting. **Paula Kölhi** and **Veli-Pekka Poutanen** were responsible for preliminary study design, in-house measurements and drafting the article. **Ari Palomäki** was the main supervisor of the research and responsible for study design and organization and drafting the article. All authors for their part critically revised the manuscript, and, finally, read and approved it.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] H. Bijwaard, M. Pruppers, I. De Waard-Schalkx, The influence of population aging and size on the number of CT examinations in the Netherlands, Health Phys. 107 (2014) 80–82, https://doi.org/10.1097/HP.0000000000000050.
[2] A. Pola, D. Corbella, A. Righini, A. Torresin, P.E. Colombo, L. Vismara, L. Trombetta, M. Maddalo, M.V. Introini, D. Tinelli, L. Strohmenger, G. Garattini, A. Munari, F. Triulzi, Computed tomography use in a large Italian region: trend analysis 2004–2014 of emergency and outpatient ct examinations in children and adults, Eur. Radiol. 28 (2018) 2308–2318, https://doi.org/10.1007/s00330-017-5225-x.
[3] OECD. stat, OECD (n.d.). https://stats.oecd.org//Index.aspx?QueryId=90712 (Accessed June 14, 2019).
[4] J. Lee, J. Kirschner, S. Pawa, D.E. Wiener, D.H. Newman, K. Shah, Computed tomography use in the adult emergency department of an academic urban hospital from 2001 to 2007, Ann. Emerg. Med. 56 (2010) 591–596, https://doi.org/10.1016/j.annemergmed.2010.05.027, e1.
[5] L. Lambert, O. Foltan, J. Briza, A. Lambertova, P. Harsa, R. Banerjee, J. Danes, Growing number of emergency cranial CTs in patients with head injury not justified by their clinical need, Wien. Klin. Wochenschr. 129 (2017) 159–163, https://doi.org/10.1007/s00508-016-1025-6.
[6] E.P. Hess, L.R. Haas, N.D. Shah, R.J. Stroebel, C.R. Denham, S.J. Swensen, Trends in computed tomography utilization rates, J. Patient Saf. 10 (2014) 52–58, https://doi.org/10.1097/PTS.0b013e3182948b1a.
[7] M.S. Linet, T.L. Slovis, D.L. Miller, R. Kleinerman, C. Lee, P. Rajaraman, A. Berrington de Gonzalez, Cancer risks associated with external radiation from diagnostic imaging procedures, CA Cancer J. Clin. 62 (2012) 75–100, https://doi.org/10.3322/caac.21132.
[8] D. Kaul, J. Kahn, L. Huizing, E. Wiener, U. Grupp, G. Boning, P. Ghadjar, D. M. Renz, F. Streitparth, Reducing radiation dose in adult head CT using iterative reconstruction - a clinical study in 177 patients, Rofo 188 (2016) 155–162, https://doi.org/10.1055/s-0041-107200 [doi].
[9] A.P. Sauter, N. Shapira, F.K. Kopp, J. Aichele, J. Bodden, A. Knipfer, E. J. Rummeny, P.B. Noël, CTPA with a conventional CT at 100 kVp vs. a spectral-detector CT at 120 kVp: Comparison of radiation exposure, diagnostic performance and image quality, Eur. J. Radiol. Open 7 (2020), 100234, https://doi.org/10.1016/J.EJRO.2020.100234.
[10] E.J. Hall, D.J. Brenner, Cancer risks from diagnostic radiology, Br. J. Radiol. 81 (2008) 362–378, https://doi.org/10.1259/bjr/01948454.
[11] Radiation Act (Säteilylaki), Valtion Säädöskokoelma Finlex (in Finnish), Finland, 2018. https://www.finlex.fi/fi/laki/ajantasa/2018/20180859.
[12] IAEA, Dosimetry in Diagnostic Radiology: an International Code of Practice, Tech. Reports Ser. No. 457, 2007, pp. 1–5 (Accessed July 16, 2019), https://www-pub.iaea.org/MTCD/publications/PDF/TRS457_web.pdf.
[13] C. Dillon, William Breeden III, Jessica Clements, D. Gress, Kalpana Kanal, James Kofler, Michael F. McNitt-Gray, James Norweck, Doug Pfeiffer, Thomas G. Ruckdeschel, Keith J. Strauss, James Tomlinson, Computed Tomography Quality Control Manual, 2017.
[14] K.A. Jessen, P.C. Shrimpton, J. Geleijns, W. Panzer, G. Tosi, Dosimetry for optimisation of patient protection in computed tomography, Appl. Radiat. Isot. 50 (1999) 165–172, https://doi.org/10.1016/S0969-8043(98)00024-4.
[15] W. Leitz, B. Axelsson, G. Szendrö, Computed tomography dose assessment - a practical approach, Radiat. Prot. Dosimetry 57 (1995) 377–380, https://doi.org/10.1093/oxfordjournals.rpd.a082564.
[16] K.J. Strauss, Dose indices: everybody wants a number, Pediatr. Radiol. 44 (Suppl 3) (2014) 450–459, https://doi.org/10.1007/s00247-014-3104-z.
[17] M.R. McEwen, J. Taank, Examining the influence of humidity on reference ionization chamber performance, Med. Phys. 44 (2017) 694–702, https://doi.org/10.1002/mp.12057.
[18] F. Hasford, B. Van Wyk, T. Mabhengu, M.D.T. Vangu, A.K. Kyere, J.H. Amuasi, Determination of dose delivery accuracy in CT examinations, J. Radiat. Res. Appl. Sci. 8 (2015) 489–492, https://doi.org/10.1016/j.jrras.2015.05.006.
[19] E. Comission, Criteria for Acceptability of Medical Radiological Equipment used in Diagnostica Radiology, Nuclear Medicine and Radiotherapy, 2012, https://doi.org/10.2768/22561.