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COMPUTED TOMOGRAPHY

Statistical analysis for obtaining optimum number of CT scanners in patient dose surveys for determining national diagnostic reference levels

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Abstract

Objectives To statistically determine an 'optimum number of CT scanners' for obtaining 'diagnostic reference levels' (DRLs) in CT examinations as close as possible to 'ideal DRLs' when all available CT scanners are considered.

Methods First, six 'ideal DRLs' ($CTDI_{Vol}$ and DLP) were determined for head, chest and abdomen/pelvis examinations by using patient-dose survey data of 100 CT scanners of different models in Tehran. Then, a 'random sampling method' was applied to different percent fractions of patient dose data of 100 CT scanners. The percent differences (PD) of the DRLs obtained from 'ideal DRLs' and their coefficients of variation (CVs) were calculated. The 'optimum number of CT scanners' determined met those of 'ideal DRL' criteria; i.e. precision (CV ≤ 10%) and accuracy (PD ≤ 10%).

Results 'Optimum number of CT scanners' for determining DRLs as close as possible to 'ideal DRLs', fulfilling the stated criteria, is 43 instead of using 100.

Conclusion 'Optimum number of CT scanners' for obtaining DRLs as close as possible to 'ideal DRLs' was determined. This optimum number can be effectively applied in patient-dose survey situations with limited resources in a time- and cost-effective manner.

Key Points

- *Ideal DRLs were determined by a CT patient-dose survey applied to available scanners.*
- *'Optimum number of CT scanners' statistically determined for DRLs is 43%.*
- *Optimum number can be used for DRLs as if 'ideal DRLs' were determined by all scanners.*

Keywords Surveys and questionnaires · Radiation protection · Statistics · Radiation dosage · Tomography scanners, X-ray computed

Abbreviations

$CTDI_{Vol}$	Volume computed tomography dose index
CV	Coefficient of variation
DLP	Dose length product
DRL	Diagnostic reference level
PD	Percent difference
PF	Percent fraction

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Introduction

Computed tomography (CT) examinations for clinical diagnosis have been increased globally due to their efficacy in the rapid extraction of precise anatomical information from a scanned area of the patient body. Despite such advantages, CT examinations have also been considered a major source of patient exposure leading to an increase in the collective dose of the public [1–3]. In order to protect patients undergoing CT examinations from unwanted exposures, the two radiation protection principles of the International Commission on Radiological Protection (ICRP), namely justification and optimization, should be applied [4–6].

A practical, powerful and efficient criterion for optimization of patient exposure in CT examinations introduced by the ICRP is 'diagnostic reference level (DRL)' [5, 6]. A DRL is defined as an advisory patient-dose level set by a regulatory authority in a country at local, regional or national levels [5–10]. The aim of applying the DRLs in a clinical practice is to optimize the patient dose and at the same time maintain the image quality at a high enough level to extract the anatomical information for diagnostic purposes. For CT examinations, the DRLs are commonly determined for the volume computed tomography dose index ($CTDI_{Vol}$) and dose length product (DLP) [7–10].

In order to determine a DRL ($CTDI_{Vol}$ and DLP) for a CT examination type, dose surveys are usually performed at local, regional or national levels. These dose surveys may apply a 'direct dose measurement method' [7], a 'data collection method' [11] or a 'quality control (QC)-based dose survey method' [12–14].

The dose surveys are expected to compromise the circumstances of the CT practices such as the state of the CT scanner technology and CT examination protocols as well as the training level of radiologists, technicians and medical physicists in setting the exposure conditions [11, 15, 16]. It would be ideal to have all the CT scanners of all models available in a country to participate in the dose survey in order to determine what is called in this paper 'ideal DRLs'. This is not usually possible in all countries; instead, it is a common practice that a limited number of CT scanners available for the dose survey are used due to limitations such as a lack of human resources, interruptions in clinical practices and requiring the collaboration of CT scanner staff as well as time and cost considerations. Therefore, the purpose of this study was to:

1. Introduce a statistical 'random sampling method' in order to determine an 'optimum number of CT scanners' for obtaining DRLs in CT examinations as close as possible to the 'ideal DRLs' when all available CT scanners have participated in the patient-dose survey;
2. Apply a patient-dose survey in a population of 100 CT scanners in Tehran by combination of CT scanners from all models proportionate to all the CT scanners available in Iran;
3. Determine the 'optimum number of CT scanners' for obtaining DRLs as close as possible to the 'ideal DRLs'; and
4. Discuss the method so that it can be applied in all countries by using limited resources in a time- and cost-effective manner.

Materials and methods

Patient dose assessment

The 'QC-based dose survey method' was applied to 100 CT scanners from 160 CT scanners in operation in Tehran, the capital city of Iran [12–14]. This population of CT scanners was actually the maximum possible coverage of the CT scanners (i.e. 62.5% of all installed and operational CT scanners) participated in the patient-dose survey. In the 'QC-based dose survey method', a 'reference exposure condition' (exposure condition and dose values of a QC dosimetry test) is extracted from a QC report of a CT scanner. Then, a typical protocol (exposure setting), commonly applied for a standard size patient or CT dosimetry phantoms that can produce an image with clinically acceptable quality from a radiologist's point of view is requested from the CT scanner operator. The $CTDI_{Vol}$ and DLP values are determined by applying corrections of mAs, kVp and beam collimation of each patient protocol to the reference exposure conditions for all CT scanners included in the dose survey and their dose distributions are developed in order to determine the DRLs [12–14].

The surveyed CT scanners in this study were selected from seven manufacturers and seven slice classes proportionate to all the CT scanners available in Iran, as indicated in Table 1. The $CTDI_{Vol}$ and DLP values included six sets of patient-dose data for each of the head, chest and abdomen/pelvis examinations with 100 samples in each category. The third quartile of each patient-dose data set constituted the 'ideal DRLs'.

Table 1 Number of CT scanners for each manufacturer and slice class type

Manufacturer	No. of CT scanners
Shimadzu	8
GE	33
Siemens	44
Philips	2
Toshiba	3
Hitachi	2
Neusoft	8
Total	100
Slice class	No. of CT scanners
1	22
2	16
4	6
6	5
8	2
16	40
64	9
Total	100

Statistical analysis: Determination of 'optimum number of CT scanners'

The statistical analysis was performed by using the MATLAB (R2013b) program and on the six $CTDI_{Vol}$ and DLP data sets corresponding to the head, chest and abdomen/pelvis examinations. A simple 'random sampling method' was selected for statistical sampling of CT scanners since in this method each of the CT scanners had the same probability to be selected regardless of their manufacturer and/or slice class; the same as dose surveys in other countries.

In order to determine the 'optimum number of CT scanners' fulfilling the criteria as close as possible to the 'ideal DRLs' also determined in this study, a parameter entitled 'percent fraction (PF)' of the 100 CT scanners' dose data was defined. The dose data of at least three CT scanners are required in order to allow calculation of the third-quartile value and in turn the relevant DRL. By increasing the number of CT scanners participating in the patient-dose survey up to the maximum available CT scanners, i.e. 100 CT scanners in this study, the DRLs calculated will achieve the 'ideal DRLs'. Therefore, a range of PF values from 3% to 100% were sampled randomly.

In order to take into account the variations due to the random nature of statistical sampling, 10,000 sampling iterations were run for each PF value since different dose data samples result in different DRLs. The DRLs ($CTDI_{Vol}$ and DLP) for the head, chest and abdomen/pelvis examinations for each PF value were determined in all sampling iterations. For consistent analysis of the DRLs obtained for each PF of the patient-dose data, two statistical parameters were used:

1) Percent difference (PD), which is the absolute value of the difference between a DRL obtained from the 'random sampling method' with the corresponding 'ideal DRL' divided by the 'ideal DRL' for each CT examination type, and
2) Coefficient of variation (CV), which is the ratio of the standard deviations of the DRLs obtained from the 'random sampling method' to their mean values averaged on all iterations for each CT examination type.

Due to the inherent difference in the exposure settings and in turn the patient-dose data in each CT examination type, some differences in the PD and CV values between different examination types are expected. Therefore, it would be more reliable if the acceptance criteria on each PF selection is set according to the mean values of the calculated PD (PD_{mean}) and CV (CV_{mean}) averaged over six patient-dose data sets corresponding to the three examination types. The acceptance criteria for each PF selection were set as $PD_{mean} \leq 10\%$ and $CV_{mean} \leq 10\%$. Finally, the 'optimum number of CT scanners' required for determining the DRLs was the minimum PF that satisfied the acceptance criteria.

Results

Ideal DRLs

'Ideal DRLs' determined were 58, 11 and 13 mGy for $CTDI_{Vol}$ and 783, 270 and 583 mGy.cm for DLP for the head, chest and abdomen/pelvis examinations, respectively. These values are considered as the ideal values since they have been determined for the maximum possible number of CT scanners (100 scanners) available to participate in an actual patient-dose survey.

'Optimum number of CT scanners'

In order to determine the 'optimum number of CT scanners', the results of the 'random sampling method' were analysed according to the PF values of a patient-dose data set. This is because the 'optimum number of CT scanners' as defined above was the minimum PF value that satisfies the acceptance criteria.

Figure 1 shows the DRLs ($CTDI_{Vol}$ and DLP) for the head, chest and abdomen/pelvis examinations versus the PF values. The solid horizontal lines are the 'ideal DRLs' of the three stated examination types and each error bar corresponds to one standard deviation. As can be seen, by increasing the number of CT scanners included in the patient-dose survey, both the accuracy and the precision of the DRLs determined increase.

Figure 2(a, b) shows the PD and CV values obtained for each CT examination type versus the PF values. The solid horizontal lines are the acceptance criteria, i.e. 10%, for the PD and CV values.

From the data given in Fig. 2(a, b), two main conclusions can be made:

1) Some differences exist between the PD and CV values of $CTDI_{Vol}$ and DLP for each CT examination type. These data show that for more precise determination of the 'optimum number of CT scanners', both the DLP and $CTDI_{Vol}$ values should be considered and analysed statistically.
2) For our dose data sets, the PD values satisfied the acceptance criteria. However, the differences observed between the CV values of the three examination types resulted in different 'optimum number of CT scanners' obtained. Hence, it was necessary to calculate the mean values of the PD and CV and then determine the 'optimum number of CT scanners' accordingly.

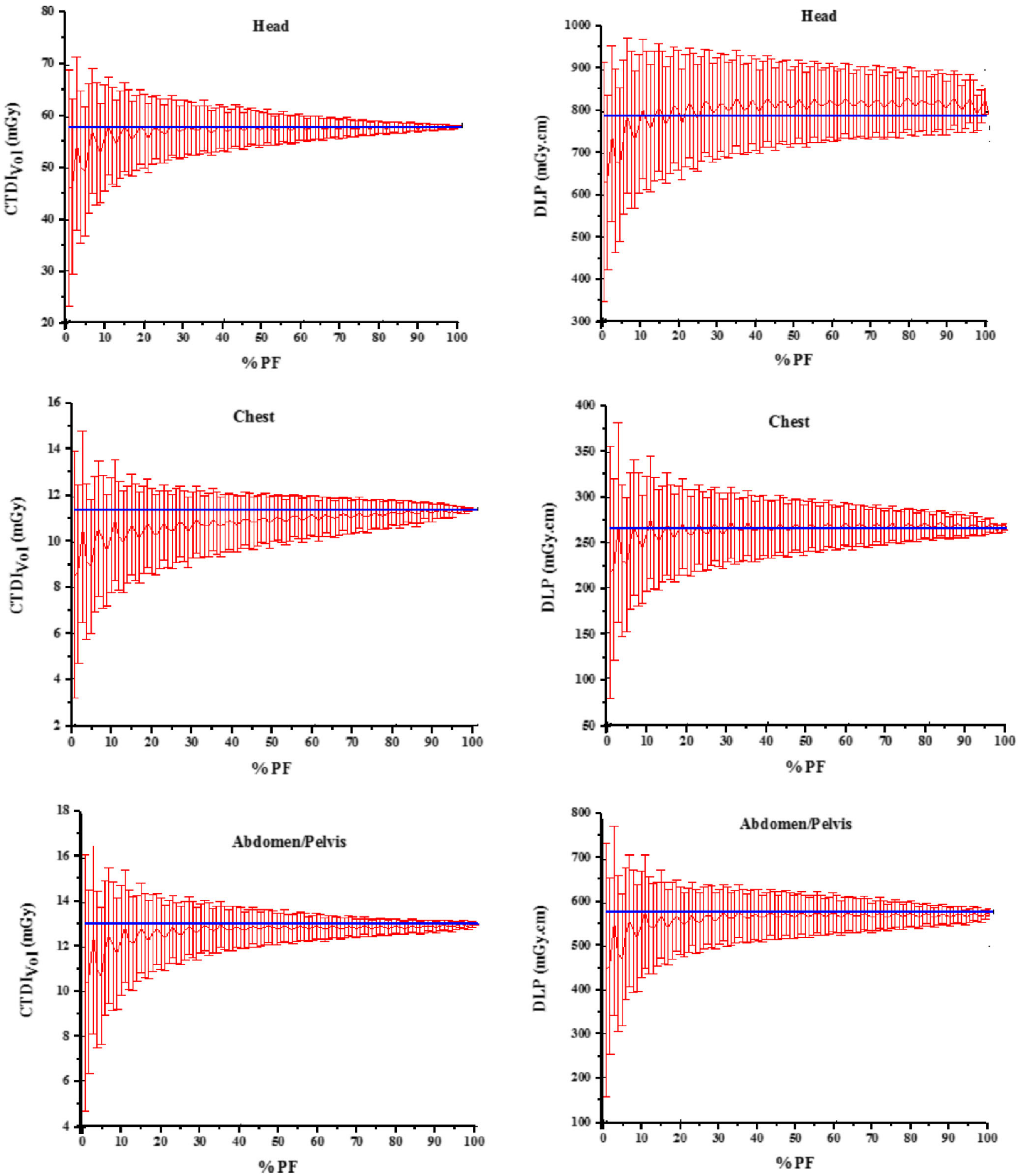

Fig. 1 DRLs ($CTDI_{Vol}$ and DLP) for the head, chest and abdomen/pelvis examinations versus the PF values. The solid horizontal lines are the 'ideal DRLs' of the three stated examination types and each error bar corresponds to one standard deviation

Figure 3(a, b) shows the PD_{mean} and CV_{mean} values for the DRLs of the six patient-dose data sets versus the PF values. The solid horizontal lines are the 10% acceptance criteria for both the PD_{mean} and CV_{mean} values. Each error bar in each of the graphs shows one standard deviation of the DRL points among the six patient-dose data sets. The PD_{mean} values for all the PF values were below the acceptance criterion. Therefore this parameter has no effect on the determination of the 'optimum

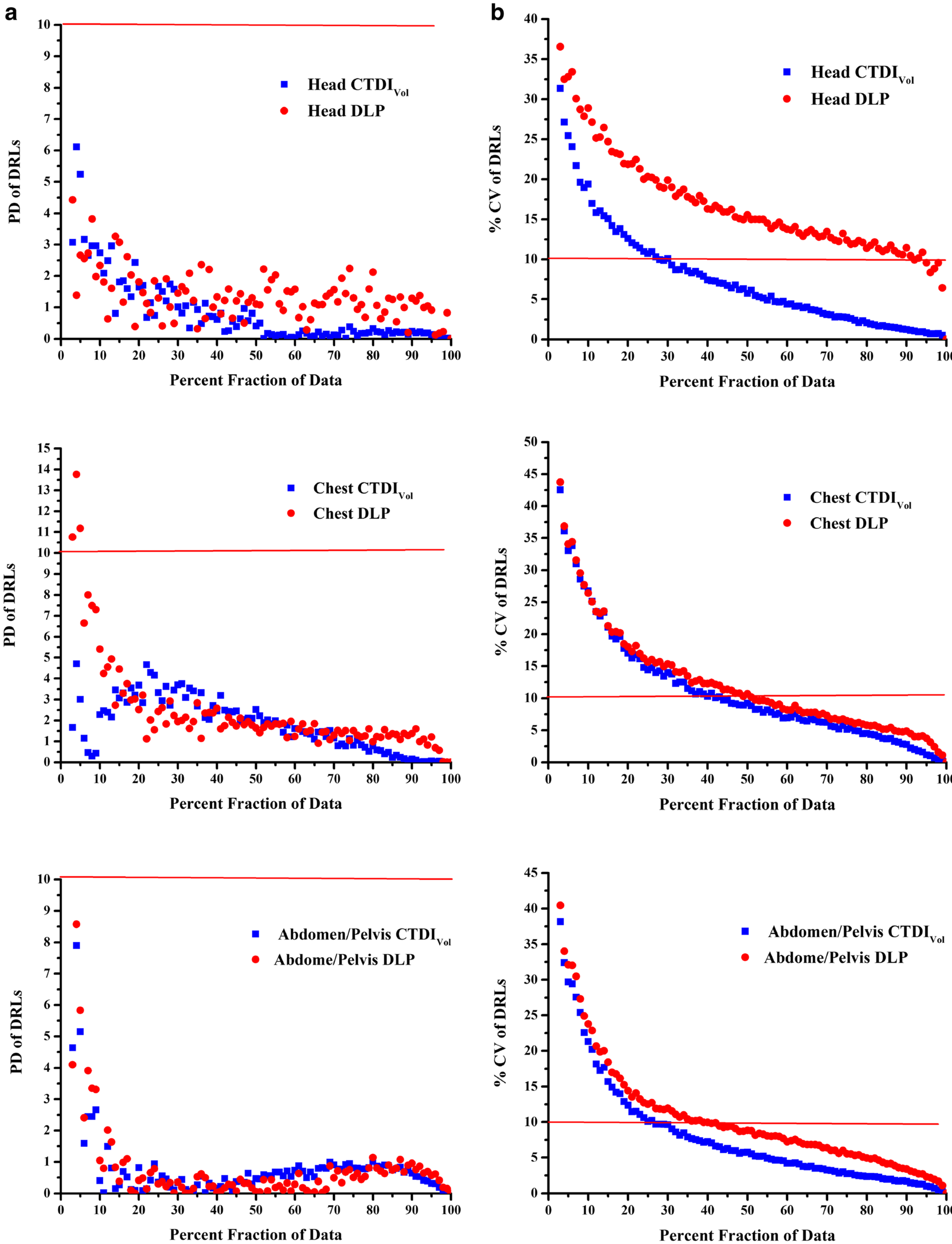

Fig. 2 (**a, b**) The PD (**a**) and CV (**b**) values obtained for each CT examination type versus the PF values. The solid horizontal lines are the acceptance criteria for the PD and CV values

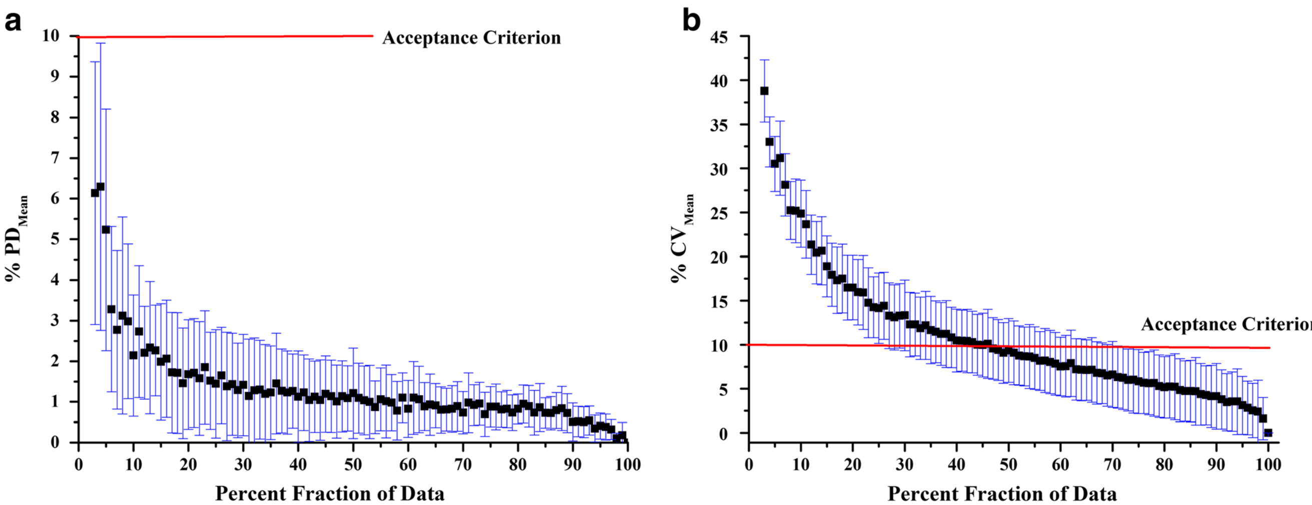

Fig. 3 (**a, b**) The PD_{mean} (**a**) and CV_{mean} (**b**) values for the DRLs of the six patient-dose data sets versus the PF values. The solid horizontal lines are the 10% acceptance criteria. Each error bar in each of the graphs shows one standard deviation of the DRL points among the six patient-dose data sets

number of CT scanners' (Fig. 3a). The error bars in Fig. 3a are the reason for uncertainty of the DRLs determined in the different values of PF of dose data sets. The relative variations of the DRLs (i.e. CV_{mean} in Fig. 3b) for each PF value, especially for low values of PF, were very large and produced a relatively high uncertainty in the DRL calculation. The minimum PF value with CV_{mean} < 10% corresponds to 43% (i.e. 43 CT scanners from 100), which is considered as the 'optimum number of CT scanners' required for DRLs calculation.

Discussion

In this paper, a 'random sampling method' was applied to 100 CT scanners (available from 160 CT scanners in operation in Tehran) in order to determine an 'optimum number of CT scanners' so that if applied for determining DRLs, the results are as close as possible to the 'ideal DRLs' when all 100 CT scanners had been considered. The method was used for obtaining DRLs for the head, chest and abdomen/pelvis examinations.

Detailed analysis of Fig. 1 shows that the DRLs obtained are different for different numbers of CT scanners included in the patient-dose survey. This result implies that the number of CT scanners included in the patient-dose survey has significant effects on the precision of DRLs determined. A dose survey with only a few CT scanners results in DRLs with relatively large uncertainties. On the other hand, a patient-dose survey with a large number of CT scanners provides more reliable DRLs, but it also requires extensive human resources involving extensive time and high costs. Therefore, it is extremely valuable and practical to determine an 'optimum number of CT scanners' required for obtaining DRLs with an acceptable precision and accuracy with reduced human resources and in a time- and cost-effective manner, as was determined for the first time with the methodology applied in this study.

It can be seen in Fig. 2(a, b) that each examination type surveyed can affect the 'optimum number of CT scanners' determined. The PD and CV values decrease by increasing the PF values, which means that the DRLs obtained from the sampling process approach the 'ideal DRLs'. The PD and CV curves can be changed by repeating the sampling process, while due to the 10,000 times resampling, the pattern is not expected to be changed. The PD values of the head examination for the DLP have significant fluctuations, possibly due to the wide variations in the dose distribution and large differences in the protocols and scan length that were represented in the statistical analysis. As such variations in a dose distribution become larger, the DRLs obtained from random sampling in each iteration will have a greater difference. This is possible since a data set sampled in each sampling iteration differs greatly from that of the data set sampled in previous iterations, depending on the CT scanners selected in each sample. By increasing the PF value in an abdomen/pelvis examination around 65–90%, such large fluctuations are further taken into account in the sampling process, which result in a great difference between the DRLs obtained and 'ideal DRLs'; and in turn a slight increase in the PD values. The relatively high value of CVs around 65–90% for the abdomen/pelvis examination can confirm the discussed reason since the CV is a surrogate of the dispersion of the data. The PD curve for the chest DLP is relatively flat, around PF of 40–90%, after which it decreases more rapidly. This shows that sampling 40–90% of the CT scanners does not significantly change the accuracy of DRLs determined (as can be seen in Fig. 2b, the 'optimum number of CT scanners' for chest examination is about 45%).

Figures 2(a, b) and 3(a, b) show that both the accuracy (PD_{mean} < 10%) and the precision (CV_{mean} < 10%) are required to be considered in the statistical analysis for determining ‘optimum number of CT scanners’ in patient-dose surveys. This can be explained by the fact that although generally the DRLs as close as possible to the ‘ideal DRLs’ can be determined for every PF value (i.e. $PD_{mean} < 10\%$), the probability of achieving precise ‘ideal DRLs’ in each sampling fraction is low especially for low values of PF (i.e. $CV_{mean} > 10\%$). It should be noted that the wide variations in the PD_{mean} and CV_{mean} values (error bars in Fig. 3a, b) of each PF value decrease by increasing the number of CT scanners.

The results obtained from this study reveal that if the DRLs were determined based on using only 43% of all 600 CT scanners in operation in Iran, it is predicted that they are very close to the ‘ideal DRLs’ obtained when all 600 CT scanners were included in the survey. This is due to the fact that the 100 CT scanners in operation in Tehran are very similar in terms of manufacturer and slice class type to those of the 600 CT scanners operational in Iran. Due to the differences in the real-world situation of CT practice in different countries, an ‘optimum number of CT scanners’ obtained in this study may differ from those of other countries. Therefore, a dedicated ‘optimum number of CT scanners’ can be deduced for each patient-dose survey in a country by applying the following steps:

1) A sample of CT scanners of all models is selected, for example in the largest city or capital of that country like Tehran in Iran, with similar trends in terms of manufacturer and slice class type of the population of CT scanners in that country. Accordingly, the ‘ideal DRLs’ of the intended CT examination types are determined for this sample size, for example similar to that determined in this study for the head, chest and abdomen/pelvis examinations by using patient-dose data of 100 CT scanners in Tehran.
2) The ‘random sampling method’ is then applied to the different percent fractions of the patient-dose data sets for all the CT examination types surveyed. The minimum PF that passes the precision and accuracy criteria is selected as the ‘optimum number of CT scanners’ required for determining DRLs.
3) The ‘optimum number of CT scanners’ obtained from step 2 above and the minimum number of patients obtained by other researchers [17] can be extended and generalized at a wider level in order to determine ‘national DRLs’. This process can effectively reduce human resources, time and cost effectiveness involved for a typical full-scale dose survey without any significant influence on the precision of the DRLs obtained.

Conclusion

A novel ‘random sampling methodology’ has been introduced in this article for first time aimed at determining an ‘optimum number of CT scanners’ required for obtaining DRLs in CT examinations in a country as close as possible to the ‘ideal DRLs’, when all CT scanners have been considered. The ‘optimum number of CT scanners’ in Iran was determined to be 43% CT scanners’ population in the country; i.e. it is expected to determine accurate and precise national DRLs in Iran by including 43% of all CT scanner population in the patient-dose survey. The methodology applied was found to be highly effective in terms of simplicity, practicality and speed for determining an ‘optimum number of CT scanners’. It is highly recommended that the method, is applied in particular in those countries with limited resources in a time- and cost-effective manner.

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Compliance with ethical standards

Guarantor The scientific guarantor of this publication is Prof. Mehdi Sohrabi from the Amirkabir University of Technology.

Conflict of interest The authors of this manuscript declare no relationships with any companies whose products or services may be related to the subject matter of the article.

Statistics and biometry One of the authors (Dr. Sanaz Hariri Tabrizi) has significant statistical expertise.

No complex statistical methods were necessary for this paper.

Informed consent Written informed consent was not required for this study because the study was based on the ‘QC-based dose-survey method’, which required no information about the CT institutes or any particular patients.

Ethical approval Institutional Review Board approval was not required because the study is based on CT scanner models, which do not involve ethical issues.

Methodology
• retrospective
• observational
• multicentre study

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