Original

Simulator-assisted Setting of Scan Protocols for X-ray CT: Development and Clinical Usefulness of the Scan Plan Simulator

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Introduction

Scan protocols have become more complicated since the introduction of multislice computed tomography (CT) systems in 1998. According to the particular diagnostic application and based on the physician's judgment, radiological technologists must set complicated combinations of parameters in scan protocols, such as X-ray tube voltage, tube current, slice thickness, scan speed, pitch factor, and reconstruction kernel.

It is difficult even for experienced technologists to ensure a stable image SD (image noise) for all combinations of scan protocols in order to obtain images suitable for the specific diagnostic application. The relationship between the combinations of parameters in scan protocols and the obtained image SD values is strongly dependent on the experience and judgment of the radiological technologist performing the study, and has yet to be systematized. Studies on methods to obtain a constant image SD value by minimizing the effects of body size have

been conducted, but in these previous studies only the tube current was controlled,¹⁻⁶⁾ and other parameters of the scan protocols were not considered. We therefore developed the Scan Plan Simulator (SPSim), which controls not only the tube current but also all combinations of parameters in scan protocols. The Scan Plan Simulator is simulation software in which the image SD value (or tube current) and the exposure dose (CTDIvol) which are obtained in actual scanning, as well as a simulated image, can be simulated instantly by entering the patient's body size and the scan protocol. This application software makes it possible to obtain optimal image SD and minimize the X-ray exposure dose according to the specific diagnostic application in each individual patient. The Scan Plan Simulator window is shown in Fig. 1. In this study, the accuracy of the Scan Plan Simulator was evaluated, and its clinical usefulness was verified. The results showed that the Scan Plan Simulator not only stabilizes image SD by minimizing the effects of body

Summary

To assist in the selection of complicated computed tomography (CT) scan protocols and to obtain stable image SD values, prototype "Scan Plan Simulator" software with the following functions was developed and evaluated. 1) The image SD value that will be obtained in actual scanning is estimated by entering the patient's body size and scan protocol, after which a simulated image is displayed so that the estimated image SD value can be checked. The exposure dose can also be estimated in the Scan Plan Simulator. 2) The appropriate tube current is automatically set by entering the required image SD value. We evaluated the accuracy of the Scan Plan Simulator by comparing the simulation results with the image SD values and exposure dose obtained in actual scanning and assessed the usefulness of this method using Monte Carlo simulation based on body thickness data obtained in clinical examinations. The results showed that the Scan Plan Simulator not only stabilizes image SD by minimizing the effects of body size but also permits the exposure dose to be reduced by optimizing tube current.

Key words: Computed tomography, Tube current time setting, Image noise, Exposure dose reduction

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size but also permits the exposure dose to be reduced by optimizing tube current.

1. Configuration of the Scan Plan Simulator

The Scan Plan Simulator consists of four tables, shown in Fig. 2: a water equivalent thickness conversion table based on the patient's body size and anatomical region, image SD and dose conversion tables based on the water equivalent thickness and scan protocols, and a simulated image table based on the estimated image SD values. The configuration of each table is described below.

1-1 Water equivalent thickness conversion table

A water equivalent thickness conversion table is used for approximating patient's body size based on water phantom data. A conversion equation for calculating the diameter of a circular water phantom with X-ray absorption equivalent to that of the body was formulated based on body thickness and anatomical region (for the head, chest, abdomen, and pelvis) and a table was then generated based on this conversion equation. Data were obtained for 80 clinical cases in which scanning was performed from the head to the pelvis using the Toshiba multislice CT scanner Aquilion 16. Then, the body thickness and water equivalent thickness of each anatomical

region were obtained from the image data to generate the table by the following formula: water equivalent thickness (mm) = antero-posterior (A-P) diameter obtained from body image (mm) $\times$ electron density of body image / electron density of water phantom. Electron density was calculated from the pixel value of the CT image. By using this table, normalized water equivalent thickness values can be used rather than combinations of the body thickness and the anatomical region in subsequent processing. Since patient's body size must be measured prior to CT scanning, it is expected that measurement should be performed easily. In previous studies on setting scan protocols by measuring patient's body size, the maximum A-P diameter (MAPD)^{2,3)} for the head or body weight⁴⁻⁶⁾ was used.

In the present study, patient's body thickness (A-P diameter) as used in plain X-ray studies, was used as an index of body size.

The method used to measure body thickness from the head to the pelvis is shown in Fig. 3. In some cases, body thickness can also be calculated automatically based on the scanogram acquired for positioning without manual measurement of the A-P diameter.²⁾

1-2 Image SD conversion table

Five circular water phantoms for calibration with

Fig. 1 Scan Plan Simulator window. Combinations of patient's body size, scan protocol, image SD, and exposure dose can be simulated in this window.

Fig. 2 Four types of tables used in the Scan Plan Simulator. These tables are used to estimate image SD values based on patient's body size and scan protocol.

diameters of 18, 24, 32, 40, and 50 cm were scanned with a total of 400 combinations of tube voltage, tube current, slice thickness, scan speed, and pitch factor. After image reconstruction was performed, image SD values were calculated by setting a circular ROI one-half the diameter of the phantom at the center of the image. By entering the water equivalent thickness and scan protocols into the image SD conversion table, the image SD value that will be obtained in actual scanning can be estimated. There is a physical relational expression based on photon absorption and dispersion between the scan protocol and image SD value. However, to shorten the calculation time, image SD values were estimated using a look-up table and linear interpolation from a database obtained by actual scanning rather than by numerical simulation. The current version of the Scan Plan Simulator assumes that the image field of view(FOV)s equal to the scan FOV.

1-3 Dose conversion table

Six circular acrylic phantoms for dose measurement with diameters of 10, 16, 20, 25, 32, and 38 cm were scanned with a total of 40 combinations of tube voltage, slice thickness, scan speed, and FOV. In this phantom study, the exposure dose(CTDIvol)was measured based on IEC60601-2-44.⁷⁾

The six phantoms and the dosimeter used for measurement are shown in Fig. 4. The tube current at the

Fig. 3 Method to measure body thickness from the head to the pelvis. Body thickness also can be calculated on the basis of the scanogram acquired for positioning.

time of scanning was fixed to 100 mAs. For mAs values other than 100 mAs, doses were calculated based on a relational expression for tube current and exposure dose.⁸⁾

According to IEC standards, a scattering object (phantom)with a diameter of 16 cm must be used to measure the dose for the head, while a scattering object (phantom)with a diameter of 32 cm must be used for the abdomen. As a result, if the scan conditions are the

Fig. 4 Six types of dose measurement phantoms with different diameters and a dosimeter.

To simulate differences in exposure dose depending on body size, six types of phantoms are used.

same, the exposure dose will remain constant even if body size differs. In practice, it is known that the smaller the diameter of the target object, the higher the exposure dose,^{9,10)} as shown in Fig. 5. In order to simulate differences in exposure dose depending on body size, six phantoms are used for actual measurement. By entering the water equivalent thickness and scan protocols into the dose conversion table, the exposure dose that will be obtained in actual scanning can be estimated.

1-4 Simulated image table

The simulated image for checking the estimated image SD value displayed in the Scan Plan Simulator window is a composite based on volunteer images previously scanned and saved for each anatomical region. One method for generating images with arbitrary image SD values is to artificially add noise to low-noise images.¹¹⁻¹³⁾ In the present study, one of the authors as a volunteer was scanned under low-noise conditions (1000 mAs) and high-noise conditions (10 mAs) for the same anatomical region. One slice per each anatomical region (for the head, chest, abdomen, and pelvis) was scanned. These scans were carried out at the National Cancer Center Hospital under the supervision of a qualified physician. Informed consent was also obtained from the volunteer. A simulated image with an arbitrary image SD value was generated by adjusting the mixing ratio of these two images. By entering the image SD values and the target anatomical region into the simulated image table, a simulated image for checking the estimated image SD value can be obtained.

Fig. 5 Differences in exposure dose depending on body size.

The smaller the diameter of the target object, the higher the exposure dose.

2. Methods

2-1 Evaluation of accuracy

In order to evaluate the accuracy of the Scan Plan Simulator, 200 combinations of body thickness and scan protocol and 20 combinations of body thickness and scan protocol were randomly selected from the following scan conditions for image SD values and exposure dose (CTDIvol) respectively:

Water equivalent thickness: 10 to 50 cm, tube voltage: 80 to 135 kV, tube current: 5 to 500 mA, acquisition slice thickness: 0.5 to 2 mm×16, image slice thickness: 0.5 to 10 mm, pitch factor: 0.625 to 1.5, scan speed: 0.4 to 3 s., FOV: 180 to 500 mm, and reconstruction kernel: FC01 to FC80.

Then, water phantoms and acrylic phantoms were scanned using these randomly generated scan protocols. Image SD values were measured after image reconstruction for 200 combinations, while CTDIvol values were measured during scanning using a dosimeter for 20 combinations. These measured data were defined as the actual data group.

The same scan protocols were entered into the Scan Plan Simulator to obtain image SD values and CTDIvol values. These obtained data were defined as the SPSim data group. Statistical tests of the correlation coefficient, mean value, and distribution between the actual data group and the SPSim data group were performed separately for image SD values (n=200) and CTDIvol values (n=20). Statistical analysis software MINITAB Release 14 produced by MINITAB was used for statistical tests.

2-2 Evaluation of clinical usefulness

To evaluate the clinical usefulness of the Scan Plan

Simulator, the following tests were performed using the body thickness data (A-P diameter) for 292 subjects who were examined at the National Cancer Center Research Center for Cancer Prevention and Screening between June and August 2004. All subjects gave informed consent for their data to be used for research purposes before undergoing examination.

2-2-1 Preparation of the simulation (testing for normality)

The distribution of body thicknesses obtained in the examinations is plotted. The Anderson-Darling test was used to determine whether or not a normal distribution could be assumed.

2-2-2 Monte Carlo simulation

Monte Carlo simulation for body thickness was performed as described below.

1. The scan protocols were set to match those employed for chest examination at the Research Center for Cancer Prevention and Screening. The scan protocols were as follows: 120 kV, 30 mA, 0.5 s. scan, 1 mm×16 rows, pitch factor 0.6875, FC50, FOV: 400 mm, image thickness: 5 mm

2. A mean value of 200.73 mm and an SD value of 20.14 mm of 292 subjects were set in the normal random number generation program to generate 10,000 patterns of body thickness data. Then, image SD values and CTDIvol values were estimated using the Scan Plan Simulator. The results obtained were defined as the SPSim (+) group. That is, the results for the SPSim (–) group were

the image SD values and CTDIvol values estimated when the tube current was set to a constant value (30 mA) regardless of patient's body size.

3. The image SD value was specified for the same body thickness so that the optimal tube current could be obtained using the Scan Plan Simulator. Simulation was performed again using the obtained tube current to estimate the image SD values and CTDIvol values. The results obtained were defined as the SPSim (+) group. For the required image SD values, the mean image SD value (SD=35.53) of the SPSim (–) group was used. That is, the results of the SPSim (+) group were the image SD values and CTDIvol values estimated when the optimal tube current was selected according to patient's body size.

3. Results

3-1 Evaluation of accuracy

3-1-1 Correlation coefficient

The correlation between the actual data group and the SPSim data group for image SD values and CTDIvol values is shown in Fig. 6. For both image SD values (correlation coefficient $R=0.998$) and CTDIvol values ($R=0.995$) a strong correlation was found between the actual data group and the SPSim data group.

3-1-2 Testing the mean values and distribution

The distribution between the actual data group and the SPSim data group for image SD values and CTDIvol values is shown in Fig. 7. The results of nonparametric testing (Wilcoxon rank sum test) for differences in the

Fig. 6 Correlation between the actual data group and the SPSim data group for image SD values and CTDIvol values.
For both image SD values and CTDIvol values, a strong correlation is seen between the actual data group and the SPSim data group.

Fig. 7 Box and whisker plot of the distribution between the actual data group and the SPSim data group for image SD values and CTDIvol values. For both image SD values and CTDIvol values, no significant differences are seen between the actual data group and the SPSim data group.

mean values showed no significant differences between the actual data group and the SPSim data group for both image SD values ($p=0.85$) and CTDIvol values ($p=0.97$). In addition, the results of nonparametric testing (Levene's test) for differences in the distribution showed no significant differences between the actual data group and the SPSim data group for both image SD values ($p=0.66$) and CTDIvol values ($p=0.99$).

3-2 Evaluation of clinical usefulness

3-2-1 Preparation of the simulation (testing for normality)

The distribution of body thicknesses obtained in the examinations is shown in Fig. 8. As shown in the figure, the results of the Anderson-Darling test were $p=0.28$ (>0.05), indicating that it is reasonable to assume a normal distribution of body thicknesses with a mean value of 200.73 mm and a standard deviation (StDev) of 20.14 mm.

3-2-2 Monte Carlo simulation

The Monte Carlo simulation results for tube current are shown in Fig. 9. The tube current was varied between 10 and 82.5 mA according to body size in the SPSim (+) group, while it was kept constant at 30 mA in the SPSim (-) group. The simulation results for image SD values are shown in Fig. 10. Image SD values were clustered near the specified value (SD=35.53) in the SPSim (+) group, while image SD values were widely distributed between 20.6 and 60.2 in the SPSim (-) group.

The simulation results for CTDIvol values are shown in Fig. 11. CTDIvol values were widely distributed between 1.96 and 9.59 mGy in the SPSim (+) group and

between 3.45 and 5.98 mGy in the SPSim (-) group. The mean CTDIvol value was 4.55 mGy in the SPSim (-) group, while it was 4.47 mGy in the SPSim (+) group, lower than that in the SPSim (-) group. A significant difference ($p=0.03$) was seen between the mean CTDIvol value of the SPSim (+) group and that of the SPSim (-) group by t-test.

4. Discussion

4-1 Accuracy of the Scan Plan Simulator

The experimental results for evaluation of accuracy using water phantoms as described in subsection 3-1 confirmed that the Scan Plan Simulator can simulate actual CT scanning with a high degree of accuracy. However, as shown in the graph of image SD (Fig. 6), the higher the image SD, the larger the error between the actual data group and the SPSim data group. Detailed analysis of the data with larger errors showed that the errors occurred when the water equivalent thickness was 40 cm or more, tube voltage was 80 kV, tube current was 50 mA or less, acquisition slice thickness was 0.5 mm $\times$ 16, image slice thickness was 1 mm or less, scan time was 0.5 s. or less, and FOV was 400 mm or more; therefore, the count value per unit area of the detector in slice acquisition was extremely low. Given that a look-up table and linear interpolation from a database obtained by actual CT scanning are used in order to display the calculation results quickly, it is considered that the cause of these errors is related to non-linearity for low count values. To reduce these errors, it is necessary to employ a more complex mathematical formula for interpolation or to consider photon noise as well as circuit noise. It is also

Fig. 8 Distribution of body thickness obtained in the examinations. The results indicate that it is reasonable to assume a normal distribution.

Fig. 9 Monte Carlo simulation results for tube current. In the SPSim(+) group, a wide distribution is observed in tube current.

Fig. 10 Monte Carlo simulation results for image SD. In the SPSim(+) group, image SD values are clustered near the specified value.

Fig.11 Monte Carlo simulation results for CTDIvol values.
The mean CTDIvol value in the SPSim(+) group is less than that in the SPSim(-) group.

necessary to review the parameters for each system because circuit noise differs slightly from system to system. However, such considerations make it impossible to display the calculation results quickly, which is a feature of the Scan Plan Simulator. Thus it is likely that the Scan Plan Simulator will not be used in actual clinical practice. In the future, the accuracy of the Scan Plan Simulator should be further improved by using the more complex mathematical modeling feasible with increasing computing power.

4-2 Clinical usefulness of the Scan Plan Simulator

In Fig. 12, the graphs of image SD values (Fig. 10) and CTDIvol values (Fig. 11) for the SPSim(-) group and the SPSim(+) group are superimposed.

In the SPSim(-) group, a wide distribution was observed in image SD values because the effects of body size were not considered in tube current setting. On the other hand, in the SPSim(+) group, image SD values were clustered near the specified value (SD=35.53) because the tube current was adjusted according to patient's body size. This indicates that the Scan Plan Simulator is effective for stabilizing image SD by minimizing the effects of body size.

For CTDIvol values, a wide distribution was observed in the SPSim(+) group, while a narrow distribution was observed in the SPSim(-) group. This indicates that the dose was insufficient for large patients and excessive for small patients in the SPSim(-) group because a constant tube current was used. In addition, the mean

CTDIvol value in the SPSim(+) group was lower than that in the SPSim(-) group. This is because the mean exposure dose for the mass of all body sizes was reduced by selecting the optimal tube current using the Scan Plan Simulator.

The above findings demonstrate that the Scan Plan Simulator not only stabilizes image SD by minimizing the effects of body size but also permits the exposure dose to be reduced by optimizing tube current.

When Monte Carlo simulation is performed using CTDIvol values based on IEC standards, constant CTDIvol values are observed in the SPSim(-) group, despite differences in body size. The exposure dose of mean A-P diameter 20.073 cm for 292 subjects is 1.8 times higher than the dose for 32 cm specified by IEC standards and is underestimated by IEC standards (Fig. 5).

In the present study, the use of CTDIvol values that take into consideration patient's body size permitted chest examinations to be simulated with a high degree of accuracy in each patient. In future studies, the calculation of CTDIvol values that take body size into consideration will be essential for evaluating the simulated dose for actual clinical cases.

5. Conclusion

The Scan Plan Simulator, which simulates the relationship between patient's body size, scan protocol, and image SD values in CT scanning with a high degree of accuracy, has been developed and evaluated. The Scan Plan Simulator permits scan protocols comparable to

Fig. 12 Comparison between image SD values and CTDIvol values for the SPSim(-) group and the SPSim(+) group.
The Scan Plan Simulator not only stabilizes image SD by minimizing the effects of body size but also permits the exposure dose to be reduced.

those prepared on the basis of the experience and judgment of the radiological technologist performing the study to be systematized. As a result, the Scan Plan Simulator stabilizes image SD values by minimizing the effects of patient's body size. It has been demonstrated that the Scan Plan Simulator is particularly useful when the same protocols are used for all patients, as at general screening centers. It has also been confirmed that the Scan Plan Simulator not only stabilizes image SD values but also permits the overall patient's exposure dose to be reduced by optimizing the tube current. In the present study, the usefulness of the Scan Plan Simulator was evaluated using

Monte Carlo simulation. In future studies, the usefulness of the Scan Plan Simulator will be evaluated in actual patient studies.

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図表の説明

- Fig. 1 スキャンプランシミュレータの画面
患者体形，スキャンプロトコル，画像SD，患者被ばくの組み合わせをシミュレートすることができる。
- Fig. 2 スキャンプランシミュレータが使用する4種類のテーブル
患者体形とスキャンプロトコルから，予想される画像SDを推定するためのテーブルである。
- Fig. 3 頭部から骨盤までの体厚の測定方法
体厚は，位置決め撮影時のスキヤノグラム像から計測することもできる。
- Fig. 4 直径の異なる6種類の線量測定用ファントムと線量計
体形による被ばく線量の違いをシミュレートするために，6種類のファントムを使用した。
- Fig. 5 体形による被ばく線量の違い
被写体の直径が小さいほど，被ばく線量は多い。
- Fig. 6 画像SD，CTDIvolの実測データ群とSPSimデータ群の相関関係
画像SD，CTDIvolともに，実測データ群とSPSimデータ群は高い相関を示した。
- Fig. 7 画像SD，CTDIvolの実測データ群とSPSimデータ群の分布の箱ひげ図
画像SD，CTDIvolともに，実測データ群とSPSimデータ群の間には有意差が認められなかった。
- Fig. 8 検診によって得られた体厚分布
検定の結果，正規分布を仮定しても問題ないことが示された。
- Fig. 9 管電流のモンテカルロ・シミュレーション結果
SPSim(+)群では，管電流が幅広い範囲に分布している。
- Fig. 10 画像SDのモンテカルロ・シミュレーション結果
SPSim(+)群では，画像SDが指定した値の近傍に集まっている。
- Fig. 11 CTDIvolのモンテカルロ・シミュレーション結果
SPSim(+)群では，CTDIvolの平均値がSPSim(-)群よりも低い。
- Fig. 12 SPSim(-)群とSPSim(+)群の画像SD，CTDIvolの比較
スキャンプランシミュレータは，体形の影響を抑えて画像SDを安定させるだけでなく，被ばくの低減にも効果があることが示唆される。