Profile of CT scan output dose in axial and helical modes using convolution

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Abstract. The profile of the CT scan output dose is crucial for establishing the patient dose profile. The purpose of this study is to investigate the profile of the CT scan output dose in both axial and helical modes using convolution. A single scan output dose profile (SSDP) in the center of a head phantom was measured using a solid-state detector. The multiple scan output dose profile (MSDP) in the axial mode was calculated using convolution between SSDP and delta function, whereas for the helical mode MSDP was calculated using convolution between SSDP and the rectangular function. MSDPs were calculated for a number of scans (5, 10, 15, 20 and 25). The multiple scan average dose (MSAD) for differing numbers of scans was compared to the value of CT dose index (CTDI). Finally, the edge values of the MSDP for every scan number were compared to the corresponding MSAD values. MSDPs were successfully generated by using convolution between a SSDP and the appropriate function. We found that CTDI only accurately estimates MSAD when the number of scans was more than 10. We also found that the edge values of the profiles were 42\% to 93\% lower than that of the corresponding MSADs.

1. Introduction

The first descriptor for estimating CT dose was a multiple scan average dose (MSAD) \cite{1}. MSAD was the average of multiple scan dose profiles (MSDP). The main drawback of measuring MSDP using thermoluminescent dosimeters (TLDs) is that it requires a very long time. The CTDI concept introduced by Shope et al. \cite{2} was a clever way to estimate the MSAD at the center of a series of axial scans. The CTDI consists of measuring the integral of the single-scan dose profile (SSDP) for a single axial scan in the standard cylindrical phantom by using a 100 mm long cylindrical ion chamber \cite{3}. This method has been used as the standard descriptor to characterize the output dose of CT. Because CTDI was measured only for the standard phantom, it was considered as the output dose of CT, not as dose to the patient \cite{3}. The patient dose was calculated as the product of output dose (CTDI) and conversion factor ($f$) based on the size and composition of the patient \cite{4}.

As an output dose descriptor, CTDI has limitations. First, the value of CTDI approximates the MSAD value only when a considerable number of scans is taken \cite{1,2}, otherwise the CTDI value is higher than the MSAD value. Second, CTDI estimates the output dose only for the center of the
scanning area. CTDI neglects the profile output dose along the scanning axis. Obtaining the MSDP and MSAD in a more convenient way is challenging. Boone et al. [5] had proposed using convolution to get the MSDP from the SSDP using Monte Carlo simulation. Dixon [6] derived a theoretical expression to give a simpler and more complete treatment for axial and helical modes, and obtained the SSDP curve from TLD measurements.

Nowadays, a dosimeter for measuring SSDP is available [7]. The purpose of this study is to implement the Dixon formula to compute MSDP from SSDP measured by such a dosimeter, and to investigate MSDP and MSAD both for axial and helical modes.

2. Methods

2.1. The single-scan output dose profile (SSDP)
SSDP was measured using a solid-state detector (RTI Electronics, Sweden). The probe is shaped like a CT pencil ionization chamber and fits in the CTDI phantom in the same holes used for the CT pencil ionization chamber. The probe consists of a thin-walled aluminum tube filled with plastic and containing a sub-millimeter thick solid-state detector. The solid-state detector is then coupled to a high sampling-rate electrometer, which records the dose measured in very small time intervals. Instead of making measurements by using the axial mode in one tube rotation, the probe and phantom are passed through the x-ray beam in the spiral scan mode [7].

SSDP was measured in the multi-detector CT (MDCT) Siemens Sensation 64 with the following scanning parameters: tube voltage 120 kVp, tube current 370 mA, tube rotation time 1 s, collimation 1.0 cm, and pitch 1. The SSDP was measured in the head CTDI phantom (16 cm in diameter and 15 cm in length), and the solid-state detector was placed in the center hole of the phantom.

2.2. The multiple scans output dose profile
The multiple-scans output dose profile (MSDP) was calculated for both axial and helical modes. For the axial mode it was calculated using equation (1). \( f(z) \) is the SSDP and \( \delta(z - nd) \) is the delta function (see figure 1). The distance between adjacent scans is 1 cm.

\[
D(z) = \sum_{n=1}^{J} f(z - nd) = f(z) \otimes \sum_{n=1}^{J} \delta(z - nd) \tag{1}
\]

![Figure 1. SSDP (left) and delta function shows the position of the scan (right).](image)

The MSDP for the helical mode was calculated using equation (2). \( f(z) \) is SSDP and \( \Pi(z/L) \) is the rectangular function (figure 2).

\[
D(z) = \frac{1}{vt} \int_{-L/2}^{L/2} f(z - y)dy = \frac{1}{vt} f(z) \otimes \Pi(z/L) \tag{1}
\]

where \( v \) is the velocity of the patient or phantom along the longitudinal axis and \( t \) is the time for one rotation. The value of pitch is 1.0.
The MSDPs for axial and helical modes were calculated for various numbers of scans: 5, 10, 15, 20 and 25. In this study, we calculated CTDI, MSAD and the edge dose of MSDP.

![Figure 2. MSDP (left) and rectangular function (right).](image)

### 3. Results

**3.1. Single-scan output dose profile (SSDP)**

The measured SSDP for a beam width of 1.0 cm is shown in figure 3. It shows that the tails in the output dose profile are very symmetrical. The curve demonstrates that there are areas in which the dose is lower than the surrounding areas (as indicated by arrows). This phenomenon is the result of the neck support that affected the dose profiles. If the radiation beam comes from the upper of phantom, the beam strikes the phantom directly and it leads to a higher dose in the center of phantom. On the other hand, if the beam comes from below the phantom, it strikes the neck support before the phantom and the dose in the center of phantom is lower.

![Figure 3. The SSDP from measurement.](image)

**3.2. Multiple-scans output dose profiles (MSDP)**

The MSDPs for various numbers of scans (1, 5, 10, 15, 20 and 25) are shown in figure 4. The axial mode is indicated by the solid line and the helical mode by the dotted line. The curves demonstrate that increasing numbers of scans leads to the increases at the top of the MSDP. These increases are due to the contribution of the many scattered radiation tails. The MSDP curves in helical mode are flat, whereas in the axial mode they are wavy or non-flat. The flatness of the MSDP curves in helical modes is due to continuous scanning, whereas in the axial mode discontinuous scanning results in a non-flat MSDP.

The MSAD is calculated as the average of the top of MSDP curve. The MSAD values for different numbers of scans are indicated in figure 5. It shows that for scan numbers lower than 10, the value of MSAD for the helical mode is higher than for the axial mode. This is because to acquire a certain number of helical scans requires more length of tissue (For example for 5 helical scans, a 6 cm length...
of tissue is scanned). For scan numbers more than 10, the MSAD value for helical and axial modes is equal. For this number of scans, the MSAD value is equal to the CTDI value.

Figure 4. MSDP for helical (solid line) and axial (dotted line) modes.

Figure 5. MSAD vs. number of scans for helical and axial modes.

Table 1. Edge dose of MSDP vs. Scan number

| Scan number | Edge dose of MSDP (%) |
|-------------|----------------------|
|             | Axial | Helical |
| 1           | 64.5  | 93.3    |
| 5           | 49.6  | 72.8    |
| 10          | 56.7  | 65.7    |
| 15          | 42.5  | 65.7    |
| 20          | 42.2  | 65.7    |
| 25          | 42.6  | 65.7    |
Figure 4 shows that the shape of the edge profiles is sigmoidal. Hence, the dose values at the edge are lower than the corresponding MSAD values. The dose values at the edge of the profiles (at the position of beam width and number scan product, e.g. for 10 scans, in the positions $z = -5\, \text{cm}$ and $z = 5\, \text{cm}$) compared to the corresponding MSAD values are listed in table 1. It is clear that the values of dose at the edge profiles are lower than corresponding MSAD values. Therefore, for establishing the patient dose profile the MSDP is important, instead of only using CTDI or MSAD.

4. Discussion

Using a solid-state moving detector and convolution, it is very easy and efficient to obtain the MSDP. By using the MSDP curve, it is also easy to calculate the MSAD. This means that obtaining the MSAD value is as easy as and as fast as obtaining the CTDI value. It has been demonstrated by this study that the MSAD has an advantage over the CTDI, because the MSAD predicts the output dose independently of the number of scans, whereas the CTDI is only valid for a considerable number of scans. Therefore, the use of MSAD as an output dose descriptor should be considered.

Using the output dose profile, the fluctuation of output dose along the scanning axis can be observed. In contrast, using CTDI predict the output dose only for the center of profile. The profile of the CT scan output dose is very important for establishing the patient dose profile, which in turn is very important for estimating the dose for an organ occupying a specific position on the scanning axis.

There were several limitations in this study. First, the SSDP scan is only performed on a standard head phantom. Scattering on a standard body phantom provides a different SSDP than on a head phantom. Therefore, further studies on the body phantom need to be done. Second, the beam width is only 1.0 cm. Currently, the multi-detector CT has a very wide beam width, more than 10.0 cm, so that it will be necessary in the future to evaluate a wider beam width. Third, this study uses a CT scanner from one particular manufacturer. The SSDP of each CT scanner is unique. However, this study has shown that the available methods provide a simple and effective way to obtain the SSDP, MSDP, and MSAD.

5. Conclusions

MSDP is very easily calculated from the convolution of the SSDP and the appropriate function. MSAD predicts the output dose independently of the number of scans, whereas CTDI is only valid for predicting the output dose when a considerable number of scans are taken.

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