Cone-beam computed tomography (CBCT) has been widely used in dental clinics for over ten years. While the benefits of CBCT examination have been reported widely, the radiation dose to the patient is also becoming a major concern. In 2010, an article entitled “Radiation worries for children in dentist’s chair” was published in The New York Times newspaper. It was the first time a major newspaper brought the radiation dosage of CBCT to the attention of the public.

Then, one may ask: What radiation dose is received by a patient who undergoes a CBCT examination? How high is the radiation dose compared with those obtained with conventional dental radiography and a helical CT examination? Are there methods for reducing the radiation dose without affecting the image quality? Answering these questions requires information on how a radiation dose is measured. Thus, this report includes the following three components: 1) measurement of radiation dosage; 2) comparison of patient radiation dose among CBCT, helical CT, and conventional dental radiography; and 3) patient protection from CBCT radiation.

Measurement of radiation dose

There are three basic concepts associated with the radiation dose: the absorbed dose, equivalent dose, and effective dose. The absorbed dose is used to describe the amount of X-ray energy absorbed by a unit mass (total weight) of tissue. The SI unit is the Gray (Gy). The equivalent dose is used to compare the biologic effect of different types of radiation on tissue or an organ. The SI unit is Sievert (Sv). For a diagnostic X-ray examination, the absorbed dose is equal to the equivalent dose, that is, 1 Gray equals 1 Sievert. For the estimation of radiation risk, which is the possibility of biological consequences after radiation exposure to human beings, the concept of effective dose is used. The effective dose is a measurement of the degree of harmful effects on the human body of one kind of radiation. The SI unit for the effective dose is the Sievert, but in practice, milli- or micro-Sievert is often used.

To determine the effective dose, a direct method is the use of an anthropomorphic phantom (Fig. 1). The phantom
can be made with a real human skull covered with soft tissue-equivalent materials or only made with bone- and soft tissue-equivalent materials. The phantom usually comprises nine sections and in each section there are holes in the places where the tissues are being measured. Thermoluminescent dosimeters (TLDs), optically stimulated luminescent dosimeters (OSLs), or radiophotoluminescence glass dosimeters can be positioned in the holes for the measurement of the absorbed dose of the corresponding tissue. The tissues measured can include the bone marrow, thyroid gland, esophagus, salivary glands, skin, bone surface, brain, pituitary, and eyes, and in most studies, TLDs are used for the measurement of the radiation dose (Fig. 2).

It is worth noticing that at this stage only the absorbed dose is measured. In order to determine the effective dose, which is used to estimate the risk in human beings, the absorbed dose for individual organs must be translated to an equivalent dose and then multiplied with a weighting factor defined by the International Commission on Radiological Protection (ICRP) for the specific organ. Later, the effective doses of these organs are summed up to obtain a total effective dose. The total dose is used to represent the potential risk of the whole body exposed to radiation. The effective dose is a calculated value rather than a directly measured value.

Comparison of patient radiation dose among CBCT, helical CT, and conventional dental radiography

We have thus shown that the effective dose is a representation of the potential risk of radiation dose to the patient, and in most studies, the effective dose is derived from absorbed dose, which is measured with TLDs by the use of an anthropomorphic phantom. Thus, in the following discussion, only the reported effective dose derived from a phantom is addressed.

Effective doses obtained with different CBCT units

Many studies have been performed to estimate the effective doses of different CBCT units. However, a simple comparison cannot be made since, as one researcher has noted, "significant differences in dose for the same examination have been reported for different CBCT units, and significant differences in dose have been reported for different examinations or techniques with the same unit" and another has observed that "the results are often difficult to compare when a number of different phantoms and dosimeters have been used together with different assumptions." To avoid these research limitations, Ludlow et al5 and Pauwels et al14 investigated the effective dose of 8 and 14 CBCT units, respectively, by using the same phantom and TLD dosimeters. The results from the two studies are summarized in Table 1.
Although the phantoms and dosimeters employed in the two studies were different, from Table 1 we can still see that the effective dose is quite different from one CBCT unit to another, irrespective of the size of the field of view (FOV) used. The highest effective dose is 1073 $\mu$Sv for CB MercuRay with a large FOV scanning for maxillofacial region, while the lowest effective dose is only 19 $\mu$Sv for the Kodak 9000 3D with a scanning area of the front region of the upper jaw. This is a difference of almost 500 times between the highest and lowest effective doses.

When we look further into the data in Table 1, we can see that the effective dose is closely related to the protocol used for scanning. Since a protocol is a combination of kVp, mAs, and voxel sizes and other factors, the effective dose is in reality closely related to the chosen exposure parameters. In the study performed by Ludlow et al, the effective dose for maximum quality CB MercuRay (1073 $\mu$Sv) is almost twice that of standard quality CB MercuRay (569 $\mu$Sv), the effective dose for CBCT unit Galileos obtained at the default exposure (70 $\mu$Sv) is almost half of that obtained at maximum exposure (128 $\mu$Sv), and the effective dose for standard and high resolution images from the PreXion 3D were 189 $\mu$Sv and 388 $\mu$Sv, respectively. The later data also indicate that with an increase in the spatial resolution, the effective dose is increased as well. This is also confirmed by the study conducted by Davies et al.16

Field of view (FOV) is another factor that plays an important role in the assessment of the effective dose of one CBCT examination. When the exposure parameters such as the kVp and mAs are maintained at the same level, the larger the FOV used, the higher the effective dose obtained. This is substantiated by the effective doses for CB MercuRay in Table 1, where the effective dose is 1073 $\mu$Sv for a large FOV with maximum quality, 560 $\mu$Sv for a medium FOV, and 407 $\mu$Sv for a small FOV. The exposure parameters for all of the three FOV examinations were kept at 120 kVp and 150 mAs. A study by Qu et al further discloses the positive relationship between the FOV and effective dose. In this study, 12 protocols that combined different patient size, FOV, kVp, mA, and exposure times were employed for the estimation of effective doses of the ProMax 3D CBCT unit. While holding all of the other exposure parameters constant, the researchers found that for a scanning area of full volume height with a full volume diameter (8 cm × 8 cm), the effective dose (298 $\mu$Sv) is much higher than the effective doses obtained from used other scanning FOVs, specifically, half the volume height (upper jaw) with a full volume diameter (4 cm × 8 cm, 131 $\mu$Sv), half the volume height (lower jaw) with a full volume diameter (4 cm × 8 cm, 171 $\mu$Sv), a full volume height with half the volume diameter (anterior region, 8 cm × 4 cm, 127 $\mu$Sv), and a full volume height with half the volume diameter (posterior region, 8 cm × 4 cm × 6 cm, 43 $\mu$Sv).

| Table 1. Effective doses from different CBCT units |
|-----------------------------------------------|
| Maxillofacial region (large FOV) | Dentoalveolar region (medium FOV) | Localised region (small FOV) |
| CBCT units | Effective dose ($\mu$Sv) | CBCT units | Effective dose ($\mu$Sv) | CBCT units | Effective dose ($\mu$Sv) |
| NewTom 3G | 68 | CB MercuRay panoramic FOV | 560 | CB MercuRay I FOV maxilla | 407 |
| CB MercuRay maximum quality | 1073 | Classic i-CAT Standard scan | 69 | Promax 3D small adult | 488 |
| CB MercuRay standard quality | 569 | Next Generation i-CAT landscape mode | 87 | Promax 3D large adult | 652 |
| Next Generation i-CAT portrait mode | 74 | Galileos default exposure | 70 | PreXion 3D standard exposure | 189 |
| Illuma standard | 98 | Galileos maximum exposure | 128 | PreXion 3D high resolution | 388 |
| Illuma ultra | 498 | | | | |
| Galileos Comfort | 84 | 3D Accuitomo 170 | 54 | 3D Accuitomo 170 (lower jaw, molar region) | 43 |
| i-GAT Next Generation | 83 | i-GAT Next Generation | 45 | Kodak 9000 3D (upper jaw, front region) | 19 |
| Illuma Elite | 368 | Vetraviewpcs 3D | 73 | Kodak 9000 3D (lower jaw, front region) | 40 |
| Kodak 9500 | 136 | Kodak 9500 | 92 | Pax-Uni 3D (upper jaw, front region) | 44 |
| NewTom VG | 194 | NewTom VG | 265 | | |
| NewTom VG | 83 | Picasso Trio (high dose) | 123 | | |
| Scanora 3D | 68 | Picasso Trio (low dose) | 81 | | |
| SkyView | 87 | ProMax 3D (high dose) | 122 | | |
| | | ProMax 3D (low dose) | 28 | | |
| | | Scanora 3D (upper jaw) | 46 | | |
| | | Scanora 3D (lower jaw) | 47 | | |
| | | Scanora 3D (both jaws) | 45 | | |
| | | | | | |

aData from the study by Ludlow et al (2008), bData from the study by Pauwels et al (2012)
The above demonstrates that the effective dose is different from one CBCT unit to another and closely related to the exposure parameters used for scanning; for a given model of a CBCT unit, the larger the FOV used for scanning, the higher the effective dose derived when all the other exposure parameters are kept at the same level. Similarly, the higher the spatial resolution chosen for scanning, the higher the effective dose is.

Effective dose of CBCT and conventional dental radiography

There are few studies focusing on the direct comparison of the effective doses obtained from CBCT and conventional dental radiography. The results from the direct comparison studies were summarized in Table 2, where the effective dose for panoramic radiography is about 22.0 μSv, for lateral cephalometric examination about 4.5 μSv and for CBCT examination the effective dose is 61-134 μSv. No study has performed a direct comparison of the effective dose from intraoral and CBCT examinations. In the guidelines\textsuperscript{19} provided by the European Academy of Dento-Maxillofacial Radiology, the suggested effective dose of one intraoral radiograph is 1.5 μSv. Other studies\textsuperscript{20-26} that exclusively estimated the effective dose of conventional dental radiography have demonstrated that the range of the effective dose for a panoramic radiograph is 3.85-38.0 μSv.

Table 2. Comparison of effective dose (μSv) of CBCT, panoramic and lateral cephalometric (ceph.) radiography

| Authors          | Panoramic<br>radiography | Lateral ceph. | Panoramic<br>+lateral ceph. | CBCT          |
|------------------|--------------------------|---------------|-----------------------------|---------------|
|                  | OP-100                   | Orthophos     | Orthophos                   | i-CAT 0.3 voxel<br>landscape | i-CAT 0.2 voxel<br>landscape | NewTom 9000 | i-CAT |
| Grünheid et al\textsuperscript{17} | 21.5                     | 4.5           | 65                          | 134.2         | 77.9                       |
| Ludlow et al\textsuperscript{13}   | 22                       |               |                             |               | 56.2                       | 61.1       |
| Silva et al\textsuperscript{18}     | 10.4                     |               |                             |               |                            |

\textsuperscript{1}: ICRP60 1990, \textsuperscript{2}: ICRP103 2007, CCD: charge-coupled device, SPP: storage phosphor plate

Table 3. Effective doses from panoramic radiography

| Authors          | Panoramic machine       | Exposure parameters | Effective dose (μSv) |
|------------------|-------------------------|---------------------|---------------------|
| Danforth et al\textsuperscript{20} | Planmeca PM 2002       | 60 kVp, 4 mA, 18 s  | 3.85\textsuperscript{*} |
| Gijbels et al\textsuperscript{21}    | Cranex tone, SPP       | 70 kVp, 4 mA, 15 s  | 8.1\textsuperscript{*}  |
|                   | Cranex Excel, CCD      | 65 kVp, 6 mA, 19 s  | 12.3\textsuperscript{*} |
|                   | Veraviewepocs SD, CCD  | 70 kVp, 4 mA, 8.2 s | 5.5\textsuperscript{*}  |
|                   | EC Proline, CCD        | 64 kVp, 7 mA, 18.3 s| 14.9\textsuperscript{*} |
|                   | Orthoralix 9200 DDE, CCD | 74 kVp, 4 mA, 12 s | 4.7\textsuperscript{*}  |
| Ludlow et al\textsuperscript{1}     | Sirona Orthophos Plus DS, CCD | 66 kVp, 16 mA, 14.1 s | 22\textsuperscript{*} |
| Gavala et al\textsuperscript{22}    | Planmeca Promax, film  | 66 kVp, 6 mA, 16 s  | 26\textsuperscript{*}   |
|                   | Planmeca PM 2002, CCD  | 66 kVp, 8 mA, 18 s  | 38\textsuperscript{*}   |
|                   | Planmeca PM 2002, CCD  | 60 kVp, 4 mA, 18 s  | 12\textsuperscript{*}   |
| Ludlow et al\textsuperscript{23}    | Orthophos XG, CCD      | 64 kV, 8 mA, 14.1 s | 14.2\textsuperscript{*b} |
|                   | ProMax, CCD            | 68 kV, 13 mA, 16 s  | 24.3\textsuperscript{*b} |

\textsuperscript{a}: ICRP60 1990, \textsuperscript{b}: ICRP103 2007, CCD: charge-coupled device, SPP: storage phosphor plate

Table 4. Effective doses from lateral cephalometric radiography

| Authors          | Instrument           | Exposure parameters | Effective doses (μSv) |
|------------------|----------------------|---------------------|----------------------|
| Visser et al\textsuperscript{24} | Siemens Orthophos C, film | 77 kV, 14 mA, 0.5 s | 2.3\textsuperscript{a} |
|                  | Siemens Orthophos DS Ceph, CCD | 77 kV, 14 mA, 0.5 s | 2.3\textsuperscript{a} |
| Gijbels et al\textsuperscript{25} | Cranex Tome, SPP    | 70 kV, 4 mAs        | 2.2\textsuperscript{a} |
|                  | Proline Ceph CM, CCD | 70 kV, 10 mA, 23 s  | 3.4\textsuperscript{a} |
| Ludlow et al\textsuperscript{23}  | unknown              | 77 kVp, 6.5 mAs     | 5.6\textsuperscript{a} |

\textsuperscript{a}: ICRP60 1990, \textsuperscript{b}: ICRP103 2007, CCD: charge-coupled device, SPP: storage phosphor plate

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μSv (Table 3), for a lateral cephalometric examination is 1.1-5.6 μSv (Table 4), for posteroanterior cephalometric radiograph, 5.1 μSv, and for one introal examination, 0.65-9.5 μSv (Table 5).

These data indicate that the effective dose of CBCT is several to hundreds of times higher than the effective dose from a conventional dental radiographic examination.

Effective dose of CBCT and helical CT

More attention is paid to the effective dose of CBCT and multislice CT (MSCT) since both techniques provide three dimensional images. The effective doses from the literature on CBCT and MSCT are shown in Table 6. Generally, the effective dose of MSCT is much higher than that of CBCT. However, in some of the studies, the scanning area, i.e. the FOV was not well defined. To avoid the effect of the FOV on the assessment of effective dose, Qu et al\textsuperscript{13} strictly defined the scanning area for both MSCT and CBCT examinations in their study. The results showed that the effective doses of MSCTs are about several to ten times higher than those of CBCTs. For example, when scanning both the maxilla and mandible, the effective dose is about 94.9 μSv for CBCT NewTom 9000, 249.1 μSv for CBCT DCT-Pro, and 1066.1 μSv for GE 8-slice MSCT. Similar results were also observerd in other studies, as shown in Table 6.

However, it should be borne in mind that although the effective dose of MSCT is much higher than that of CBCT, the image qualities for the two techniques are quite different. For hard tissue, such as bone and tooth, the image quality of CBCT is equal to or better than the image quality of MSCT, but for soft tissues, the image from CBCT is not satisfactory due to the inherent drawbacks of the technique.

Patient radiation protection from CBCT

To perform one medical X-ray examination, three main factors must be taken into account: the X-ray unit, patient for examination, and receptor used for capturing the image.

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Table 5. Effective doses from intra-oral examinations

| Authors         | Exposure parameters                                      | Total (average) effective dose (μSv) |
|-----------------|---------------------------------------------------------|-------------------------------------|
| Gibbs\textsuperscript{26} | 70 kVp, short cone bisecting angle, round collimation, 18 E-speed films | 100 (5.6)\textsuperscript{a}       |
|                 | 70 kVp, long cone parallel, round collimation, 21 E-speed films | 74 (3.5)\textsuperscript{a}        |
|                 | 70 kVp, long cone parallel, rectangular collimation, 21 E-speed films | 14 (0.67)\textsuperscript{a}      |
|                 | 70 kVp, short cone bisecting angle, round collimation, 4 E-speed bitewings | 14 (3.5)\textsuperscript{a}       |
|                 | 70 kVp, long cone parallel, round collimation, 4 E-speed bitewings | 12 (3)\textsuperscript{a}         |
|                 | 70 kVp, long cone parallel, rectangular collimation, 4 E-speed bitewings | 2.6 (0.65)\textsuperscript{a}     |
| Ludlow et al\textsuperscript{23} | 70 kVp, 8 mA, round collimation, 18 D-speed films | 388 (21.6)\textsuperscript{b}   |
|                 | 70 kVp, 8 mA, round collimation, 18 SPP or F-speed films | 170.7 (9.5)\textsuperscript{b}   |
|                 | 70 kVp, 8 mA, rectangular collimation, 18 SPP or F-speed films | 34.9 (1.9)\textsuperscript{b}   |
|                 | 70 kVp, 8 mA, rectangular collimation, 4 SPP or F-speed bitewings | 5.0 (1.25)\textsuperscript{b} |

\textsuperscript{a}: ICRP60 1990, \textsuperscript{b}: ICRP103 2007, SPP: storage phosphor plate

Table 6. Effective dose (μSv) of CBCT and MSCT from literatures

| Authors         | CBCT exposure parameters                          | MSCT exposure parameters                                                                 |
|-----------------|--------------------------------------------------|------------------------------------------------------------------------------------------|
| Ludlow et al\textsuperscript{3} | CB mercuray pan. Mode 264 i-CAT 77 3D Accuitomo CCD | Somatom VolumeZoom 453 GE 4-slice 1110 GE 4-slice (both jaws) 1066.1 Somatom Sensation 429.7 |
| Loubele et al\textsuperscript{12} | Next generation i-CAT landscape mode 36 NewTom 3G 3D Accuitomo FSP | Somatom Sensation 16-slice 995 GE 16-slice 1410 GE 8-slice (upper jaws) 506.7 |
| Suomalainen et al\textsuperscript{9} | Classic i-CAT standard 29 ProMax 3D 674 NewTom 9000 (lower jaw) 86.7 | M x 8000 IDT 1160 GE 8-slice (lower jaws) 829.9 |
| Qu et al\textsuperscript{27} | Galileos default 28 Scanora 3D 91 DCT Pro (both jaws) 249.1 |                                |
| Silva et al\textsuperscript{18} | Galileos maximum 52 DCT Pro (upper jaws) 125.8 |                                |

MSCT: multi-slice CT

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of the patient. Therefore, when an X-ray examination is indicated for a patient, the patient dose can be reduced by the reduction of the X-ray intensity emitted from the employed x-ray unit, increasing of the imaging receptor capturing speed and collimation, or shielding of the x-ray beam to the patient. This section will only focus on the shielding devices for the reduction of the radiation dose.

The shielding devices include a leaded thyroid collar for the protection of the thyroid gland, leaded glasses for the protection of the eye lens, a leaded hat for the protection of the brain, and a leaded apron for the protection of the body trunk. It is well known that a thyroid collar is effective for the protection of the thyroid gland in an intraoral examination. However, for a CBCT examination, is it still effective when the X-ray unit rotates around the patient?

With this question in mind, two studies were conducted. One study was mainly aimed to identify the effectiveness of a thyroid collar on the dose reduction of the thyroid gland. In this study, five conditions were tested as follows: 1) without a collar around the neck; 2) with one collar loosely on the front of the neck; 3) with two collars loosely on the front and back of the neck; 4) with one collar tightly on the front of the neck; and 5) with two collars tightly on the front and back of the neck. The results showed that when the thyroid collars were used loosely around the neck, no effective organ dose reduction was observed. When one thyroid collar was used tightly on the front of the neck, the effective organ dose to the thyroid gland and esophagus were reduced to 15.9 μSv (48.7% reduction) and 1.4 μSv (41.7% reduction), respectively. A similar organ dose reduction (46.5% and 41.7%) was achieved when CBCT scanning was performed with two collars tightly affixed to the front and back of the neck. The study supported the use of a thyroid collar during a CBCT scan. In a subsequent study, different oral and maxillofacial regions were scanned with the phantom tightly wearing one or two thyroid collars. The results also supported the use of thyroid collars (61% thyroid dose reduction for a large view examination, 72% thyroid dose reduction for a medium FOV, and 70% thyroid dose reduction for a small FOV) and further disclosed that the total effective dose for medium and small FOV examinations were also significantly reduced by the use of a thyroid collar.

The use of leaded glasses during a CBCT examination was also investigated. In the study performed by Prins et al, three phantoms representing an adult male, an adult female, and a child were employed. The results showed that the radiation dose to the eye lens could be reduced by over 60% without having a deleterious effect on the image quality in the area of clinical significance for dental imaging.

Considering the above, one conclusion that could be drawn was that a thyroid collar and leaded glasses should be used during a CBCT examination, given that diagnostic information and image quality are not reduced.

**Summary**

The effective dose of CBCT, conventional dental radiography, and multislice CT and the effect of a thyroid collar and leaded glasses on the dose reduction was presented in this paper. Based on the above analysis, we can conclude the following:

1. The patient radiation dose is much lower for CBCT than for helical CT;
2. The patient radiation dose is closely related to the FOV and exposure parameters used for a CBCT examination. Without alteration of any other exposure parameters, the larger the FOV used for scanning, the higher the radiation dose is;
3. Compared with conventional dental radiography, the effective dose of CBCT is several to hundreds of times higher;
4. To reduce the patient dose to the greatest possible extent, the chosen CBCT scanning protocol should be in accordance with the diagnostic task at hand;
5. A thyroid collar should be used for CBCT scanning; wearing leaded glasses is recommended when it does not detract from imaging quality.

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