Update on the biological effects of ionizing radiation, relative dose factors and radiation hygiene

SC White,* SM Mallya*

*Section of Oral and Maxillofacial Radiology, School of Dentistry, The University of California, Los Angeles, USA.

ABSTRACT

Diagnostic imaging is an indispensable part of contemporary medical and dental practice. Over the last few decades there has been a dramatic increase in the use of ionizing radiation for diagnostic imaging. The carcinogenic effects of high-dose exposure are well known. Does diagnostic radiation rarely cause cancer? We don’t know but we should act as if it does. Accordingly, dentists should select patients wisely – only make radiographs when there is patient-specific reason to believe there is a reasonable expectation the radiograph will offer unique information influencing diagnosis or treatment. Low-dose examinations should be made: intraoral imaging – use fast film or digital sensors, thyroid collars, rectangular collimation; panoramic and lateral cephalometric imaging – use digital systems or rare-earth film screen combinations; and cone beam computed tomography – use low-dose machines, restrict field size to region of interest, reduce mA and length of exposure arc as appropriate.

Keywords: Cone beam computed tomography, neoplasms, radiation-induced, radiobiology, radiation protection, radiography, dental.

Abbreviations and acronyms: ALARA = As Low As Reasonably Achievable; CBCT = cone beam computed tomography; CT = computed tomography; LNT = linear non-threshold; MSCT = multislice computed tomography.

INTRODUCTION

In recent decades there have been dramatic advances in imaging technology, including both the resolution of the detectors and the reconstruction software displaying the anatomical results. As a consequence, there has been a substantial increase in the use of imaging for a wide variety of clinical conditions. This increased use has contributed to ever rising health care costs as well as a steady rise in per capita exposure, particularly from computed tomography (CT) and nuclear medicine examinations. While in 1980 per capita exposure to the US population from medical imaging was only about one-sixth that of natural background, medical exposure now equals natural background (Fig. 1). This situation is the result of both more radiation per exposure as well as more people being exposed. The collective effective dose to the US population rose from 835 000 person-Sv to 1 870 000 person-Sv over this period. Similarly, the annual effective dose per individual rose from 3.6 to 6.2 mSv. A similar trend has also been observed in Australia – the per head radiation dose from CT has increased from 0.8 mSv in 2002 to an estimated 1.2 mSv, a growth of 50%. The principal sources of non-background exposure in the US are: CT (24%); nuclear medicine (12%); interventional fluoroscopy (7%); and conventional radiography/fluoroscopy (5%). Of the 5% dose from the conventional radiography/fluoroscopy category, conventional dental imaging contributes only 2.5%. Note that this value does not include cone beam imaging which has been
rapidly gaining in popularity. While there are clear health benefits derived from these exposures, there are a number of unresolved issues including societal costs for making these exposures, optimizing the utility of these examinations in terms of potential over utilization, and unknown risks associated with exposure to ionizing radiation. This article will focus on the potential risks associated with exposure to diagnostic imaging and the means by which dentists can minimize risks to our patients.

**Radiation injury**

Radiation effects are broadly classified as deterministic or stochastic. Deterministic effects result from killing cells. A common example is the oral mucositis associated with radiation therapy to the oral cavity. Deterministic effects typically require a high dose. Further, there is a threshold dose level below which no clinical changes are seen. Conventional dental imaging never causes deterministic effects. Alternatively, stochastic effects result from damaging DNA. Examples of stochastic effects are cancer, leukaemia and, to a much lesser extent, genetic (heritable) damage. Stochastic effects can result from very low exposures and there is no evidence of a threshold dose. Dental exposures do carry the risk of causing cancers and leukaemia. It is believed that the risk of cancer induction following exposure extends over the lifetime of the exposed individual.8

**Estimating risk**

There is an extensive body of literature linking radiation to cancer formation (both solid tumours and leukaemias), both in humans and research animals. Human epidemiological studies include those exposed as survivors of the atomic bombings in Hiroshima and Nagasaki, in the course of diagnostic radiology, multiple fluoroscopies or radiation therapy, occupationally, or environmentally.8,9 Analysis of this literature has led to the development of the linear non-threshold (LNT) hypothesis (Fig. 2). This hypothesis holds that there is a linear relationship between dose and the risk of inducing a new cancer. Further, in this hypothesis there is no threshold or ‘safe dose’ below which there is no added risk. It should be recognized that the LNT is a hypothesis that has been accepted widely for setting policy in radiation safety and protection. It is not a demonstrated scientific fact.10 There is a solid body of work demonstrating increased risk of tumours in individuals exposed to more than about 100 mGy.11 However, there are relatively few studies showing a risk at lower doses, i.e. in the diagnostic range. In this low-dose range the LNT has neither been consistently verified nor falsified. One of the major difficulties in such studies is that at doses lower than 100 mGy, studies require such large sample sizes as to be impractical. Thus, the validity of the model is uncertain, and this situation is not expected to change in the near future.12

In spite of its uncertainties in the low-dose range, there are several reasons for using the LNT to estimate risk from diagnostic exposures. First, there needs to be a policy to set exposure limits for individuals exposed in the low-dose range including diagnostic radiology, workers in nuclear power plants and other industries, individuals on long airline flights, and other exposures. Second, there are several lines of evidence that support the LNT. The dose-response at doses greater than 100 mGy is linear. Further, complex damage to DNA, the basis of cancer formation, may occur with even one X-ray photon (Fig. 3).13 While there are sophisticated DNA repair mechanisms, some types of complex damage to DNA are beyond the enzymatic repair.14 And finally, much epidemiological data are consistent with, and do not exclude, a risk at very low doses.15 Accordingly, most radiation protection organizations believe that it is prudent to assume that risk is proportional to dose, even for diagnostic exposures, and that there is no safe threshold. While the LNT is the consensus opinion of most radiation safety groups around the world,4,9,16–18 there is controversy about whether there really is a risk.19 Some argue that there is no demonstrated risk below 100 mGy and on balance patients may not reap the full diagnostic benefits by avoiding diagnostic imaging due to inappropriate fear.20–23 Indeed, if the actual risk is less than predicted by the LNT, then there is a risk of harm to patients from making too few exposures. Alternatively, if the actual risk is greater than estimated by the LNT, then patients suffer more harm than what we currently estimate.
Medical exposures

Estimates of risk from diagnostic imaging can be calculated from LNT models that consider the age and gender of exposed population and the organ doses from the examinations. In the US, approximately 70 million CT examinations are made annually. Using risk models from the BEIR-VII report, age- and gender-specific dose data from NEXT surveys, and age- and gender-specific scan frequencies, one research team estimated that the CT exposures made in the US in 2007 will result in 29 000 additional solid cancers (95% probability range of 15 000 to 45 000) over the lifetime of the exposed individuals. These cancers will result primarily from scans of the abdomen, pelvis, chest and head (Table 1). Others have estimated that one additional cancer may be expected from every 47 620 full-mouth examinations made with D-speed film and round collimation or from every 17 000 CBCT examinations made with a CB Mercuray (facial FOV maximum quality). These estimated risks are lower risk than for multislice CT (MSCT) examinations (above) because of lower dose. As with medical imaging, these risk estimates are derived from the LNT.

Dental exposures

Radiosensitive structures in the head and neck include the thyroid glands, salivary glands, bone marrow (leukaemia) and brain. Dental exposures have been specifically linked to meningiomas, salivary gland tumours and thyroid tumours. Estimates have also been made of the risks from dental exposures. For instance, 1 excess cancer fatality may be expected from every 47 620 full-mouth examinations made with D-speed film and round collimation or from every 17 000 CBCT examinations made with a CB Mercuray (facial FOV maximum quality). These estimated risks are lower risk than for multislice CT (MSCT) examinations (above) because of lower dose. As with medical imaging, these risk estimates are derived from the LNT.

What should the dentist do?

It is broadly, and appropriately, assumed that the benefits of diagnostic imaging far outweigh its risks. Accordingly, it is desirable to use diagnostic imaging whenever appropriate, while simultaneously reducing all unnecessary exposure. We must act on the assumption that diagnostic imaging carries a risk. Therefore, it is incumbent upon dentists to use this tool wisely. This means that the dentist should consider carefully the justification for every exposure and the means to optimize any actual examination.

Regulatory requirements and guidelines for radiation protection in dentistry have been published by the Australian Radiation Protection and Nuclear Safety Agency.

Justification

Justification refers to determining the appropriateness of each examination. There are no limits on patient exposure as there are for those exposed occupationally or for members of the public exposed incidentally such as a secretary in an office adjacent to a radiographic operatory. This places a responsibility on the clinician to assure that each exposure is justified. Is the contemplated radiographic examination likely to add new information that will influence patient outcome? This decision is made on the findings from the patient history, clinical examination and review of any prior radiographs. These issues should be considered both generally as well as specifically for each individual patient. For example, we know that generally bitewing radiographs are useful for detecting interproximal caries that cannot be detected clinically. But specific issues pertaining to each individual should also be considered. Are the posterior contacts open? Are recent bitewing radiographs available? Do the clinical and

Table 1. Estimated median number of 40-year-old patients undergoing CT that would lead to 1 radiation-induced cancer

<table>
<thead>
<tr>
<th>Examination</th>
<th>Female</th>
<th>Male</th>
</tr>
</thead>
<tbody>
<tr>
<td>Routine head</td>
<td>8100</td>
<td>11 080</td>
</tr>
<tr>
<td>Routine chest</td>
<td>720</td>
<td>1566</td>
</tr>
<tr>
<td>Multiphase abdomen-pelvis</td>
<td>460</td>
<td>498</td>
</tr>
</tbody>
</table>

Adapted from Smith-Bindman et al.
historical findings indicate that the patient is at an increased risk of caries? The point is that the dentist must make these decisions for each patient. The anticipated individual benefits must be that the radiographic examination is likely to add new information to aid the patient’s management or outcome.\textsuperscript{37,38} A number of professional societies have published selection criteria, guidelines, to assist the dentist with this process.\textsuperscript{39–41}

When contemplating obtaining a CBCT examination for a patient there are several factors for the dentist to consider. As a general rule it is more appropriate to initially use low-dose conventional examinations such as a periapical, bitewing or panoramic views to examine a patient. Then, if on the basis of these images it is determined that cross-sectional information is needed, a CBCT, MSCT or MRI examination could be considered.

There are many clinical situations where clinical experience has shown that CBCT examinations are valuable. For instance, if a panoramic view reveals close proximity of the roots of an unerupted mandibular third molar to the mandibular canal, then CBCT imaging has the potential to provide additional information that adds value to the treatment plan and assessing the risks associated with extraction. For treatment planning of dental implant placement, cross-sectional information provided by CBCT reveals the height and width of the residual alveolar ridge. In the posterior regions of the jaws, CBCT also provides information on the location of anatomic structures influencing implant placement, such as the maxillary sinus and the mandibular canal. Alternatively, most endodontic problems are well diagnosed with a history, clinical examination and periapical radiographs. However, patients with persistent pain following endodontic therapy may benefit by detection of root fracture, untreated accessory canals, or persistent periapical disease not detected on conventional radiographs.\textsuperscript{42}

If radiographic examination of the temporomandibular joints is indicated because of signs or symptoms, then a small field of view, high-resolution examination of each TMJ provides high quality images at a low dose. When it is necessary to image the disc or other soft tissues in the region, then MRI examinations are required; and there is no associated radiation exposure. The use of CBCT in orthodontics is complex. Certainly when there are impacted cuspids or facial asymmetry or orthognathic surgery is contemplated then there is a reasonable likelihood that a CBCT examination will be diagnostically productive. Although for cases involving simple malalignment of teeth, many orthodontists find that CBCT examinations do not provide useful information beyond that already gained from clinical examination and conventional imaging.\textsuperscript{43}

However, in situations where a panoramic examination reveals an apparent cyst or tumour that will be referred to an oral surgeon for management, then ordering advanced imaging should be deferred to that individual. It is often the case that patients with these conditions will benefit from the three-dimensional information provided by CBCT or MSCT examinations. If the lesions are small and clearly benign such as a dentigerous cyst, then perhaps no further imaging is required or only a CBCT examination will suffice. However, if the lesion is expansile, potentially extends outside of bone or the nature of the lesion is not clearly identifiable, then MSCT offers multiple advantages over CBCT including measuring tissue density (in Hounsfield units), added information from the use of contrast agents, a soft-tissue window and reduced noise and beam hardening artefacts. In such cases MRI is often of great value in supplementing MSCT imaging because of the detail with which the soft tissues may be examined. Consideration of these issues will help to minimize unproductive patient exposures and maximize patient benefits.

**Optimization**

Once the dentist has determined that a radiographic examination is likely to add clinically useful information, then he or she should make every effort to use the least amount of radiation necessary to address the issue. This concept is known as the principle of ALARA – each exposure should be As Low As Reasonably Achievable.\textsuperscript{36} The goals here are first to use the examination with the lowest dose that will accomplish the diagnostic task (Table 2) and second to use the techniques that will reduce patient exposure from the selected examination. Note that the data in Table 2 represent only dose data. There are other considerations in purchasing a CBCT machine such as flexibility in making images at different fields of view, maximum and minimum fields of view, and diagnostic image quality. There are multiple steps each dental office can readily use to reduce exposure to both the patient and operator (Table 3).

**Children**

Thyroid collars should be used during intraoral radiography for all individuals under 20 due to the relatively high radiosensitivity of the thyroid gland in this age group compared to adults.\textsuperscript{27,44} Protective lap aprons should be used where required by local statute. Their use has been justified by concern for genetic damage. It is now known that the risks from genetic damage are far less than from carcinogenesis in directly exposed tissues. Accordingly, if the rest of the following recommendations are followed, and if allowed by local
regulations, then use of leaded lap aprons is of little value and may be considered optional.\textsuperscript{35,45}

\textbf{Intraoral imaging}

When making periapical or bitewing radiographs, dentists should use F-speed film or digital imaging as these modalities will result in significantly less patient exposure than D-speed film. When using digital imaging dentists should guard against making excessive numbers of radiographs as this will reduce the intrinsic dose advantage of this technology.\textsuperscript{46} Importantly, in digital radiography the density of an overexposed image can be adjusted after the exposure. To gain the benefits of decreased exposure that digital imaging offers, operators should optimize exposure factors to use the minimal exposure time required to produce diagnostic quality images. Thus, it is important that dentists optimize the exposure times for their particular receptors. Rectangular collimation should be used with intraoral film or digital imaging as this will reduce patient exposure by at least half (Fig. 4).\textsuperscript{31}

\begin{table}[h]
\caption{Effective dose from selected dental examinations}
\begin{tabular}{|l|l|}
\hline
Examination & Effective dose (microSv) \\
\hline
Cephalometric\textsuperscript{31} & 6 \\
Panoramic\textsuperscript{31} & 24 \\
FMX – PSP or F-speed film-rectangular collimation\textsuperscript{31} & 35 \\
FMX – D-speed film – round collimation\textsuperscript{31} & 388 \\
CBCT – large field of view & \\
Galileos Comfort\textsuperscript{47} & 84 \\
i-CAT NG\textsuperscript{47} & 83 \\
Iluma Elite\textsuperscript{47} & 368 \\
Kodak 9500\textsuperscript{47} & 136 \\
NewTom VG\textsuperscript{47} & 83 \\
NewTom VGt\textsuperscript{47} & 194 \\
Scanora 3D\textsuperscript{47} & 68 \\
SkyView\textsuperscript{42} & 87 \\
CBCT – medium field of view & \\
3D Accuitomo 170/upper jaw\textsuperscript{47} & 54 \\
i-CAT NG\textsuperscript{47} & 45 \\
Kodak 9500\textsuperscript{47} & 92 \\
NewTom VG\textsuperscript{47} & 265 \\
Picasso Trio/high dose\textsuperscript{47} & 123 \\
Picasso Trio/low dose\textsuperscript{47} & 81 \\
ProMax 3D/high dose\textsuperscript{47} & 122 \\
ProMax 3D/low dose\textsuperscript{47} & 28 \\
Scanora 3D/upper jaw\textsuperscript{47} & 46 \\
Scanora 3D/lower jaw\textsuperscript{47} & 47 \\
Scanora 3D/both jaws\textsuperscript{47} & 45 \\
Veraviewepocs 3D\textsuperscript{47} & 73 \\
CBCT – small field of view & \\
3D Accuitomo 170/lower jaw, molars\textsuperscript{47} & 43 \\
Kodak 9000 #D/lower jaw, front\textsuperscript{47} & 19 \\
Kodak 9000 #D/lower jaw, molars\textsuperscript{47} & 40 \\
Pax-Uni3D\textsuperscript{47} & 44 \\
Multislice CT conventional protocol head\textsuperscript{48} & 1500 \\
Multislice CT low-dose protocol head\textsuperscript{48} & 180 \\
\hline
\end{tabular}
\end{table}

\*These values represent exposures to the entire head. More limited views to the jaws will result in lower values.

\begin{table}[h]
\caption{Means for reducing X-ray exposure}
\begin{itemize}
\item Use selection criteria to assist in determining type and frequency of radiographic examinations
\item Use E/F-speed film or digital imaging
\item Use rectangular collimation for periapical and bitewing images
\item Use rare-earth screens for panoramic and cephalometric imaging
\item Use thyroid collars for children under 20
\item Stand at least 6' away from patient and away from the X-ray machine
\item Reduce CBCT beam size to region of interest
\item Any dentists still using short pointed aiming tubes should replace them with open-ended aiming cylinders
\item Dentists still using manual film processing should use the time-temperature method rather than ‘sight’ processing, or use an automatic processor
\end{itemize}
\end{table}

Film-based panoramic and cephalometric imaging

When making either panoramic or cephalometric images with film/screen systems it is important to use intensifying screens that use rare-earth elements. These phosphors are more sensitive than the older, less efficient, calcium tungstate screens. The dose-sparring rare-earth screens fluoresce either blue or green light so it is important to use the appropriate film matched to your screens. Digital systems result in patient doses comparable to that of modern screen/film systems.

Cone beam imaging

When a CBCT examination is indicated there are a number of means by which the operator may reduce exposure than D-speed film. When using digital imaging dentists should guard against making excessive numbers of radiographs as this will reduce the intrinsic dose advantage of this technology. Importantly, in digital radiography the density of an overexposed image can be adjusted after the exposure. To gain the benefits of decreased exposure that digital imaging offers, operators should optimize exposure factors to use the minimal exposure time required to produce diagnostic quality images. Thus, it is important that dentists optimize the exposure times for their particular receptors. Rectangular collimation should be used with intraoral film or digital imaging as this will reduce patient exposure by at least half (Fig. 4).\textsuperscript{31}

Fig 4. Child demonstrating use of rectangular collimation while making a CCD image of mandibular central incisors. Such collimators reduce patient exposure by about half by limiting the beam size. (Image courtesy of JADRAD Dental Diagnostics, Farmington, CT, USA).
patient exposure. First, the range of exposure from competing CBCT units is quite remarkable (Table 2). Use a low-dose CBCT machine whenever possible. Next, when a given machine is used, it is appropriate to use the smallest field size that will cover the region of interest. Some machines allow the operator to adjust the size of the imaging field, either by restricting the beam to, for example, the maxilla or mandible. Other machines allow the operator to restrict the diameter of the volume exposed, for instance from 12” to 9” or 6” (30.5 cm to 22.9 or 15.2 cm). Using either, or both, these means to collimate the beam are highly desirable as it will reduce patient exposure and improve the quality of the resulting image by minimizing degradation by scattered radiation. Other important means to reduce patient exposure include reducing the mA setting or reducing the length of the arc through which the machine moves while exposing the patient, from 360 degrees to 180 degrees for instance. These methods may degrade the image somewhat so should be considered in light of the diagnostic question being asked. The goal is to find the minimal exposure possible consistent with the diagnostic task.

Whenever a CBCT examination is made the entire volume should be reviewed carefully. This means not only reviewing each of the reconstructions but also individually stepping through each of the axial, coronal and sagittal images as well. Our experience, as well as that of many other individuals around the world, has been that we have detected multiple instances of significant disease (including intraosseous carcinoma, tumours of the pituitary gland and fibrous dysplasia of the sphenoid bone compromising the optic canal) on examinations made for unrelated purposes. It is incumbent on each clinician to examine all images made on all patients. Note that the occasional detection of unexpected findings does not support the routine exposure of all patients for screening purposes (because of the low detection rate) but rather for the complete examination of all indicated radiographs. All individuals reading CBCT examinations should receive training in this modality.

**SUMMARY AND CONCLUSIONS**

Diagnostic imaging is an indispensable part of contemporary medical and dental practice. Does diagnostic radiation rarely cause cancer? We don’t know but we should act as if it does. Accordingly, dentists should select patients wisely — only make radiographs when there is a patient-specific reason to believe there is a reasonable expectation the radiograph will offer unique information influencing diagnosis or treatment.

Dentists should also make low-dose examinations: (1) intraoral imaging — use fast film or digital sensors, thyroid collars, rectangular collimation; (2) panoramic and lateral cephalometric imaging — use digital systems or rare-earth film screen combinations; and (3) CBCT — use low-dose machines, restrict field size to region of interest, and reduce mA and length of exposure arc as appropriate.

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Address for correspondence:
Dr Stuart C White
Section of Oral and Maxillofacial Radiology
School of Dentistry
The University of California
Los Angeles CA 90095-1668
USA
Email: swhite@ucla.edu