OPEN

Paper

TRENDS IN ESTIMATED THYROID, SALIVARY GLAND, BRAIN, AND EYE LENS DOSES FROM INTRAORAL DENTAL RADIOGRAPHY OVER SEVEN DECADES (1940 TO 2009)

R.C. Fontana,[1,2,3] E. Pasqual,[3,4,5] D.L. Miller,[6] S.L. Simon,[7] E. Cardis,[3,4,5] and I. Thierry-Chef[3,4,5]

Abstract—**The purpose of this study is to support retrospective dose estimation for epidemiological studies by providing estimates of historical absorbed organ doses to the brain, lens of the eye, salivary glands, and thyroid from intraoral dental radiographic examinations performed from 1940 to 2009. We simulated organ doses to an adult over 10 y time periods from 1940 to 2009, based on commonly used sets of x-ray machine settings collected from the literature. Simulations to estimate organ dose were performed using personal computer x-ray Monte Carlo software. Overall, organ doses were less than 1 mGy for a single intraoral radiograph for all decades. From 1940 to 2009, doses to the brain, eye lens, salivary glands, and thyroid decreased by 86, 96, 95, and 89%, respectively. Of these four organs, the salivary glands received the highest doses, with values decreasing from about 0.23 mGy in the 1940s to 0.025 mGy in the 2000s for a single intraoral radiograph. Based on simulations using collected historical data on x-ray technical parameters, improvements in technology and optimization of the technical settings used to perform intraoral dental radiography have resulted in a decrease in absorbed dose to the brain, eye lens, salivary glands, and thyroid over the period from 1940 to 2009.**
Health Phys. 118(2):136–148; 2020

[1] Universitat de Barcelona (UB), Barcelona, Spain; [2]Radboud University (RU), Nijmegen, The Netherlands; [3]Barcelona Institute for Global Health (ISGlobal), Barcelona, Catalonia, Spain; [4]Universitat Pompeu Fabra (UPF), Barcelona, Spain; [5]CIBER Epidemiología y Salud Pública (CIBERESP), Madrid, Spain; [6]Center for Devices and Radiological Health, Food and Drug Administration, Silver Spring, MD; [7]Division of Cancer Epidemiology and Genetics, National Institutes of Health, National Cancer Institute, Bethesda, MD.

The authors declare no conflicts of interest.

For correspondence contact Isabelle Thierry-Chef, Barcelona Institute for Global Health–Campus MAR Barcelona Biomedical Research Park (PRBB) Doctor Aiguader, 88 08003 Barcelona, Spain, or email at **isabelle.thierrychef@isglobal.org**.

(*Manuscript accepted* 29 *May* 2019)

Supplemental digital content is available in the HTML and PDF versions of this article on the journal's website www.health-physics.com.

0017-9078/20/0

DOI: 10.1097/HP.0000000000001138

Key words: diagnostic radiology; epidemiology; radiation, medical; x rays, dental

INTRODUCTION

Ionizing radiation (IR) plays an essential role in medicine and dentistry by improving diagnosis and supporting patient care. The use of x rays as a diagnostic tool in almost all fields of medicine has resulted in an increase in IR exposure for the general population (Hall and Brenner 2008). Medical radiation has become the main source of man-made IR exposure (UNSCEAR 2000a and b). IR is known to cause several types of detrimental health effects, including carcinogenesis (NRC 2006). Thus, this increase in the use of IR in medicine has raised public health and radiological protection concerns.

The use of IR in dentistry began in 1896 (Todd 2014) and had become common practice by the 1950s due to its powerful diagnostic capabilities. Imaging of the teeth and supporting bone permits detection of many clinical conditions (e.g., caries, gingival and osseous diseases) (Iannucci and Howerton 2006). Dental x rays have become common practice and a routine part of patient evaluation in dentistry. The common use of x-ray imaging in dentistry is evidenced by the large numbers of images obtained as well as by the number of radiological procedures per patient (Wrzesien and Olszewski 2017; UNSCEAR 2008): in 1970 in the United States, 59 million people underwent a total of 278 million dental radiographs, corresponding to approximately 5 radiographs per patient (Lee 1974). The number of dental radiographs is increasing worldwide: in 1988, 340 million dental radiology examinations were performed, while in 2008 this number increased to about 480 million (UNSCEAR 2008).

Efforts worldwide have been made to keep the radiation dose of each radiograph as low as possible with the goal of minimizing patient exposure while obtaining an image of adequate quality. Technological improvements and optimization of x-ray technical and operating parameters throughout the last century have improved image quality while reducing exposure (Doi 2006). However, while the relationship between radiation and carcinogenesis at low doses and low dose rates remains uncertain and difficult to quantify, exposure to low-dose levels of IR could potentially result in adverse stochastic effects (NRC 2006). Organs that may present a particular concern in dental radiography are the brain, the lens of the eye, the salivary glands, and the thyroid because they are near the primary beam, and they are known to be radiosensitive. Multiple or frequent exposures to dental x rays have been found to be associated with an increased risk of thyroid cancer (Memon et al. 2010), brain cancer (Picano et al. 2012; Lin et al. 2013; Claus et al. 2012; Preston-Martin and White 1990), and salivary gland tumors (Preston-Martin and White 1990; Horn-Ross et al. 1997; Preston-Martin et al. 1988).

Risk estimations in the low-dose range are challenging; large epidemiological studies are required to reach an adequate study power (NRC 2006). Some published risk estimates rely on the total number or frequency of dental radiographs, a proxy for IR exposure. However, the radiation dose quantity that is most appropriate for cancer risk estimation is organ absorbed dose, defined as the mean energy imparted to the organ mass by ionizing radiation (NRC 2006). Absorbed dose is measured in gray (Gy), which is equivalent to J kg^{-1}. Estimating dose on an individual basis is extremely challenging because neither the delivered doses nor the technical parameters used are routinely recorded in medical databases, particularly for dental x rays. When subject information comes from questionnaire data or medical records with no information on radiation dose, an alternative that can be used to support risk estimates in epidemiological studies is a dose estimate based on typical technical parameters (i.e., machine settings) in specific time periods (Chang et al. 2017; Melo et al. 2016; Preston-Martin and Pogoda 2003; Mathews et al. 2013).

In this study, we estimated the organ dose received by the brain, lens of the eye, salivary glands, and thyroid during adult intraoral dental radiography using technical parameters derived from the literature that we believe were commonly employed between 1940 and 2009. Dose estimation was performed with the Personal Computer X-ray Monte Carlo (PCXMC 2.0) software (Radiation and Nuclear Safety Authority [STUK], Helsinki, Finland) (Tapiovaara et al. 1997) using the Excel spreadsheet application (Microsoft Corp., Redmond, Washington, US).

MATERIALS AND METHODS

Definition of dental procedures of interest in this study

In dental intraoral radiography, the x-ray film (or in modern practice, the digital imaging sensor) is placed inside the patient's mouth to obtain an image of the surrounding teeth, gum, and bone (Iannucci and Howerton 2006). A complete mouth examination is performed by obtaining multiple intraoral radiographs until the entire dentition has been imaged. In this study, we simulated only absorbed doses from intraoral radiography as our focus was on the years before cone-beam computed tomography (CT) and other techniques became commonplace.

Sources of information

We sought national and regional reports of radiological practice, radiological textbooks, and studies describing common radiological techniques in a particular decade. We conducted a literature search in PubMed, entering the following keywords: radiology, radiography, dental, x ray, organ dose. Additional publications were found by reviewing the reference lists of publications of interest. Data from dental radiology textbooks and guidebooks were also collected as available at our university medical library (Universitat de Barcelona). A set of inclusion criteria was defined, as described in Table 1, to select appropriate studies and reports. We evaluated the representativeness of the reported technical parameters using a relevance score. A high relevance score was given to studies based on nationwide collection of parameters commonly used in dental practice. A medium relevance score was given to (1) textbooks and guidebooks for undergraduate students and dentists in practice, and (2) studies describing practice in a region or a limited number of facilities. Publications reporting ideal settings were given a low relevance. We also gave higher priority to publications that provided a complete set of machine settings, to avoid unrealistic combinations of technical parameters.

Data extraction

The following information was collected from the selected studies: the full reference, country and decade

Table 1. Inclusion criteria for reports/studies selection.

Criteria	Definition
Dental x-ray procedure	The study reports parameters of intraoral periapical x-ray techniques
Time period/country	The study was performed between 1940 and 2009 in a country that is considered to be level I[a] according to UNSCEAR
Technical parameters	The study details the technical parameters used, including the type of examination, focus-skin distance, beam size, tube potential, tube current, filtration, and exposure time
Type of study	The study provides measurements of parameters representative of the common practice in a country during the time period when the study was performed
Language	English

[a]Level I countries were defined as those in which there was at least 1 physician for every 1,000 people in the general population (United Nations 2008).

of examination, information about the study design, and the technical parameters needed for the organ dose simulation (as listed below). If, for a given decade, we could not find any publication that provided a complete set of technical parameters, we gave priority to the most complete ones by using additional publications from the same decade to complete the set. For instance, for the 1940s decade, values were extracted from two publications (Clark 1949; Sante 1949). Values provided in each publication were considered as one set and were completed with filtration and beam area values provided by Jamieson (1952) and Richards (1958), respectively. When a specific parameter could not be found for a given decade, we used the value given in publications for the previous decade.

Input parameters

The dose absorbed by a specific organ is estimated by the software using the following inputs: (a) factors based on patient characteristics such as age and body mass; and (b) a series of x-ray machines settings defined by the practitioner, including tube potential (x-ray voltage), filtration, focus-to-skin distance, projection angle, oblique angle, x-ray beam height and width, and the exposure.

Tube potential is measured as peak kilovoltage (kVp) and represents the potential applied across the x-ray tube. Filtration is measured in millimeters of aluminum (mm Al) and corresponds to the equivalent thickness of aluminum placed in front of the x-ray tube to filter out low-energy x-ray photons. The focus-to-skin distance (cm) is the distance between the x-ray source and the patient's skin. X-ray beam height and width correspond to the size of the x-ray beam as it exits the collimator. The exposure corresponds to the radiation dose at the entrance surface of the patient. PCMXC software allows entry of this variable in any of five different units (mGy free in air, mR free in air, mGy cm^{-2}, rad cm^{-2}, mAs). In this study, we entered the tube current time product (milliamp seconds, mAs), hereafter referred as tube current.

Values of these parameters have changed over time due to continuing technological advances. To capture these changes, the technical parameters listed above were collected for each decade from 1940 to 2009.

Dose estimation

PCXMC software was used to simulate brain, salivary gland, and thyroid doses, using as input the technical parameters considered to be most commonly used in each decade between 1940 and 2009. The software calculates absorbed dose to 29 different organs and is well suited to simulate a wide range of radiological procedures including intraoral dental radiography (Lee et al. 2016; Aps and Scott 2014; Koivisto et al. 2012; Lindfors et al. 2017; Vassileva and Stoyanov 2010). PCXMC does not provide dose estimates for the lens of the eye. However, this organ dose value can be approximated by the entrance dose to the skin at the level of the eyes, as confirmed by the estimated tissue dose per unit air kerma (D_T/K_a) factors for the lens of the eye (Simon 2011), for diagnostic x-ray energies, which are centered around unity. Eye lens doses were estimated by deriving the air kerma from the PCXMC-calculated brain dose using the conversion coefficient between brain dose and air kerma provided in Table 7 of the same publication (Simon 2011) for 70 kV as the most relevant tube potential for dental procedures. The air kerma at the level of the eyes was therefore considered a reasonable estimation of the eye lens dose.

Once sets of typical parameters for each dental projection were collected for each time period, simulations with PCXMC 2.0 were performed. When possible, for each decade we performed a simulation by cone (collimator) type (short or long), for each projection (maxillary or mandibular teeth), and for each tooth (incisor, canine, molar, or premolar). Therefore, for most decades we performed at least 16 different simulations. Median values were reported and considered as representative for each decade. Patient sex and age were set at male and 30 y (PCXMC uses an adult model, with a reference body mass and height for a male of 73.2 kg and 178.6 cm). The position of the phantom towards which the central beam was directed was set at the level of the mouth, using the software reference points Xref = 0, Yref = −5, and Zref = 80. Table 2 summarizes the applied projection and oblique angles for each target tooth (Williamson 2006).

The use of patient-shielding devices was not considered in this study though it is widely understood that lead thyroid collars can reduce the dose to the thyroid gland substantially. This is especially true when anterior maxillary teeth are exposed. In those cases, thyroid collar use reduces thyroid dose levels around 75% (Hoogeveen et al. 2016). The extent to which protective devices have been used over time in different facilities is unknown. Therefore, for the dose calculation we assumed no shielding was used.

RESULTS

Of the 55 publications reviewed, we selected 18 that fulfilled the inclusion criteria. Table 3 summarizes the characteristics of the selected studies. For each decade, the

Table 2. Angles used in simulations of intraoral examinations for the visualization of different teeth.

Examination	Projection angle (°)	Oblique angle (°)
Maxillary incisor	270	45
Maxillary canine	225	45
Maxillary premolar	210	30
Maxillary molar	180	20
Mandibular incisor	270	−12.5
Mandibular canine	225	−12.5
Mandibular premolar	210	−12.5
Mandibular molar	180	0

Table 3. Summary of the characteristics of the publications from which the technical parameters were obtained.

Reference	Country	Brief description	Relevance score[a]
1940–1949			
Clark (1949)	UK	Radiography textbook	Medium
Sante (1949)	US	Radiography textbook	Medium
1950–1959			
Jamieson (1952)	New Zealand	Provided a distribution of parameters commonly used in a regional reference hospital (Dunedin, New Zealand) and therefore representing regional practice	Medium
Ardran and Crooks (1953)	UK	Defined new settings to reduce patient's dose; the publication also provided radiographic factors used in routine practice at Atomic Energy Research Establishment (AERE)	High
Richards (1958)	US	Defined new settings to reduce patient's dose; common practice settings were not provided and can be assumed to deliver a higher dose	Low
1960–1969			
Bjärngard (1960)	Sweden	Provided parameters come from a limited survey of dental x-ray units representing, at least, a regional common practice	Medium–high
Richards and Webber (1964)	US	Aimed to estimate doses to the head and neck due to intraoral procedures; this purpose led the authors to assume that the parameters used are representative of common practice	Medium
Rogers (1969)	UK	Provided factors come from radiographical views detailed in *Positioning in Radiography* by K.C. Clark (1964), which is a reference radiology textbook	Medium
1970–1979			
Alcox and Jameson (1974)	US	Reported technical parameters are from a 1970 study conducted by the Bureau of Radiological Health that collected parameters commonly used by US dentists	High
Antoku et al. (1976)	Japan	Provided technical parameters commonly used by dentists	Medium
Wohni (1977)	Norway	Study intended to measure absorbed doses in Norway from dental radiography; the authors assumed that the technical parameters they used were representative of common practice	Medium
1980–1989			
Gibbs et al. (1988)	US	Provided technical parameters commonly used by dentists	High
Serro et al. (1992)	Portugal	Portuguese nationwide survey, performed between 1988 and 1989; the methodology used to collect parameters was similar to the US NEXT survey	High
1990–1999			
CRCPD (1993)	US	US nationwide report that collected radiation exposure data for different radiological examinations from a representative number of clinical facilities	High
Syriopoulos et al. (1998)	Greece	Nationwide survey conducted at a representative number of facilities that reported common techniques used in dental radiography in Greece	High
NEXT 1999 (Moyal 2003)	US	US nationwide report that collected radiation exposure data from different radiological examinations from a representative number of clinical facilities	High
2000–2009			
Whaites (2006)	UK	Textbook on dental radiography and radiology	Medium
Iannucci and Howerton (2006)	US	Textbook on dental radiography and radiology	Medium

[a]See text for details.

number of relevant references used was two or three. Among the selected studies, only one study was scored with low relevance (Richards 1958), the majority were judged to be of medium relevance, and seven studies were scored as highly relevant. The high-relevance studies were generally descriptions of more recent practice. The technical parameters used to perform the simulations are reported in Table 4 for each of the seven decades between 1940 and 2009. Median organ dose estimates for the brain, eye lens, salivary glands, and thyroid for a single intraoral radiograph are provided together with ranges in Table 5. The ranges provided in Table 5 reflect the variability of doses which we have estimated from all combinations of parameters. The wide range of doses in the first decade reflects the very different tube current values reported for the period in the two available reports (Clark 1949; Sante 1949).

Table 4. Technical parameters used for organ absorbed dose estimation. References are provided as author and date.

	Technical parameter									
	Tube voltage (kV)		Filtration (mm Al)		Focus-skin distance (cm)		Beam area (cm²)		Tube current (mAs)	
Decade	Value	Reference	Value	Reference	Value	Reference	Value	Reference	Value	Reference
1940–1949	55 50	Clark (1949) Sante (1949)	1.6	Jamieson (1952)	20 48	Clark (1949) Sante (1949)	49	Richards (1958)	4–8 100–150	Clark (1949) Sante (1949)
1950–1959	60	Ardran and Crooks (1953)	3	Ardran and Crooks (1953)[a]	20	Ardran and Crooks (1953)[b]	49	Richards (1958)	12.5–15	Ardran and Crooks (1953)
1960–1969	60; 70	Rogers (1969)	2.5	Rogers (1969)	27 37	Rogers (1969) Rogers (1969)	39.56	Richards and Webber (1964); Bjärngard (1960)	25; 10	Rogers (1969)
1970–1979	60 70	Alcox and Jameson (1974) Alcox and Jameson (1974)	2	Wohni (1977)	20; 40 15.5	Alcox and Jameson (1974) Antoku et al. (1976)	49 42.25; 64	Alcox and Jameson (1974) Antoku et al. (1976)	3–10	Antoku et al. (1976)
1980–1989	58	Serro et al. (1992)	0.83	Serro et al. (1992)[c]	22	Serro et al. (1992)[b]	49	Gibbs et al. (1988)	3–10	Antoku et al. (1976)
1990–1999	71 72	Moyal (2003) CRCPD (1993)	2.3	Moyal (2003); CRCPD (1993)[d]	20; 40	Gibbs et al. (1988)	36	Syriopoulos et al. (1998)	3.6 4.2	Moyal (2003) CRCPD (1993)
2000–2009	60;70	Iannucci and Howerton (2006); Whaites (2006)	1.5; 2.5	Iannucci and Howerton (2006); Whaites (2006)	20; 40	Iannucci and Howerton (2006); Whaites (2006)	20	Iannucci and Howerton (2006); Whaites (2006)	3.75; 1.25	Iannucci and Howerton (2006); Whaites (2006)

[a]Added filtration. Total filtration is likely to be slightly higher.
[b]Focus-skin distance was obtained by subtracting 3 cm to the provided value of focus-film distance.
[c]A half-value layer (HVL) of 1.1 mm Al was converted into total filtration. Value valid for direct current (DC), with a tungsten anode, no ripple, an angle of 14°, and a voltage of 60 kV (RTI 2016).
[d]An HVL of 2.3 mm Al was converted into total filtration. Value valid for DC, with a tungsten anode, no ripple, an angle of 14°, and a voltage of 70 kV (RTI 2016)

Table 5. Derived organs absorbed doses (mGy) to the brain, eye lens, salivary glands, and thyroid.

Decade	Brain		Lens of the eye		Salivary glands		Thyroid	
	Median organ absorbed dose (range)	% change[a]	Median organ absorbed dose (range)	% change[a]	Median organ absorbed dose (range)	% change[a]	Median organ absorbed dose (range)	% change[a]
1940–1949	0.0062 (0.0025, 0.025)	—	0.083 (0.034, 0.33)	—	0.23 (0.072, 1.71)	—	0.11 (0.042, 0.83)	—
1950–1959	0.015 (0.012, 0.018)	+142%	0.092 (0.074, 0.11)	+11%	0.47 (0.13, 1.40)	+104%	0.15 (0.13, 0.59)	+36%
1960–1969	0.0091 (0.0043, 0.021)	−39%	0.049 (0.023, 0.11)	−47%	0.26 (0.072, 1.16)	−45%	0.089 (0.027, 0.44)	−41%
1970–1979	0.0095 (0.0021, 0.032)	+4%	0.036 (0.0080, 0.12)	−27%	0.23 (0.029, 2.64)	−12%	0.12 (0.018, 0.89)	+35%
1980–1989	0.0063 (0.0034, 0.012)	−34%	0.024 (0.013, 0.045)	−33%	0.21 (0.046, 1.64)	−9%	0.098 (0.044, 0.25)	−18%
1990–1999	0.0042 (0.0013, 0.013)	−33%	0.016 (0.0049, 0.050)	−33%	0.10 (0.023, 0.52)	−52%	0.036 (0.0075, 0.22)	−63%
2000–2009	0.00088 (0.00021, 0.0028)	−79%	0.0034 (0.00080, 0.011)	−79%	0.025 (0.0047, 0.15)	−75%	0.0060 (0.00097, 0.029)	−83%

[a]Change in dose from the immediate prior decade.

The salivary glands received the highest absorbed doses, ranging from about 0.23 mGy in the earliest decade evaluated (1940–1949) to about 0.025 mGy in the most recent decade evaluated (2000–2009). Estimated absorbed doses to the brain were the lowest among the studied organs, ranging from 0.014 mGy in the 1950s to 0.00088 mGy in the 2000s.

The percentage change in dose from the previous decade was calculated and is reported in Table 5. For the four organs studied, the largest decrease in dose was seen between the 1990s and the 2000s (around 80%). Table 6 provides comparisons of our results to organ doses reported in previous publications.

Figs. 1 to 4 show the absorbed dose to the selected organs by decade. Each point represents the dose received by the organ of interest from an intraoral radiograph performed to visualize a specific tooth (incisor, canine, premolar, molar) from each projection (maxillary and mandibular) using both techniques (short and long cone). The dose range represents the variability obtained from simulating the procedure (as described above) with the set of parameters relevant for the given decade. For all organs studied, there was a trend towards decreasing dose over time.

DISCUSSION

The absorbed doses reported in our study characterize the general trends in doses received from intraoral dental radiography as they evolved over time. Our methodology was designed to provide values of doses representative of exposure of the general adult population within each decade. Overall, the dose from intraoral radiography was very low; none of the median organ doses estimated here exceeded 1 mGy. However, intraoral radiography is performed often throughout a patient's lifetime. For instance, the American Dental Association recommends regular routine intraoral examinations with bilateral posterior bitewing radiographs every 12 to 24 mo for children, every 18 to 36 mo for adolescents, and every 24 to 36 mo for adults who are recall patients with no clinical caries and no increased risk of caries (ADA/FDA 2012). Based on these recommendations and our estimates of organ dose, this means that, on average, a 70-y-old male in 2010 with no history of caries and no increased risk for caries development could have received 20 dental radiographic examinations during adulthood, each with bilateral posterior bitewing radiographs, leading to brain, eye lens, salivary gland, and thyroid cumulative absorbed doses of approximately 0.5 mGy, 2 mGy, 13 mGy, and 6 mGy, respectively. A similar adult with a history of caries or increased risk for caries development could undergo dental radiography with bilateral posterior bitewing radiographs at intervals of 6 to 18 mo according to current American Dental Association (ADA) recommendations,

Table 6. Absorbed organ dose value comparisons with previously published articles. Values in bold are comparable values.

Decade	Our work (median dose)	Other publication	Reference
Thyroid absorbed dose (mGy)			
1950–1959	**0.15**	**0.19–0.36**[a]	Bjärngard (1959)
1960–1969	**0.089**	**0.074–0.64**[b]	Bjärngard (1960)
	0.089	0.00093	Richards and Webber (1964)
	0.089	0.39[c]	Richards and Webber (1964)
1970–1979	**0.12**	**0.20**	Antoku et al. (1976)
	0.12	0.03	Bengtsson et al. (1978)
	0.12	0.03[c]	Alcox and Jameson (1974)
	0.12	0.02–0.04	Alcox and Jameson (1974)
	0.12	**0.17**	Maruyama et al. (1977)
	0.12	0.01[c]	Chang et al. (2017)
1980–1989	0.098	0.047	Underhill et al. (1988)
	0.098	**0.080**	Benedittini et al. (1989)
	0.098	**0.01**[c]	Chang et al. (2017)
1990–1999	0.036	0.0084	Lecomber and Faulkner (1993)
	0.036	0.01[c]	Chang et al. (2017)
	0.043[e]	**0.023**[e]	Hayakawa et al. (1993)
2000–2009	**0.043**[d]	**0.035**[d]	Ekestubbe et al. (2004)
	0.0060	**0.00**[c]	Chang et al. (2017)
Brain absorbed dose (mGy)			
1980–1989	**0.0063**	**<0.01**	Benedittini et al. (1989)
1990–1999	**0.0042**	**0.0039**	Lecomber and Faulkner (1993)
Salivary glands absorbed dose (mGy)			
1960–1969	0.26	1.02[c]	Richards and Webber (1964)
	0.26	0.0022	Richards and Webber (1964)
1980–1989	**0.21**	**0.39**	Underhill et al. (1988)
	0.21	**0.28**	Benedittini et al. (1989)
1990–1999	0.10	0.03	Lecomber and Faulkner (1993)
	0.091[e]	0.033[e]	Hayakawa et al. (1993)
2000–2009	0.40[d]	2.87[d]	Ekestubbe et al. (2004)
Eye lens absorbed dose (mGy)			
1960–1969	0.049	0.28[c]	Richards and Webber (1964)
	0.049	0.0015	Richards and Webber (1964)
1970–1979	**0.036**	**0.065**	Antoku et al. (1976)
1980–1989	0.024	0.06	Benedittini et al. (1989)
1990–1999	**0.016**	**0.016**	Lecomber and Faulkner (1993)
2000–2009	0.0061[d]	0.055[d]	Ekestubbe et al. (2004)

[a]Thyroid dose value for a complete mouth examination was 5 mGy.
[b]Thyroid dose values for a complete mouth examination were between 2 and 9 mGy.
[c]Values for bitewing dental diagnostic procedures.
[d]Upper and lower molar dose values.
[e]Maxillar incisor and mandibular molar values.

with resultant greater absorbed doses to the brain, eye lens, salivary glands, and thyroid (ADA/FDA 2012). Of course, this estimation assumes that the recommendations and practices with regard to the frequency of dental radiography were the same in previous decades.

The dose values presented in this report are for a single radiograph. As noted above, routine dental radiography typically includes bilateral posterior bitewing radiographs. In some clinical situations, it is necessary to obtain a picture of the entire dentition, leading to the performance of full-mouth examinations. Throughout the studied decades, the number of images necessary to obtain a full-mouth examination has been reported as between 14 and 27 (Alcox and Jameson 1974; Richards and Webber 1964; Underhill et al. 1988; Gofman and O'Connor 1985; Lee 1974; Weissman and Sobkowski 1970; Stanford and Vance 1955; Baily 1957; Lecomber and Faulkner 1993). This number of images would entail a concomitant increase in absorbed organ dose.

The decision to evaluate brain, eye lens, salivary glands, and thyroid dose was based on the biological relevance, radiosensitivity, and proximity to the radiation beam of these organs. Another organ of interest in radiation epidemiology is active bone marrow, also known for its radiosensitivity. However, we are not presenting any results on this organ because the amount of bone marrow at the dental arch is negligible (Cristy 1981), and as expected, PCMCX estimated doses for the bone marrow were close to 0 (data not shown).

Trends over time

In every decade studied, the salivary glands received the highest absorbed dose among the four organs studied. Overall, there was a decreasing trend over time in the dose received by each of the organs evaluated. This can be explained largely by technological changes in x-ray equipment and imaging techniques. Between 1940 and 2009 these changes resulted in a decrease of about 90% in organ dose from intraoral imaging. One important factor for this decline was the increase in total filtration to at least 2.5 mm Al for tube potentials higher than 70 kV, first implemented between the 1970s and 1980s. This decrease in exposure is related to changes in regulations (Iannucci and Howerton 2006; Whaites 2006; Mason 1988; Browne et al. 1995), based on the guidelines provided by the International Commission on Radiological Protection (ICRP) and in the United States, the National Council on Radiation Protection and Measurements (NCRP). Those two agencies represent, since the 1930s, the main advisory organizations for the limits for ionizing radiation exposure and protection of the public (IoM 1996). Reduction in the tube current (mAs) was a result of the introduction of faster films. Faster films require less radiation than slower films to produce the same film blackening. For instance, Kodak films available in 1980 reduced patient exposure over 95% compared with those available in 1940 from the same manufacturer (Richards and Colquitt 1981). Moreover, the subsequent introduction of F-speed films allowed reduction in patient exposure by half compared with E-speed films without loss of image quality (Farman and Farman 2000). Most recently, the advent of digital receptor technology has provided the opportunity for even further dose reduction (Farman and Farman 2005).

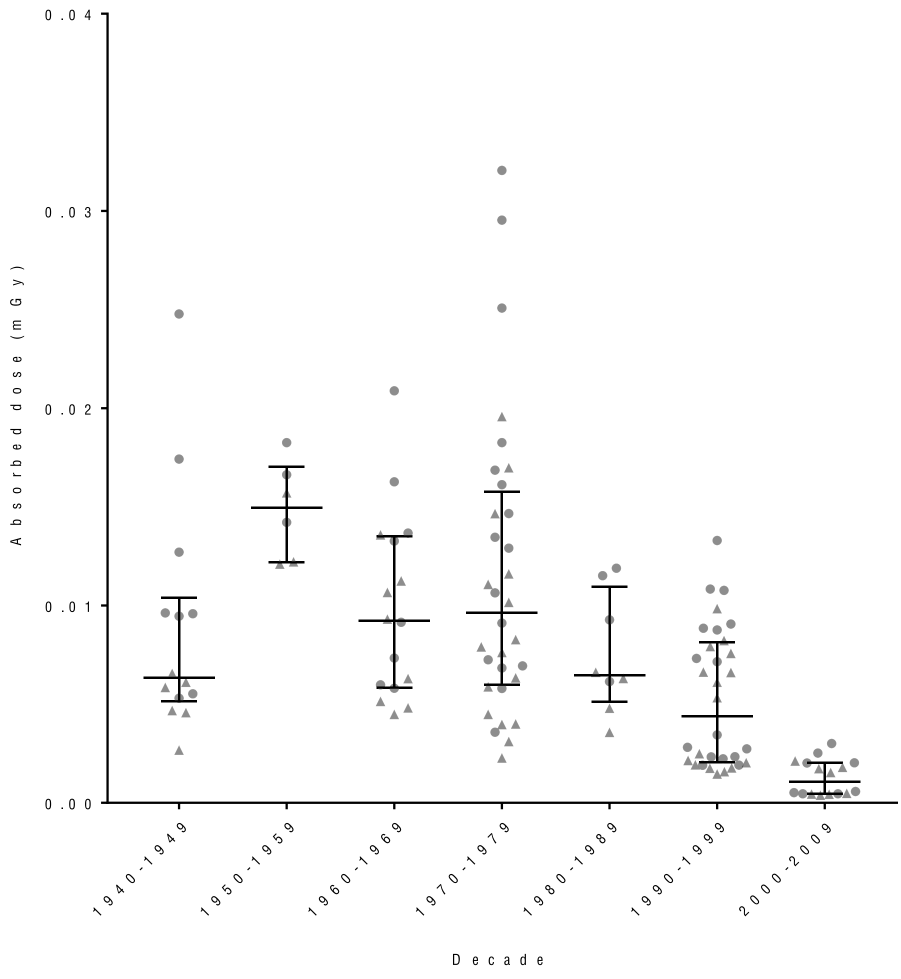

Fig. 1. Absorbed doses (median and interquartile range) to the brain due to single intraoral examinations between 1940 and 2009.

The estimated dose in the 1940s was lower than the dose in the decades that immediately followed. This might be explained by the lack of availability of data for the 1940s as only two sources of data for this decade (both of medium relevance) could be identified. Therefore, the dose estimates for this decade should be used with caution.

Comparison with previous studies

We found several publications that reported absorbed organ doses due to intraoral examinations. These publications allowed comparison with our results, as shown in Table 6. There were clear methodological differences, including the choice of technical parameters, phantom material, and dosimeter type and positioning compared to our calculations, and these could explain some of the differences with our results. When these publications provided doses only for specific projections, comparison was made to the corresponding estimated values.

The doses provided by Ekestubbe et al. (2004), for a comparison of absorbed and effective doses between scanographic and zonographic examinations with intraoral periapical radiography, are higher than what would be expected for the 2000–2009 decade. Their results are explained by their use of a higher tube current (15 mAs and 9.4 mAs for the maxillary and mandibular molars, respectively).

For the decade 1960–1969, the organ doses provided by Richards and Webber (1964), using phantom measurements in the head and the neck, are much lower than our estimates. As mentioned by Ekestubbe et al. (2004), the considerable differences in exposure due to changes of the x-ray beam direction relative to the position of the ionization chamber could explain this difference. Furthermore, they report that their results were lower than the ones that had been presented previously in the dental literature.

Sources of uncertainty

In dental radiographic procedures, the thyroid gland, brain, and eyes are near the edge of the radiation field, so doses to these organs can be affected by patient positioning. Slight positioning differences can result in important

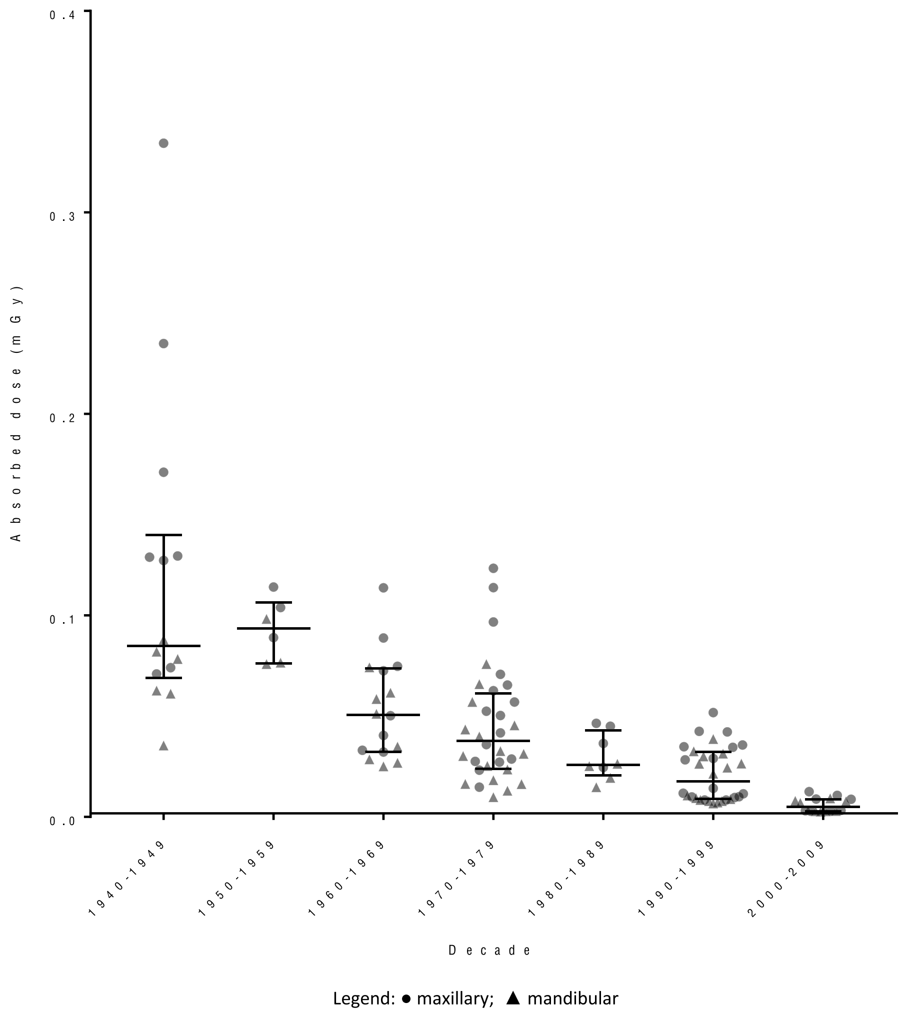

Fig. 2. Absorbed doses to the lens of the eye (median and interquartile range) due to single intraoral examinations between 1940 and 2009.

changes in absorbed dose to these organs (Kapila 2014). The difference between an organ falling completely inside the beam or on its edge can produce substantial variation in the resulting dose.

We present absorbed dose values for a single intraoral radiographic projection. However, in routine practice more than one projection may be obtained, depending on the clinical indication. The number of images recommended to obtain a complete mouth series varies, even within an individual decade. This variation is especially important for epidemiological studies where retrospective dose estimations are performed and cumulative doses are required. The dose values for a complete mouth series are derived from multiplication of the dose for a single intraoral radiograph by the number of radiographs obtained. Also, retakes of the image within the same clinical examination may be performed if the initial image is judged to be inadequate. Information on frequency of examinations may be collected through self-administered questionnaires or medical records reviews, but in both cases the exact number of projections may not be reported precisely. This can introduce additional uncertainty.

Another factor that influences doses to nearby organs is collimation. Both the degree of collimation and the beam shape (circular or rectangular) are important determinants of these doses. Although some of the sources we consulted specified the type of collimation used (circular or rectangular), we were restricted to defining beam height and width in a rectangular field in PCXMC. We have converted the diameter of circular beams to height and width values for a rectangle, making our estimations more conservative.

Kilovoltage values used for our simulation are those that dental radiographers were reported to have used or that were recommended, but values delivered in practice might have differed. In some detailed surveys, both the selected and the measured tube potential were provided. Selected values are those that the technician sets (theoretical ones); measured values are those actually generated by the radiographic system. Although measured tube potential is more accurate for estimating absorbed dose, we used the selected

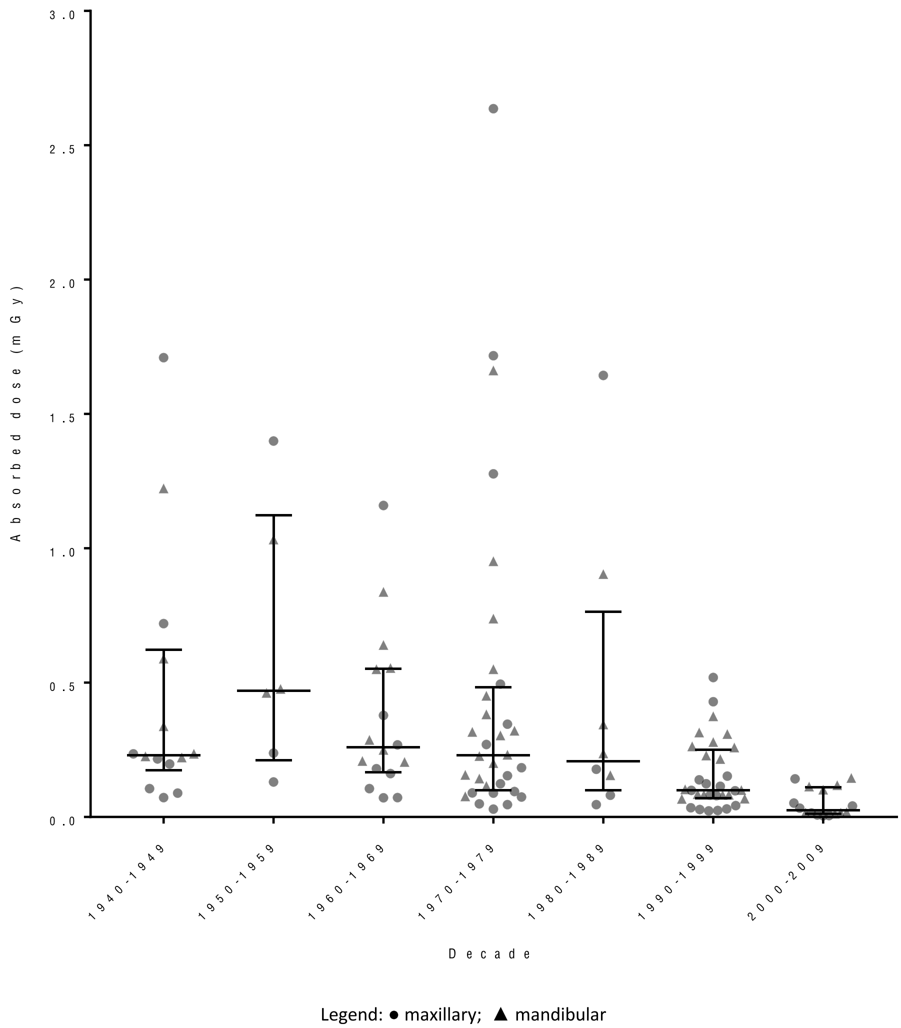

Fig. 3. Absorbed doses to the salivary glands (median and interquartile range) due to single intraoral examinations between 1940 and 2009.

values for our simulations to allow better comparison among published studies. The 1999 Nationwide Evaluation of X-ray Trends (NEXT) Survey in the United States determined a mean absolute value difference between measured and selected values of intraoral tube potential of 3.8 kV (Moyal 2003).

Limitations

The major limitation of the present study was the paucity of relevant information in the literature for some of the time periods. Most articles that reported estimates of dose compared the impact of using several technical parameters with the goal of optimizing settings to reduce patient dose. Very few publications provided representative values that corresponded to common practice in a specific decade. The doses estimated in this work were based on typical technical parameters provided by a series of scientific publications, reports, and guidebooks for the last seven decades and a series of assumptions made to reconstruct typical protocols when only partial information was provided in the literature. The values we used for the various parameters are believed to be representative of those used in a high health-level country (UNSCEAR 2000), but variation around these values is expected between different countries, facilities, and radiographers. We considered the most common projections used to perform intraoral radiography, but alternative examination settings could also have been used, and this could have resulted in a modest variation in dose. For example, the difference in the dose medians between two sets of examination settings, both reported as common during the 1990s (Moyal 2003), was 0.0017 mGy, 0.0066 mGy, 0.049 mGy, and 0.013 mGy for the brain, eye lens, salivary glands, and thyroid, respectively.

Additional limitations related to data sources include our restriction to publications in the English language and our exclusion of reports from countries other than United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) level I. This means that our dose estimates may not be applicable worldwide or in less developed countries.

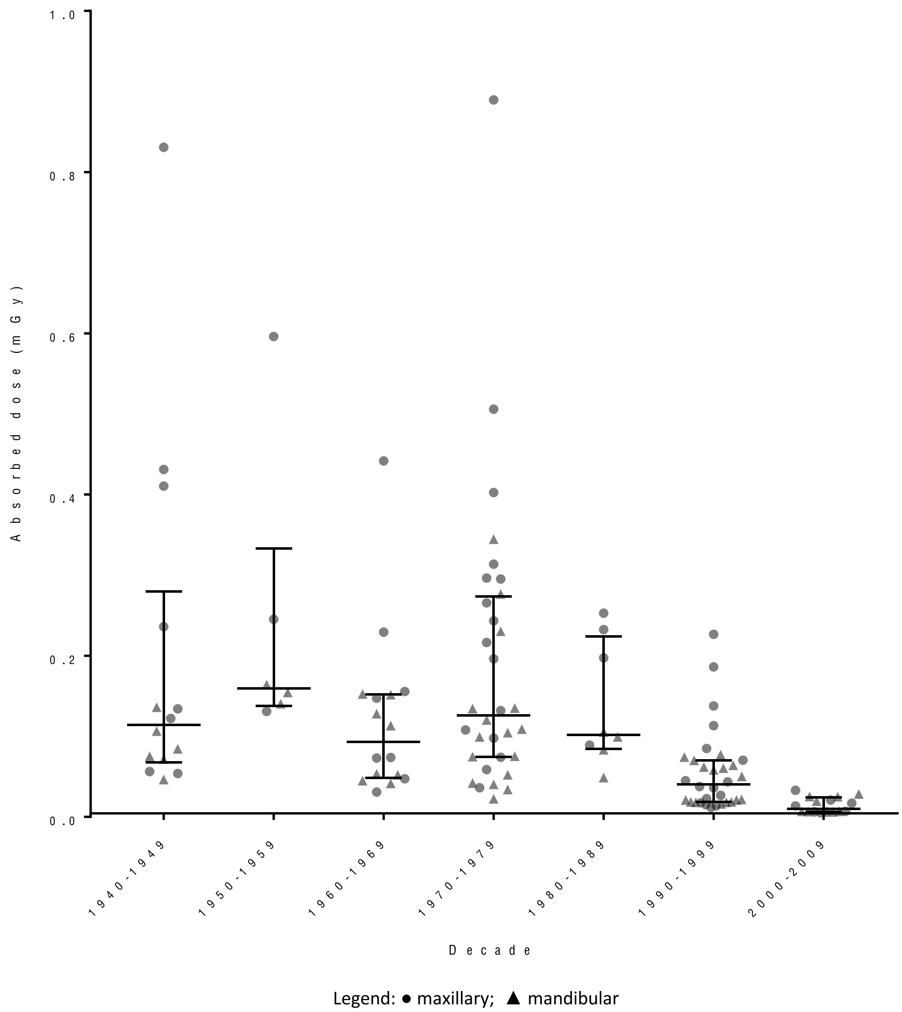

Fig. 4. Absorbed doses to the thyroid (median and interquartile range) due to single intraoral examinations between 1940 and 2009.

We calculated our estimates of organ dose using the PCXMC adult model with a reference male. We have not estimated absorbed dose to the relevant organs for children or adolescents because of the very limited data on typical technical parameters for dental radiography for those age groups. Doses that we report for adults should be used in epidemiological investigations of children with great caution.

We present estimates for median absorbed dose to each organ in each decade. As is apparent from Figs. 1–4, there was likely substantial variation in absorbed dose depending on which tooth was radiographed, especially in earlier decades (supplemental digital content [SDC] Appendix SDC 1, http://links.lww.com/HP/A172). Use of the median absorbed dose may result in systematic errors when only specific portions of the dentition are examined, such as in current American Dental Association recommendations (ADA/FDA 2012) where routine radiography consisting of bilateral posterior bitewing radiographs is recommended. Recommendations or common practice regarding routine examinations might have differed throughout the studied decades regarding the portion of the dentition examined.

CONCLUSION

Our estimates of absorbed organ dose may be used in epidemiological research either where the study seeks to examine the association between the radiation delivered during dental diagnostic procedures and the risk for development of cancer or lens opacity or where dental irradiation must be accounted for as part of the total exposure profile.

Dental procedures, as shown in the present work, have generally delivered very low doses, especially in recent decades, but their extensive and repeated use in the general population raises public health and radiological protection concerns. By collecting information on the frequency of dental examinations, epidemiological studies may estimate the health effect of such low-dose exposures. Studies that aim to predict lens opacity or cancer incidence attributable to diagnostic x-ray examinations may benefit from the results presented here. Such studies would require collecting, for each decade, detailed information on the frequency of each type of dental examination separately (intraoral periapical or bitewing, cephalometric, and panoramic x ray).

Acknowledgments—ISGlobal is a member of the Catalan Research Centres Institute (CERCA) program. Participation of author SLS was made possible by the Intramural Research Program of the National Cancer Institute, National Institutes of Health.

This work has been partially developed during author RCF's master thesis internship at ISGlobal within the Biomedical Engineering Master's Program of Universitat de Barcelona. We thank Mercè Ginjaume for her supervision and suggestions during the master thesis development.

The present work has been supported by the European Commission (EC) through the GERONIMO project (project 603794 under FP7-ENV) and the Spanish Nuclear Safety Authority (Consejo de Seguridad Nuclear)—under a grant titled "Epidemiological study to quantify risks for paediatric computerized tomography and to optimise doses (Epi-CT)."

The present work has also been performed in the framework of the KIDMEDRAD project (PI16/00120), funded by Instituto de Salud Carlos III and cofunded by the European Union (ERDF, "A way to make Europe").

REFERENCES

Alcox RW, Jameson WR. Patient exposures from intraoral radiographic examinations. J Am Dent Assoc 88:568–579; 1974.

American Dental Association/US Food and Drug Administration. Dental radiographic examinations: recommendations for patient selection and limiting radiation exposure [online]. 2012. Available at ***www.fda.gov/downloads/radiationemittingproducts/radiationemit-tingproductsandprocedures/medicalimaging/medicalx-rays/ucm329746.pdf***. Accessed 30 April 2019.

Antoku S, Kihara T, Russell WJ, Beach DR. Doses to critical organs from dental radiography. J Oral Maxillofac Surg Med Pathol 41: 251–260; 1976. DOI 10.1016/0030-4220(76)90237-1.

Aps JKM, Scott JM. Oblique lateral radiographs and bitewings. Estimation of organ doses in head and neck region with Monte Carlo calculations. Dentomaxillofac Radiol 43:20130419; 2014. DOI 10.1259/dmfr.20130419.

Ardran GM, Crooks HE. A comparison of radiographic techniques with special reference to dosage. Br J Radiol 26:352–357; 1953. DOI 10.1259/0007-1285-26-307-352.

Baily NA. Patient exposure to ionizing radiation in dental radiography. Radiol 69:42–45; 1957. DOI 10.1148/69.1.42.

Benedittini M, Maccia C, Lefaure C, Fagnani F. Doses to patients from dental radiology in France. Health Phys 56:903–910; 1989.

Bengtsson G, Blomgren PG, Bergman K, Aberg L. Patient exposures and radiation risks in Swedish diagnostic radiology. Acta Radiol Oncol Radiat Phys Biol 17:81–105; 1978.

Bjärngard B. Radiation doses in oral radiography. I. Measurements of doses to gonads and certain parts of head and neck during full mouth roentgenography. Odont Revy 10:355–366; 1959.

Bjärngard B. Radiation doses in oral radiography. II. The influence of technical factors on the dose to the patient in full mouth roentgenography. Odont Revy 11:100–112; 1960.

Browne RM, Edmondson HD, Rout PGJ. Atlas of dental and maxillofacial radiology and imaging. St. Louis, MO: Mosby-Wolfe; 1995.

Chang LA, Miller DL, Lee C, Melo DR, Villoing D, Drozdovitch V, Thierry-Chef I, Winters SJ, Labrake M, Myers CF, Lim H, Kitahara CM, Linet MS, Simon SL. Thyroid radiation dose to patients from diagnostic radiology procedures over eight decades: 1930–2010. Health Phys 113:458–473; 2017. DOI 10.1097/HP.0000000000000723.

Clark KC. Positioning in radiography. London: Ilford Ltd. William Heineman Medical Books; 1949.

Claus EB, Calvocoressi L, Bondy ML, Schildkraut JM, Wiemels JL, Wrensch M. Dental x-rays and risk of meningioma. Cancer 118:4530–4537; 2012. DOI 10.1002/cncr.26625.

Conference of Radiation Control Program Directors, Inc. Nationwide evaluation of x-ray trends (NEXT) 1993 dental x-ray data. Frankfurt, KY: CRCPD. 1993. Available at ***https://cdn.ymaws.com/www.crcpd.org/resource/collection/81C6DB13-25B1-4118-8600-9615624818AA/93DentalTrifold.pdf***. Accessed on 30 April 2019.

Cristy M. Active bone marrow distribution as a function of age in humans. Phys Med Biol 26:389–400; 1981.

Doi K. Diagnostic imaging over the last 50 years: research and development in medical imaging science and technology. Phys Med Biol 51:R5–27; 2006. DOI 10.1088/0031-9155/51/13/R02.

Ekestubbe A, Thilander-Klang A, Lith A, Gröndahl HG. Effective and organ doses from scanography and zonography: a comparison with periapical radiography. Dentomaxillofac Radiol 33: 87–92; 2004. DOI 10.1259/dmfr/24877187.

Farman AG, Farman TT. A Comparison of 18 different x-ray detectors currently used in dentistry. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 99:485–489; 2005. DOI 10.1016/j.tripleo.2004.04.002.

Farman TT, Farman AG. Evaluation of a new F speed dental x-ray film. The effect of processing solutions and a comparison with D and E speed films. Dentomaxillofac Radiol 29:41–45; 2000. Erratum in Dentomaxillofac Radiol 20:131; 2000.

Gibbs SJ, Pujol A, Chen TS, James A. Patient risk from intraoral dental radiography. Dentomaxillofac Radiol 17:15–23; 1988. DOI 10.1259/dmfr.1988.0002.

Gofman JW, O'Connor E. X-rays: health effects of common exams. New York: Random House; 1985.

Hall EJ, Brenner DJ. Cancer risks from diagnostic radiology. Br J Radiol 81:362–378; 2008. DOI 10.1259/bjr/01948454.

Hayakawa Y, Fujimori H, Kuroyanagi K. Absorbed doses with intraoral radiography. Function of various technical parameters. Oral Surg Oral Med Oral Pathol 76:519–24; 1993.

Hoogeveen RC, Hazenoot B, Sanderink GC, Berkhout WE. The value of thyroid shielding in intraoral radiography. Dentomaxillofac Radiol 45:20150407; 2016. DOI: 10.1259/dmfr.20150407.

Horn-Ross PL, Ljung BM, Morrow M. Environmental factors and the risk of salivary gland cancer. Epidemiol 8:414–419; 1997.

Iannucci JM, Howerton LJ. Dental radiography: principles and techniques. Philadelphia, PA: Saunders Elsevier; 2006.

Institute of Medicine. Radiation in medicine: a need for regulatory reform. Washington, DC: National Academies Press; 1996. Available at ***https://www.ncbi.nlm.nih.gov/books/NBK232717/***. DOI 10.17226/5154. Accessed 30 April 2019.

Jamieson HD. X-ray dosage to patients and staff in diagnostic radiology: an investigation at Dunedin hospitals. N Z Med J 51: 159–167; 1952.

Kapila SD. Cone beam computed tomography in orthodontics: indications, insights, and innovations. New York: John Wiley & Sons; 2014.

Koivisto J, Kiljunen T, Tapiovaara M, Wolff J, Kortesniemi M. Assessment of radiation exposure in dental cone-beam computerized tomography with the use of metal-oxide semiconductor field-effect transistor (MOSFET) dosimeters and Monte Carlo simulations. Oral Surg Oral Med Oral Pathol 114:393–400; 2012. DOI 10.1016/j.oooo.2012.06.003.

Lecomber AR, Faulkner K. Organ absorbed doses in intraoral dental radiography. Br J Radiol 66:1035–1041; 1993. DOI 10.1259/0007-1285-66-791-1035.

Lee C, Lee SS, Kim JE, Huh KH, Yi WJ, Heo MS, Choi SC. Comparison of dosimetry methods for panoramic radiography: thermoluminescent dosimeter measurement versus personal computer-based Monte Carlo method calculation. Oral

Surg Oral Med Oral Pathol 121:322–329; 2016. DOI 10.1016/j.oooo.2015.10.030.

Lee W. Comparative radiation doses in dental radiography. Oral Surg Oral Med Oral Pathol 37:962–968; 1974. DOI 10.1016/0030-4220(74)90449-6.

Lin MC, Lee CF, Lin CL, Wu YC, Wang HE, Chen CL, Sung FC, Kao CH. Dental diagnostic x-ray exposure and risk of benign and malignant brain tumors. Ann Oncol 2:1675–1679; 2013. DOI 10.1093/annonc/mdt016.

Lindfors N, Lund H, Johansson H, Ekestubbe A. Influence of patient position and other inherent factors on image quality in two different cone beam computed tomography (CBCT) devices. Eur J Radiol Open 4:132–137; 2017. DOI 10.1016/j.ejro.2017.10.001.

Maruyama T, Nishizawa K, Hashizume T. Estimation of population doses form dental radiography in Japan. J Dent Radiol 17:52–53; 1977.

Mason RA. A guide to dental radiography. New York: John Wright; 1988.

Mathews JD, Forsythe AV, Brady Z, Butler MW, Goergen SK, Byrnes GB, Giles GG, Wallace AB, Anderson PR, Guiver TA, McGale P, Cain TM Dowty JG, Bickerstaffe AC, Darby SC. Cancer risk in 680000 people exposed to computed tomography scans in childhood or adolescence: data linkage study of 11 million Australians. BMJ 346:f2360; 2013. DOI 10.1136/bmj.f2360.

Melo DR, Miller DL, Chang L, Moroz B, Linet MS, Simon SL. Organ doses from diagnostic medical radiography—trends over eight decades (1930 to 2010). Health Phys 111:235–255; 2016. DOI 10.1097/HP.0000000000000524.

Memon A, Godward S, Williams D, Siddique I, Al-Saleh K. Dental x-rays and the risk of thyroid cancer: a case-control study. Acta Oncol 49:447–453; 2010. DOI 10.3109/02841861003705778.

Moyal A. Nationwide evaluation of x-ray trends (NEXT) tabulation and graphical summary of the 1999 dental radiography. Rockville, MD: Conference of Radiation Control Program Directors, Inc; CRCPD Publication E-03-6-a; 2003.

National Research Council. Health risks from exposure to low levels of ionizing radiation: BEIR VII Phase 2. Washington, DC: National Academies Press; 2006.

Picano E, Vano E, Domenici L, Bottai M, Thierry-Chef I. Cancer and non-cancer brain and eye effects of chronic low-dose ionizing radiation exposure. BMC Cancer 12:157; 2012. DOI 10.1186/1471-2407-12-157.

Preston-Martin S, Thomas DC, White SC, Cohen D. Prior exposure to medical and dental x-rays related to tumors of the parotid gland. J Natl Cancer Inst 80:943–949; 1988.

Preston-Martin S, White SC. Brain and salivary gland tumors related to prior dental radiography: implications for current practice. J Am Dent Assoc 120:151–158; 1990.

Preston-Martin S, Pogoda JM. Estimation of radiographic doses in a case-control study of acute myelogenous leukemia. Health Phys 84:245–259; 2003.

Richards AG. Roentgen-ray doses in dental roentgenography. J Am Dent Assoc 56:351–368; 1958.

Richards AG, Colquitt WN. Reduction in dental x-ray exposures during the past 60 years. J Am Dent Assoc 103:713–718; 1981.

Richards AG, Webber RL. Dental x-ray exposure of sites within the head and neck. Oral Surg Oral Med Oral Pathol 18: 752–756; 1964.

Rogers R. Radiation dose to the skin in diagnostic radiography. Br J Radiol 42:511–518; 1969. DOI 10.1259/0007-1285-42-499-511.

RTI. From radiation to information/x-ray quality assurance [online]. 2016. Available at ***http://rtigroup.com/***. Accessed on 28 June 2018.

Sante LR. Manual of roentgenology tech. Ann Arbor, MI: Edward Brothers, Inc.; 1949.

Serro R, Carreiro JV, Galvao JP, Reis R. Population dose assessment from radiodiagnosis in Portugal. Radiat Protect Dosim 43:65–68; 1992. DOI 10.1093/rpd/43.1-4.65.

Simon SL. Organ-specific external dose coefficients and protective apron transmission factors for historical dose reconstruction for medical personnel. Health Phys 101:13–27; 2011. DOI 10.1097/HP.0b013e318204a60a.

Stanford RW, Vance J. The quantity of radiation received by the reproductive organs of patients during routine diagnostic x-ray examinations. Br J Radiol 28:266–273; 1955. DOI 10.1259/0007-1285-28-329-266.

Syriopoulos K, Velders XL, Van der Stelt PF, Van Ginkel FC, Tsiklakis K. Mail survey of dental radiographic techniques and radiation doses in Greece. Dentomaxillofac Radiol 27: 321–328; 1998. DOI 10.1038/sj/dmfr/4600385.

Tapiovaara M, Lakkisto M, Servomaa A. PCXMC: a PC-based Monte Carlo program for calculating patient doses in medical x-ray examinations. Helsinki: Finnish Centre for Radiation and Nuclear Safety; 1997.

Todd R. Dental imaging—2D to 3D: a historic, current, and future view of projection radiography. Endod Topics 31:36–52; 2014. DOI 10.1111/etp.12067.

Underhill TE, Chilvarquer I, Kimura K, Langlais RP, McDavid WD, Preece JW, Barnwell G. Radiobiologic risk estimation from dental radiology. Part I. Absorbed doses to critical organs. Oral Surg Oral Med Oral Pathol 66:111–120; 1988.

United Nations Scientific Committee on the Effects of Atomic Radiation. Sources and effects of ionizing radiation. Vol. I, Annex A. UNSCEAR 2008 report to the General Assembly with scientific annexes. New York: United Nations; 2008.

United Nations Scientific Committee on the Effects of Atomic Radiation. Sources and effects of ionizing radiation. Vol. I: sources. UNSCEAR 2000 report to the General Assembly with scientific annexes. New York: United Nations; 2000a.

United Nations Scientific Committee on the Effects of Atomic Radiation. Sources and effects of ionizing radiation. Vol. II: effects. UNSCEAR 2000 report to the General Assembly with scientific annexes. New York: United Nations; 2000b.

Vassileva J, Stoyanov D. Quality control and patient dosimetry in dental cone beam CT. Radiat Protect Dosim 139:310–312; 2010. DOI 10.1093/rpd/ncq011.

Weissman DD, Sobkowski FJ. Comparative thermoluminescent dosimetry of intraoral periapical radiography. Oral Surg Oral Med Oral Pathol 29:376–386; 1970. DOI 10.1016/0030-4220(70)90137-4.

Whaites E. Essentials of dental radiography and radiology [e-book]. London: Churchill Livingstone; 2006.

Williamson G. Intraoral radiography: positioning and radiation protection [online]. 2006. Available at ***https://www.researchgate.net/publication/237822140_Intraoral_Radiography_Positioning_and_Radiation_Protection***. Accessed 30 April 2019.

Wohni T. Phantom measurements of absorbed doses in dental radiography. Acta Radiol Ther Phys Biol 16:194–98; 1977.

Wrzesien M, Olszewski J. Absorbed doses for patients undergoing panoramic radiography, cephalometric radiography and CBCT. Int J Occup Med Environ Health 30:705–713; 2017. DOI 10.13075/ijomeh.1896.00960.

■■