Public Health England

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PHE-CRCE-59: Dose to patients from dental radiographic X-ray imaging procedures in the UK

2017 review

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Introduction

Public Health England (PHE) and its predecessor organisations have carried out national reviews of patient dose indices at regular intervals for over 2 decades.

The last review of radiographic and fluoroscopic imaging procedures in 2010 formed the basis of the current UK National Diagnostic Reference Levels (NDRLs) for these applications (Hart et al, 2012). As it has been a significant time since the 2010 review it is necessary to carry out the next review of current practice in the UK to either confirm that the existing NDRLs are still suitable or to set new values. The current review will consider patient doses from all types of radiographic and fluoroscopic procedures. However, unlike the 2010 review it is the intention to collect and report on data in several stages. This first stage is a review of patient doses from dental radiography.

National Diagnostic Reference Levels (NDRLs) for dental radiography are currently set for a set of standard examinations, with separate NDRLs for adults and children. Dental X-ray equipment is typically far less complex than general diagnostic medical X-ray equipment, with fixed exposure parameters and collimation, meaning that there is little variation in patient exposure for the same examination. It is therefore not necessary to collect individual patient data; the doses for these standard examinations assessed during routine quality assurance testing are adequate.

NDRLs currently exist for intra-oral and panoramic radiography which are by far the most common dental X-ray modalities (PHE, 2018). For intra-oral radiography the standard examination chosen is a mandibular molar radiograph and for panoramic radiography it is the standard full panoramic radiograph. For this survey, data was also requested for cephalometric radiography and Cone Beam Computed Tomography (CBCT).

Although cephalometric radiography has been an available technique for many years, by comparison to intra-oral or panoramic radiography it is a much less common technique and, as such, was not considered in previous reviews. It was decided to include it in this review as there is evidence of a wide range of doses from the equipment currently in use (Holroyd, 2011). The examination chosen as representative for this technique is a standard lateral radiograph.

The use of CBCT equipment is a relatively recent development in dental radiography, having been in clinical use for less than 15 years. The doses delivered to patients during CBCT are typically much higher than those from other modes of dental radiography, therefore it is considered particularly important to include doses from CBCT in this review. Previous work by PHE established an achievable dose for CBCT (Holroyd and Walker, 2010) as a dose guide for users of CBCT. A lack of available data and a wide variability in patient doses meant it was not possible to set a NDRL at that time. However, CBCT equipment is now much more widely used, so in this review it was possible to obtain enough data to propose a NDRL. Unlike other dental X-ray equipment where dose data was collected for a standard examination and a standard patient, due to the wide range of uses of CBCT equipment 2 specific clinical indications were included in the request, to ensure comparable patient dose data was obtained. The clinical indications were:

a) imaging prior to placement of a maxillary molar implant in a standard adult patient, and
b) imaging of an impacted maxillary canine tooth of a 12-year-old child.

Method

An Excel (Microsoft, USA) workbook was designed to collect information on each dental X-ray set, exposure parameters and patient dose delivered for the standard examinations identified. The workbook was trialled with 1 NHS Hospital Trust that frequently carries out dose measurements on all types of dental X-ray equipment with the feedback from this Trust being used to refine the workbook.

The template workbook was posted to the MEDICAL-PHYSICS-ENGINEERING e-mail distribution list (JiscMail, 2018). This distribution list is viewed by the UK medical physics community and those who carry out dose assessments on dental X-ray equipment. A 2-month period was allowed for providing data, during November and December 2017, and regular reminder e-mails were sent during this period. Data was requested from measurements made since 2014 to account for the fact that the recommended frequency for making measurements of patient dose is every 3 years (NRPB, 2001), apart from CBCT equipment for which it should be measured annually (Holroyd and Walker, 2010). Data was only requested for sets which were currently in clinical use and for only the most recent measurement. All the data was compiled into a single workbook for analysis. Any data which appeared to be anomalous was queried with the respondent for clarification, and either confirmed or removed from the analysis. A small number of workbooks were returned shortly after the deadline and these were also included in the analysis.

Results

Data was received from 32 respondents. This covered patient dose measurements made on a total of 11,331 intra-oral X-ray sets, 1,500 panoramic X-ray sets, 152 cephalometric X-ray sets and 215 CBCT X-ray sets.

In the following tables, CR is used to denote computed radiography systems (for example, the use of phosphor plates) and DR for digital radiography systems (for example, the use of charge coupled devices or complementary metal oxide semiconductor sensors). Dose measurement results are presented as percentiles of the total dose distribution. The 50th percentile, or median, can be considered a typical dose for that examination and the 75th percentile (third quartile) is the value used to establish a NDRL for dental radiography.

Intra-oral

A breakdown of the imaging method used with each X-ray set can be seen in Table 1 and the choice of collimation is shown in Table 2.

Table 1 Choice of imaging method for intra-oral radiography

Imaging type	Number of X-ray sets	% of total	% Film or digital
D speed film	115	1%	28%
E/F speed film	361	3%	
E speed film	863	8%	
F speed film	1572	15%	
Self-developing film	7	0%	
Film (unknown type)	14	0%	
CR	5699	54%	72%
DR	1459	14%	
Digital (unknown type)	452	4%	
Total	**10542**		

Table 2 Choice of collimation for intra-oral radiography

Collimator	Number of X-ray sets	% of total
Circular	3595	33%
Rectangular	7321	67%
Total	**10961**	

The 5th to 95th percentile values for the patient dose distribution are shown in Table 3. The dose distribution was sub-divided by the choice of imaging method and the results are shown in Table 4.

Table 3 Patient entrance doses (mGy) reported for a standard adult mandibular molar intra-oral radiograph

Patient group	Number of X-ray sets	Dose (mGy) at a given percentile				
		5th	25th	50th	75th	95th
Adult	11320	0.3	0.6	0.9	1.2	2.0
Child	7888	0.2	0.4	0.6	0.7	1.2
Ratio - Child/Adult		0.6	0.6	0.6	0.6	0.6

Table 4 Intra-oral adult mandibular molar patient entrance doses (mGy) sorted by imaging method

Imaging method	Number of X-ray sets	Dose (mGy) at a given percentile				
		5th	25th	50th	75th	95th
D speed film	115	0.7	0.9	1.2	1.9	2.7
E speed film	863	0.6	0.8	1.0	1.4	2.2
E/F speed film	361	0.6	0.8	1.0	1.2	1.7
F speed film	1572	0.5	0.7	1.0	1.3	2.1
CR	5699	0.3	0.6	0.8	1.1	1.9
DR	1459	0.3	0.5	0.7	1.0	1.9

In order to visualise the range of doses delivered for the standard mandibular molar radiograph, the dose results were sorted into 0.2 mGy bins and a histogram plotted to show the range of doses for adult examinations (Figure 1) and child examinations (Figure 2).

Figure 1 Dose distribution for adult intra-oral mandibular molar radiographs. The vertical bar approximately represents the third quartile value.

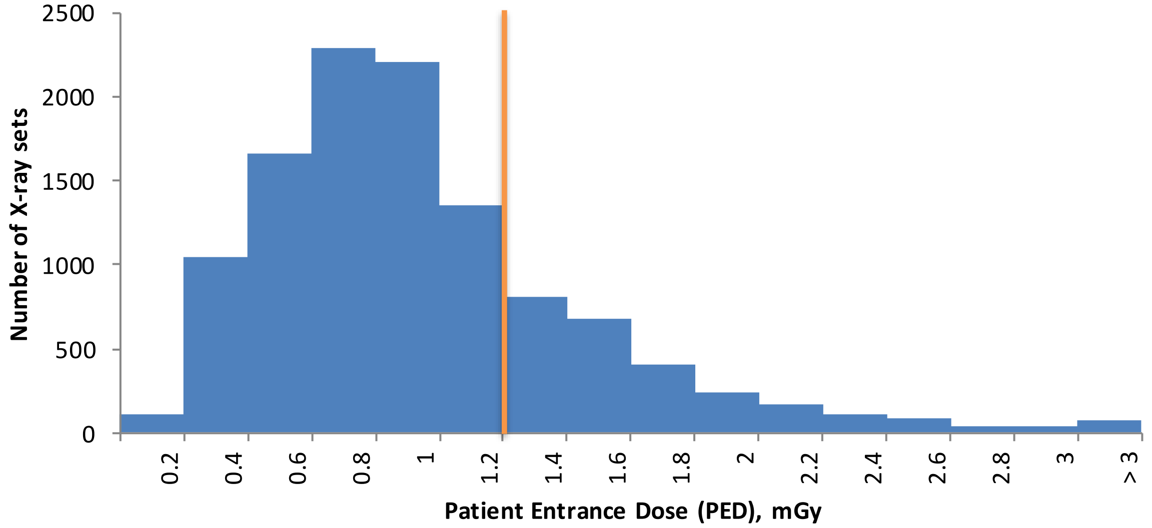
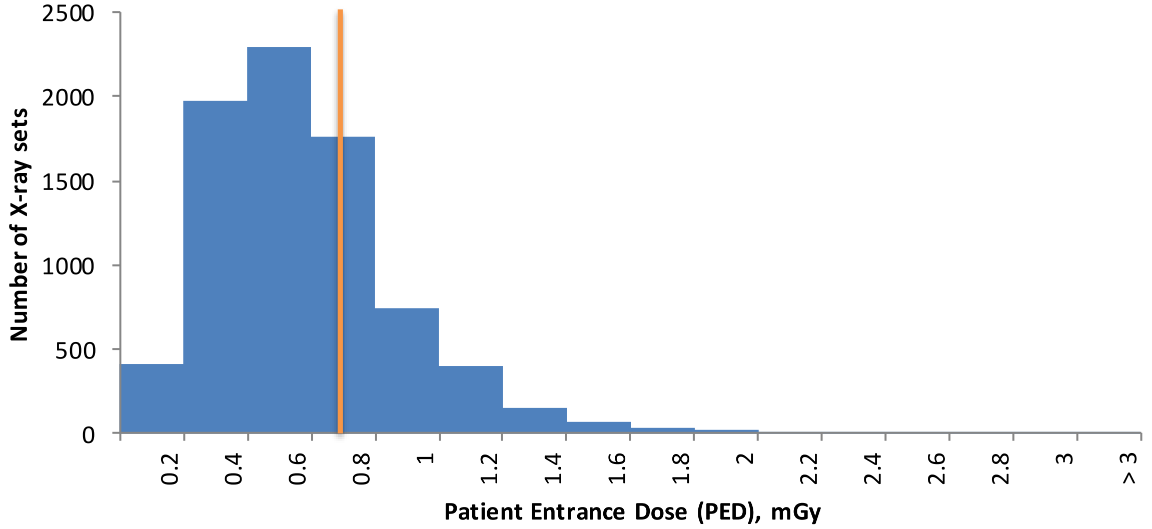
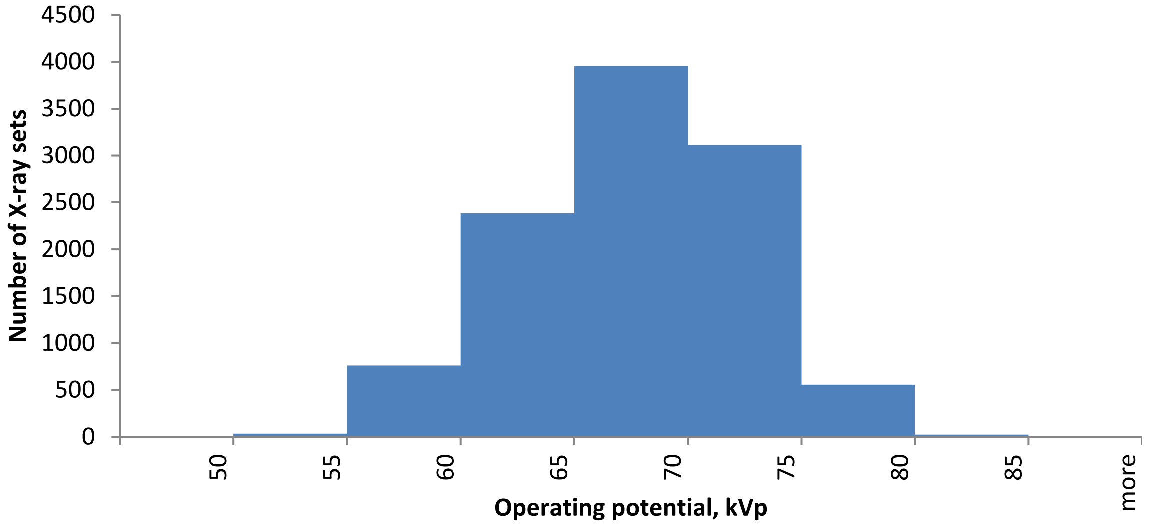


Figure 2 Dose distribution for child intra-oral mandibular molar radiographs. The vertical bar approximately represents the third quartile value.



The operating potential for each X-ray set is shown in Figure 3. Data was requested for the actual operating potential as measured during the most recent equipment testing; however, it was apparent from the data received that some data were a measured operating potential and other data were the rated operating potential for that X-ray set. Figure 3 includes all the data received, which provides useful information on likely operating potentials in use, but as it combines both measured and rated values, more meaningful analysis is not possible.

Figure 3 Distribution of operating potential for intra-oral X-ray sets



Panoramic

The different types of image receptor in use are shown in Table 5.

Table 5 Choice of imaging method for panoramic radiography

Imaging method	Number of X-ray sets	% of total	% Film or digital
Film	290	23%	23%
CR	238	19%	
DR	560	44%	77%
Digital (unknown type)	179	14%	
Total	**1267**		

The 5th to 95th percentile values for the patient dose distribution are shown in Table 6. The dose distribution was sub-divided by choice of imaging method and the results are shown in Table 7

Table 6 Dose area product ($mGy.cm^2$) reported for a standard panoramic radiograph

Patient size	Number of X-ray sets	Dose area product ($mGy.cm^2$) at a given percentile				
		5th	25th	50th	75th	95th
Adult	1499	28	49	65	81	119
Child	1435	18	34	46	60	85
Ratio - Child/Adult		0.7	0.7	0.7	0.7	0.7

Table 7 Standard panoramic adult dose area product ($mGy.cm^2$) sorted by imaging method

Imaging	Number of X-ray sets	Dose area product ($mGy.cm^2$) at a given percentile				
		5th	25th	50th	75th	95th
Film	289	38	56	69	82	120
CR	238	34	55	69	80	109
DR	560	27	48	64	81	118

The dose results were sorted into 10 $mGy.cm^2$ bins and a histogram plotted to show the range of doses for adult examinations (Figure 4) and child examinations (Figure 5).

Figure 4 Dose distribution for standard adult panoramic radiographs. The vertical bar approximately represents the third quartile value.

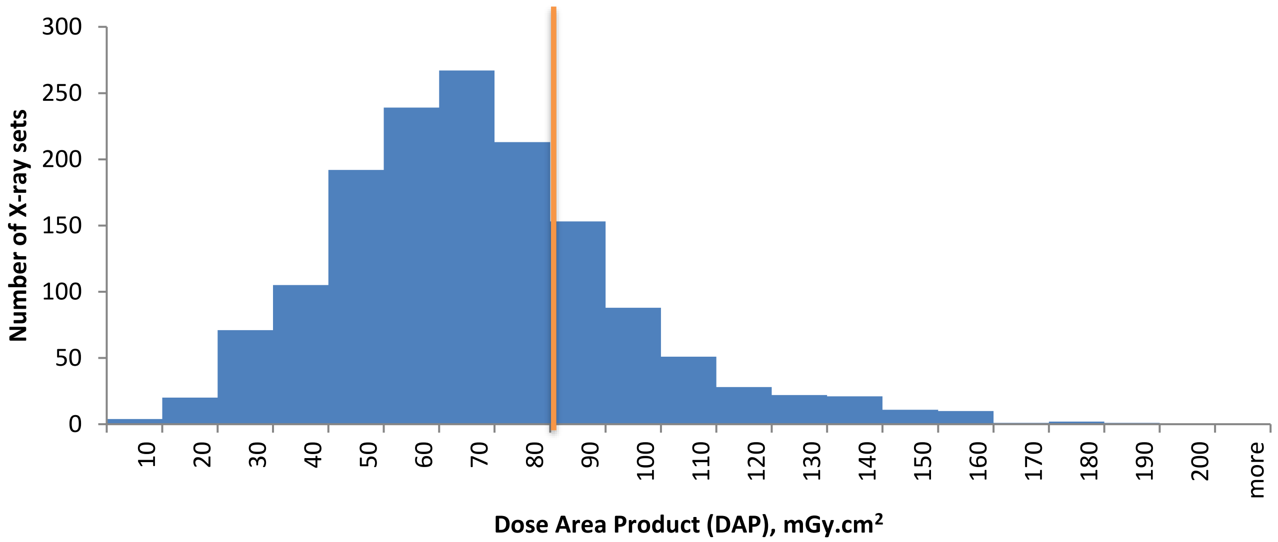
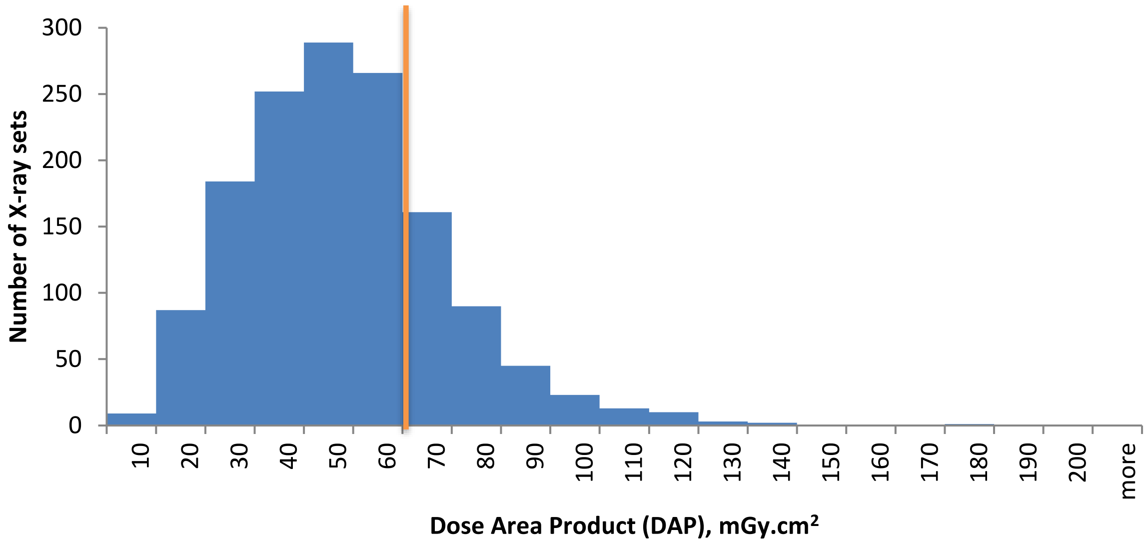


Figure 5 Dose distribution for standard child panoramic radiographs. The vertical bar approximately represents the third quartile value.



Lateral cephalometric

The different types of image receptor in use are shown in Table 8.

Table 8 Choice of imaging method for cephalometric radiography

Imaging method	Number of X-ray sets	% of total	% Film or digital
Film	14	9%	9%
CR	17	11%	91%
DR	120	79%	
Total	**151**		

For DR imaging there are 2 methods that can be used for image capture. The entire image is captured in a single short duration exposure (static method), as for film and CR systems, or a narrow X-ray beam is scanned across the patient to acquire the image (scanning method). The number of each type of system included in this study is shown in Table 9.

Table 9 Choice of DR system for cephalometric radiography

DR imaging method	Number of X-ray sets
Scanning	87
Static	33
Total	**120**

The 5th to 95th percentile values for the DAP distribution are shown in Table 10. The adult DAP distribution was sub-divided by choice of imaging and the results are shown in Table 11.

Table 10 Dose area product ($mGy.cm^2$) reported for a lateral cephalometric radiograph

Patient size	Number of X-ray sets	Dose area product ($mGy.cm^2$) at a given percentile				
		5th	25th	50th	75th	95th
Adult	150	8	17	24	35	74
Child	143	7	14	20	24	53
Ratio - Child/Adult		0.8	0.8	0.9	0.7	0.7

Table 11 Adult lateral cephalometric dose area product ($mGy.cm^2$) sorted by imaging method

Imaging method	Number of X-ray sets	Dose area product ($mGy.cm^2$) at a given percentile				
		5th	25th	50th	75th	95th
Film	14	15	28	37	39	50
CR	17	19	27	31	46	58
DR (all)	118	8	16	22	32	87
DR (static)	32	25	32	37	69	107
DR (scanning)	86	6	13	19	23	35

Table 12 details the dose incident on the detector, sorted by the choice of imaging method.

Table 12 Adult dose measured at the detector (mGy) for a lateral cephalometric examination, sorted by imaging method

Imaging method	Number of X-ray sets	Dose (mGy) at a given percentile				
		5th	25th	50th	75th	95th
Film	9	0.07	0.08	0.10	0.11	0.14
CR	8	0.05	0.08	0.10	0.12	0.15
DR (static)	21	0.05	0.08	0.09	0.13	0.28
DR (scanning)	71	0.28	0.85	1.60	2.25	3.85

The dose results were sorted into 10 $mGy.cm^2$ bins and a histogram plotted to show the range of doses for adult examinations (Figure 6) and child examinations (Figure 7).

Figure 6 Dose distribution for adult lateral cephalometric radiographs. The vertical bar approximately represents the third quartile value

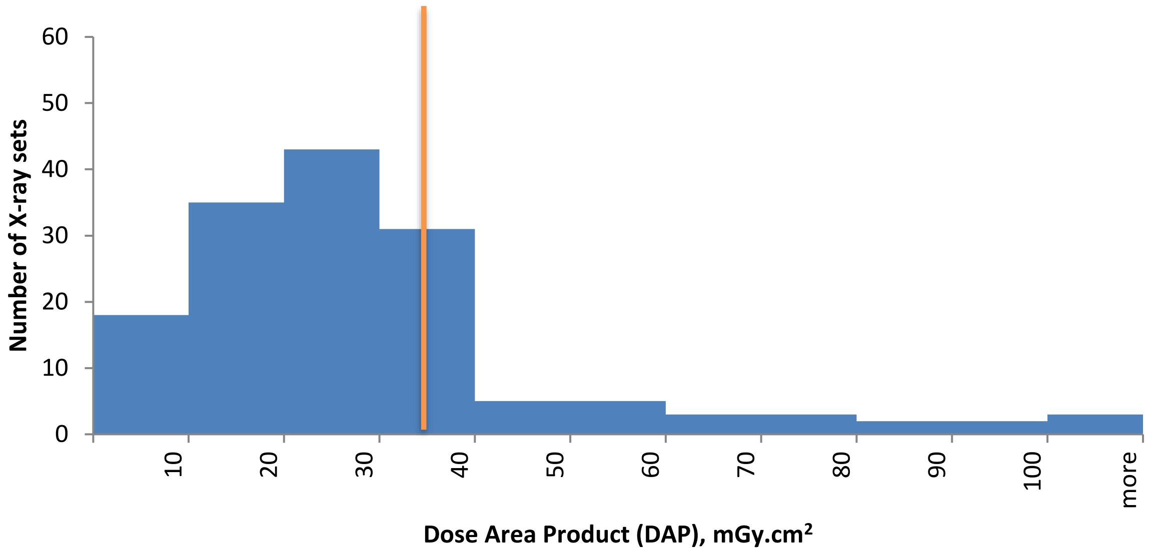


Figure 7 Dose distribution for child lateral cephalometric radiographs. The vertical bar approximately represents the third quartile value

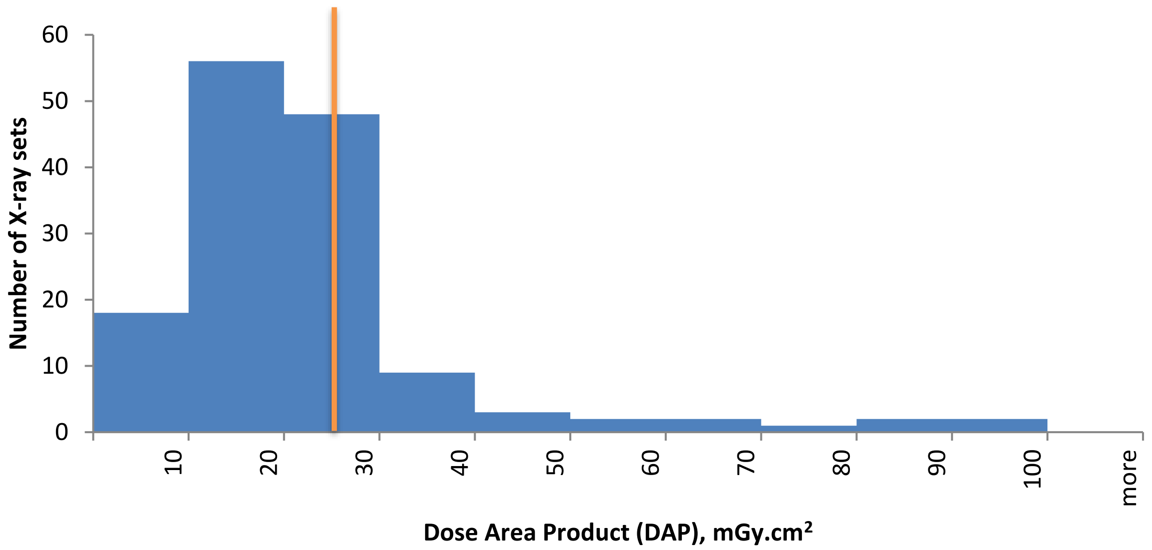


Table 13 details a summary of the beam size measurements, sorted by choice of imaging method.

Table 13 Range of lateral cephalometric beam sizes measured at the detector

Beam size (mm)	Film	CR	DR (static)	DR (scanning)
Average Width	170	177	203	6
Minimum Width	140	150	130	3
Maximum Width	232	240	260	10
Average Height	213	223	248	217
Minimum Height	172	160	190	147
Maximum Height	230	300	325	275

Cone beam computed tomography

The 5th to 95th percentile values for the DAP distribution are shown in Table 14.

Table 14 CBCT dose area product (mGy.cm^2) reported

Patient size	Number of X-ray sets	Dose area product (mGy.cm^2) at a given percentile				
		5th	25th	50th	75th	95th
Adult[1]	214	112	164	217	265	458
Child[2]	135	62	86	138	169	335
Ratio - Child/Adult		0.6	0.5	0.6	0.6	0.7

The dose results were sorted into 50 mGy.cm^2 bins and a histogram plotted to show the range of doses for adult examinations (Figure 8) and child examinations (Figure 9).

[1] Imaging prior to placement of a maxillary molar implant in a standard adult patient.
[2] Imaging of an impacted canine tooth of a 12-year-old child.

Figure 8 Dose distribution for adult CBCT radiographs. The vertical bar approximately represents the third quartile value.

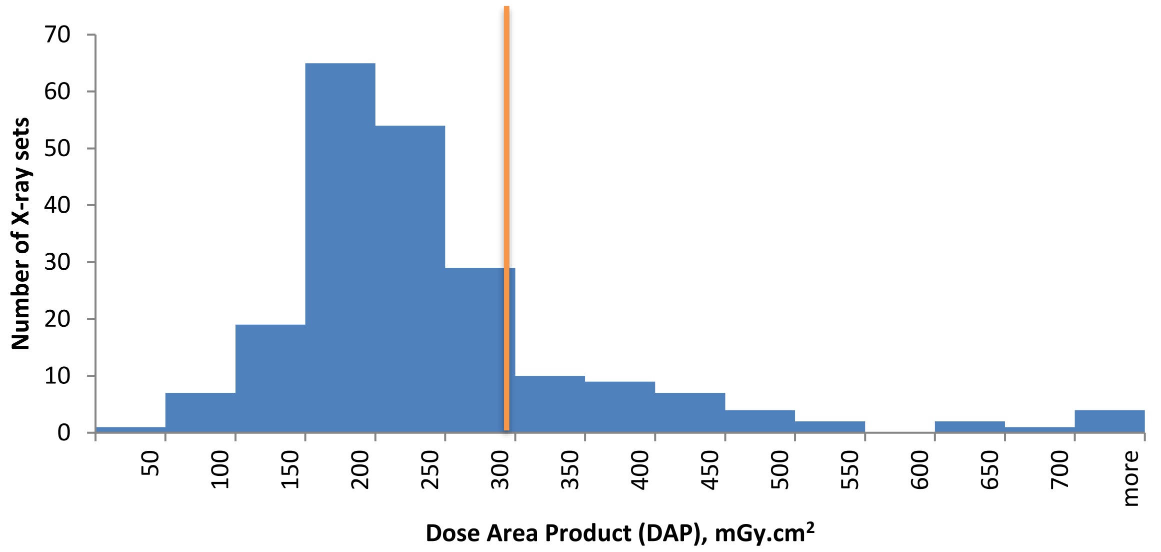


Figure 9 Dose distribution for child CBCT radiographs. The vertical bar approximately represents the third quartile value.

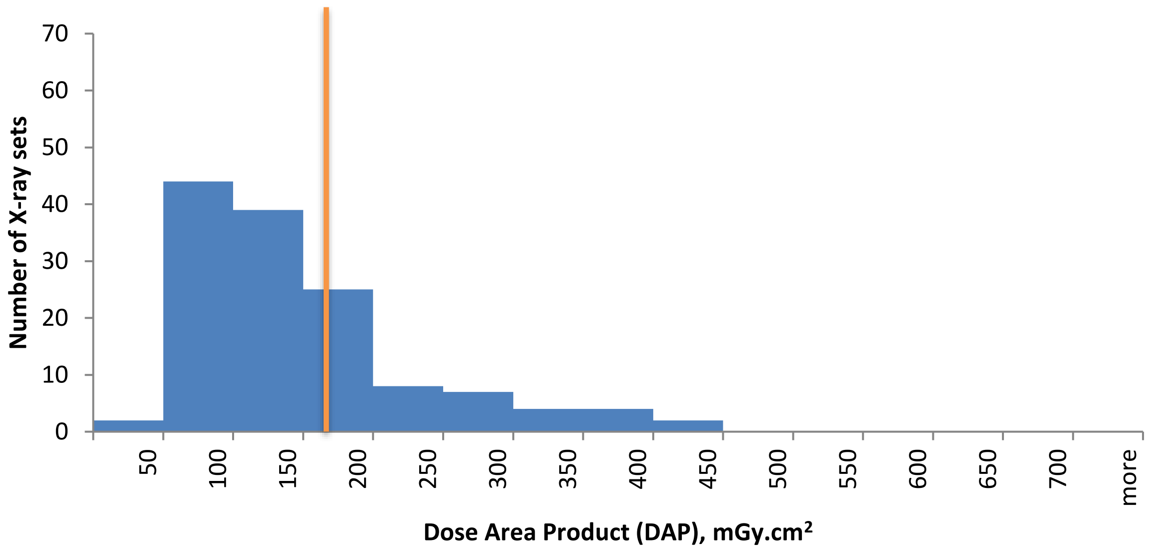


Table 15 shows the average, minimum and maximum beam area used by CBCT equipment, as measured at the detector.

Table 15 Range of CBCT beam sizes measured at the detector

	Adult	Child
Number	185	117
Average area (cm^2)	67	64
Minimum area (cm^2)	27	27
Maximum area (cm^2)	253	160

Summary of typical doses

Table 16 shows the median doses for each X-ray examination. The median dose can be viewed as the typical dose for an examination and is a useful tool to aid optimisation. Compared to the NDRL it may more closely represent an optimum dose (ICRP, 2017).

Table 16 Summary of median doses for all types of dental imaging

X-ray type	Patient size (clinical indication)	Median dose
Intra oral	Adult mandibular molar	0.9 mGy
	Child mandibular molar	0.6 mGy
Panoramic	Standard full adult	65 $mGy.cm^2$
	Standard full child	46 $mGy.cm^2$
Cephalometric	Adult lateral	24 $mGy.cm^2$
	Child lateral	20 $mGy.cm^2$
Dental CBCT	Adult (imaging prior to placement of a maxillary molar implant)	217 $mGy.cm^2$
	Child (imaging of an impacted maxillary canine of a 12 year old child)	138 $mGy.cm^2$

Discussion

Representation

The locations of the respondents were:
- 24, England
- 4, Scotland
- 3, Wales
- 1, Northern Ireland

The individual X-ray set data did not include specific locations, and some respondents may cover a larger geographical area than 1 nation, however, this shows that data was received from across the UK. Data was received from private dental practices, NHS practices and NHS hospital-based practice.

As of 2017 there were 12,010 dental practices in the UK (Office for National Statistics, 2018). There is no available data on the total number of X-ray sets in use in the UK, however, data available from PHE's radiation protection services to dental practices indicates that there are on average approximately 2.5 intra-oral X-ray sets per practice. This data also indicates that around 27% of practices have panoramic X-ray equipment, 5% have cephalometric equipment and 9% have CBCT equipment. If these values are extrapolated to the total number of UK dental practices, it would imply that the data submitted to this survey represents around 37% of intra-oral sets, 46% of panoramic sets, 23% of cephalometric sets and 19% of CBCT sets in the UK. These numbers confirm that this survey is a reasonable guide to UK practice.

Digital imaging

In the 2010 review, 27% of intra-oral X-ray sets were being used with digital imaging (CR or DR systems) compared to 72% in this review, indicating a significant increase in the number of dental practices using digital imaging. Digital imaging is typically associated with lower patient doses than film imaging (Doyle and Finney, 2005; Berkhout et al., 2004) and this is evidenced in Table 4, with the median dose for digital systems 20-30% lower than that for F-speed film.

For panoramic imaging, digital imaging is far more common than film, with 77% of sets using some form of digital imaging. However, unlike intra-oral radiography, there does not appear to be a significant reduction in patient dose with the use of a digital system.

Cephalometric imaging

Digital imaging in cephalometry can utilise 1 of 2 methods. Scanning systems employ a narrow X-ray beam and detector, like panoramic radiography, which is scanned across the patient to produce an image. Static systems employ a large X-ray beam and detector, like traditional film-based systems. The DAP values presented in Table 11 show a clear difference between the 2 methods, as has previously been highlighted (Holroyd, 2011). The median DAP for scanning systems is 19 mGy.cm^2 versus 37 mGy.cm^2 for static systems. It is difficult to suggest a reason for this difference; however, scanning systems can provide a considerable dose saving to the patient and for a dental practice considering updating to digital technology this should certainly be taken into consideration.

The design of static systems is comparable to film systems, so it is possible to provide a comparison. The median dose to the film or detector is approximately the same (Table 12), however the average size of the image is 17 cm x 21 cm for film and 20 cm x 25 cm for static systems (Table 13). This is an increase in area of around 40%, which may explain the difference in DAP values between the two. There is no apparent technical reason why a digital system would require a larger image to be generated. When purchasing new equipment, an important consideration is the selection of equipment that gives the smallest field size necessary.

Dental CBCT

Dental CBCT is a relatively recent introduction. It was in very limited use at the time of the last national patient dose review and was therefore not considered. For this review, data was provided for over 200 units, highlighting the rapid adoption of this technology. Table 16 shows that CBCT is generally associated with higher patient doses than other forms of dental imaging. Comparing median DAP values, the patient dose is approximately 3-times higher than for a panoramic radiograph.

Different models of CBCT set allow a range of image sizes (fields of view), ranging from capturing a single tooth to the entire head. For this review, limited data was provided on the field of view used, however there was a good amount of data presented on the beam size measured at the detector, which is reasonably well correlated with field of view size.

Table 15 shows the range of beam areas measured. For adults, this shows a factor of approximately 10 from minimum to maximum size. As data for this review was requested for imaging a single tooth, it would be expected that a small field of view option would be selected. This data suggests this is not always the case, which may be either because the operator has chosen too large a field of view; or it may be that the equipment is not provided with a small field of view option (approximately 5 cm x 5 cm or smaller).

National DRLs

National DRLs have been typically set at a rounded 75th percentile of the dose distribution. The values presented in Table 17 are proposed as new NDRLs for the UK.

Table 17 Proposed NDRLs

X-ray type	Patient size (clinical indication)	Proposed NDRL
Intra oral	Adult mandibular molar	1.2 mGy
	Child mandibular molar	0.7 mGy
Panoramic	Adult full jaw	81 mGy.cm^2
	Child full jaw	60 mGy.cm^2
Cephalometric	Adult lateral	35 mGy.cm^2
	Child lateral	24 mGy.cm^2
Dental CBCT	Adult (imaging prior to placement of a maxillary molar implant)	265 mGy.cm^2
	Child (imaging of an impacted maxillary canine of a 12 year old child)	170 mGy.cm^2

Comparing these values to the current NDRLs shows that there has been a significant reduction in the third quartile value of patient dose distribution for a standard adult intra-oral mandibular molar examination (29%). This is likely to be due to the increased adoption of digital imaging detectors, which require lower radiation exposure to produce a clinically acceptable image than the film that they have replaced. There have also been small decreases in patient doses delivered during both adult (13%) and child (10%) panoramic radiography. These smaller decreases perhaps reflect the fact that there is not a significant dose saving to be made using digital detectors in panoramic radiography, although there are some models of digital systems which can operate with reduced exposure compared to film or computed radiography systems.

Although there are no NDRLs for lateral cephalometric radiography, a 2011 paper (Holroyd, 2011) reported third quartile DAP values of 40 mGy.cm2 and 25 mGy.cm2 for adult and child radiography from a national dose survey. These are broadly in agreement with the values presented in this report.

For dental CBCT an achievable dose of 250 mGy.cm2 has previously been recommended for adult imaging (Holroyd and Walker, 2010). The proposed NDRL in this paper is similar, suggesting that many practices have been able to meet the achievable dose.

Dose trends

PHE has carried out regular dose surveys approximately every 5 years since 1999 for intra-oral and panoramic radiography. Table 18 shows the third quartile values of the adult dose distributions for each dose survey (Napier, 1999; Hart et al., 2007; Hart et al., 2012). This shows that patient doses from intra-oral radiography have significantly decreased in this time, whereas panoramic doses have stayed broadly similar. This can be explained by the dose saving provided by the adoption of digital intra-oral systems and the use of equipment with higher operating potentials. For panoramic radiography, digital systems do not appear to offer the same potential for dose saving.

Table 18 Summary of PHE dose survey results from 1998 to present

Year of data collection	1998	2005	2010	2017 (current)
Intra-oral (mGy)	3.9	2.3	1.7	1.2
Panoramic (mGy.cm^2)	92	82	93	81

While there has been a gradual reduction in patient dose from dental examinations in the UK, it is useful to compare UK doses to other countries. Table 19 shows published NDRLs in other countries (Kim et al., 2012; Kim et al., 2014; Rocha et al., 2018; Poppe et al., 2007a, 2007b; Looe et al., 2007; Grey et al., 2004; Tierris et al., 2004; Alcaraz et al., 2010).

Table 19 Summary of published national DRLs outside the UK

Country	Exam details	Year	Intra-oral	Panoramic	Cephalometric
South Korea	Adult lower molar	2012	3.1		
	Child exam	2014		96	121
France	Adult exam	2018		136	
Germany	Adult lower molar, Adult male panoramic, Adult lateral cephalometric	2006	1.5	87	32.6
US	Adult bitewing	2005	2.3		
Greece	Adult male pan	2004		117	
	Upper molar	2013	2.75		
Spain	Upper molar	2010	3.6		

The authors were unable to find any published NDRLS for CBCT radiography. Although some of these studies are for different examinations (for example, examinations of children or different intra-oral teeth), the proposed UK NDRLs are lower than most other published values and comparable to the values in Germany. This may be in part due to the long-established process of patient dose reviews carried out in the UK.

Conclusion

As a result of this review, PHE recommends the establishment of new NDRLs for child intra-oral radiography, lateral cephalometric radiography and dental CBCT imaging and updates to the existing NDRLs for adult intra-oral and adult and child panoramic imaging. The NDRL for adult intra-oral radiography has decreased significantly when compared to the previous value; and the NDRLs for panoramic radiography are slightly reduced. When compared with NDRLS established in other countries, the UK NDRLs are generally lower and this may be in part due to the long-established process in the UK of periodically reviewing patient doses and regularly updating NDRLs.

References

Alcaraz M.,Velasco E.,Martınez-Beneyto Y.,Velasco F.,Armero D.,Parra C. and Canteras M., 2010. The status of Spain’s dental practice following the European Union directive concerning radiological installations: 11 years on (1996–2007). Dentomaxillofacial Radiology, 39, pp.468–474.

Berkhout, W.E.R., Beuger, D.A., Sanderink, G.C.H. and van der Stelt, P.F., 2004. The dynamic range of digital radiographic systems: dose reduction or risk of overexposure? Dentomaxillofacial Radiology, 33, pp.1-5.

Doyle, P. and Finney, L., 2005. Performance Evaluation and Testing of Digital Intra-Oral Systems. Radiation Protection Dosimetry, 117(1-3), pp.313-317.

Eun-Kyung Kim, Won-Jeong Han, Jin-Woo Choi, Yun-Hoa Jung*, Suk-Ja Yoon**, Jae-Seo Lee, 2012. Diagnostic reference levels in intraoral dental radiography in Korea. Imaging Science in Dentistry, 42, pp.237-42.

Gray, J.E., Archer, B.R., Butler, P.F., Hobbs, B.B., Mettler, F.A., Pizzutiell, R.J., Schueler, B.A., Strauss, K.J., Suleiman, O.H. and Yaffe, M.J., 2005. Reference Values for Diagnostic Radiology: Application and Impact. Radiology, 235, pp.354-358.

Hart, D., Hillier, M.C., Wall, B.F., 2007. HPA-RPD-029. Doses to Patients from Radiographic and Fluoroscopic X-ray Imaging Procedures in the UK - 2005 Review. Chilton, Oxford: Health Protection Agency.

Hart, D., Hillier, M.C. and Shrimpton, P.C., 2012. HPA-CRCE-034. Doses to Patients from Radiographic and Fluoroscopic X-ray Imaging Procedures in the UK - 2010 Review. Chilton, Oxford: Health Protection Agency.

Holroyd, J.R. 2011. National reference doses for dental cephalometric radiography. British Journal of Radiology, 84(1008), pp.1121–1124.

Holroyd, J.R. and Walker, A. 2010. HPA-RPD-065. Recommendations for the Design of X-ray Facilities and the Quality Assurance of Dental Cone Beam CT (Computed Tomography) Systems. Chilton, Oxford: Health Protection Agency.

International Commission on Radiological Protection (ICRP), 2017. Diagnostic reference levels in medical imaging. ICRP Publication 135. Ann. ICRP 46(1).

JiscMail. Medical-physics-engineering mailing list. 2018. Available from: http://www.jiscmail.ac.uk/MEDICAL-PHYSICS-ENGINEERING [cited 6 February 2018]

Kim, Y., Yang, B.,Yoon, S., Kang, B. and Lee, J., 2014. Diagnositc reference levels for panoramic and lateral cephalometric radiography of Korean children. Health Physics, 107(2), pp.111-116.

Looe, H.K., Eenboom, F.,Chofor, N., Pfaffenberger, A.,Sering, M., Rühmann, A., Poplawski, A., Willborn, K. and Poppe, B., 2007. Dose-area product measurements and determination of conversion coefficients for the estimation of effective dose in dental lateral cephalometric radiology. Radiation Protection Dosimetry, 124(2), pp.181-186.

Manousaridis G., Koukorava C., Hourdakis, C. J.,Kamenopoulou V.,Yakoumakis, E. and Tsiklakis, K., 2013. Establishment of diagnostic reference levels for dental intraoral radiography. Radiation Protection Dosimetry, 156(4), pp.455–457.

National Radiological Protection Board (NRPB), 2001. Guidance Notes for Dental Practitioners on the Safe Use of X-ray Equipment. Chilton, Oxford: NRPB.

Office for National Statistics. Freedom of information request FOI 3748. Available at https://www.ons.gov.uk/aboutus/transparencyandgovernance/freedomofinformationfoi/numberofdentistsanddentalpracticesintheuk (accessed May 2018).

Poppe, B., Looe, H.K., Pfaffenberger, A., Eenboom, F., Chofor, N., Sering, M., Ruhmann, A., Poplawski, A. and Willborn, K., 2007a. Radiation Exposure and Dose Evaluation in Intraoral Dental Radiology. Radiation Protection Dosimetry, 123(2), pp.262-267.

Poppe, B., Looe, H.K., Pfaffenberger, A., Chofor, N., Eenboom, F., Sering, M., Ruhmann, A., Poplawski, A. and Willborn, K., 2007b. Dose-area product measurements in panoramic dental radiology. Radiat Prot Dosimetry, 123(1), pp.131-134.

Public Health England. 2018. National Diagnostic Reference Levels (NDRLs). Available at: https://www.gov.uk/government/publications/diagnostic-radiology-national-diagnostic-reference-levels-ndrls. Accessed 10 April 2019.

Rocha, P., Céliera D., Dessaudb, C., Etarda, C., 2018. Using diagnostic reference levels to evaluate the improvement of patient dose optimisation and the influence of recent technologies in radiography and computed tomography. European Journal of Radiology, 98, pp.68–74.

Tierris, C.E., Yakoumakis, E.N., Bramis, G.N. and Georgiou, E., 2004. Dose Area Product Reference Levels in Dental Panoramic Radiography. Radiation Protection Dosimetry, 111(3), pp.283-287.

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