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Occupational radiation exposure among dental practitioners using digital intraoral and panoramic imaging systems: A systematic review and meta-analysis

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► ***Review article***

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ABSTRACT

Background: Digital intraoral and panoramic radiography have significantly reduced patient radiation exposure; however, occupational exposure among dental practitioners in the digital era requires quantitative synthesis. This systematic review and meta-analysis aimed to estimate mean occupational radiation dose among dental professionals using digital 2D imaging systems and to explore heterogeneity sources. ***Materials and Methods:*** Five electronic databases were searched from January 2000 to January 2025 following PRISMA 2020 guidelines. Observational and experimental studies reporting quantitative occupational dose measurements (mSv/µSv) were included. Risk of bias was assessed using ROBINS-E and ROB-2 tools. A random-effects meta-analysis was performed. Heterogeneity was evaluated using I^2 statistics, and subgroup analyses were conducted based on practitioner type and imaging system. ***Results:*** Ten studies met inclusion criteria. The pooled correlation effect size was 0.11 (95% CI: 0.06–0.54; p=0.004), with extremely high heterogeneity (I^2=99.94%). Subgroup analysis showed dentists had a higher pooled mean dose estimate (0.91 mSv; 95% CI: −0.01 to 1.82) compared to mixed dental staff (0.08 mSv; p=0.000 for subgroup difference). No significant differences were observed between handheld, panoramic, and mixed digital systems. Meta-regression demonstrated a weak but statistically significant association between mean dose and effect size (slope=0.02; p=0.050). ***Conclusion:*** Occupational radiation exposure in digital dentistry remains substantially below international safety limits but demonstrates significant variability. Practitioner behaviour and workflow factors appear more influential than equipment type, reinforcing strict adherence to ALARA principles.

INTRODUCTION

Radiation exposure at work in dentistry is a long-standing and serious work-related health issue. The dental practitioners such as the dentists, dental hygienists and dental assistants regularly engage in the acquisition and processing of radiographic images that are diagnostic. Although the introduction of digital radiography, which consists of digital intraoral sensors and panorama imaging systems, significantly decreased the radiation dose to patients relative to the traditionally used film-based methods, its effect on the occupational dose to practitioners should be critically considered [(1)]. The exposure parameters and the workflow are considered to be the core difference, but the closeness of the operator to the X-ray source and the number of examinations is the major factors of cumulative occupational exposure [(2)].

Ionizing radiation is an already known carcinogen, and the chronic exposure at low doses, including that which is deemed to be safe, presents a stochastic risk of malignancies and other adverse effects. In the case of dental personnel scattered radiation of the patient head is the main one, and the thyroid gland, eyes (lens), and hands are the most susceptible anatomical locations [(3)]. Occupational exposure to radiations has been restricted to very low levels per year by national and international organizations, including the International Commission on Radiological Protection (ICRP) and the National Council on Radiation Protection and Measurements (NCRP) (with the effect that such exposure should be kept as low as reasonably achievable), (ALARA) [(4)].

The coming of the digital imaging with the help of the transition of the film to digital imaging was supposed to make the industry safer. Digital intraoral perioral sensors make use of charge-coupled devices (CCD) and complementary metal-oxide-semiconductor (CMOS) and photostimulable phosphor plates (PSP); these devices are more sensitive, and exposure time per image should theoretically reduce by 50-80%. In a similar manner, the current digital panoramic units tend to have the features of collimation enhancement and high-speed detectors. However, this dose decreases at the detector do not necessarily translate to a corresponding decrease in the amount of scatter radiation which is the primary cause of operator exposure [(5)]. Moreover, this very sense of security of digital systems can be a source of complacency (e.g. not using personal protective gear e.g. thyroid collars, lead aprons) or not keeping safe distances during exposure, which can defeat the tech advantages [6].

Although the practice is common, the data on the real level of occupational dose in the digital age is diverse. Various methodologies have been used in the studies, like thermoluminescent dosimeters (TLDs) attached to different body parts, use of direct ion chambers, practice patterns surveys. Reported doses can be no more than small portions of the limit in a year, and may even be close to alarming cumulative values in large volume practice [7]. The discrepancy here highlights the necessity of a synthesized and quantitative analysis.

Hence, this systematic review and meta-analysis were done to synthesize the available data in order to determine the mean occupational radiation exposure of dental practitioners using digital intra oral imaging systems and panoramic imaging systems in particular. Through a critical review of the literature and a synthesis of data where necessary, this review aims at demystifying the existing risk situation, aiding the factors that escalate exposure, and providing evidence-based recommendations to streamline radiation safety standards in the contemporary dental practice.

This study represents the first quantitative synthesis exclusively evaluating occupational radiation exposure associated with digital two-dimensional intraoral and panoramic imaging systems, excluding CBCT modalities. Furthermore, it provides subgroup analyses based on practitioner role and equipment type while investigating heterogeneity sources using meta-regression, thereby offering practical insights into exposure determinants in contemporary digital dental practice.

MATERIALS AND METHODS

The systematic review and meta-analysis will be done and reported following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement [8]. The protocol was registered in prospect at the International Prospective Register of Systematic Reviews (PROSPERO).

Rationale and execution of the systematic literature search

The search strategy was carefully planned to reach the highest levels of sensitivity and specificity of literature identification. There were five major multidisciplinary and biomedical databases that were chosen to guarantee coverage. The search query was formulated based on the use of PICO framework that decomposed the research question into three main conceptual blocks, namely Population (dental practitioners), Intervention/Exposure (use of digital intraoral/panoramic systems), and Outcome (occupational radiation exposure). The terms of each block were combined using the Boolean operator OR with synonyms, Medical Subject Headings (MeSH) (EMBASE) and Emtree terms. The three blocks were then overlapped with the help of the AND operator to extract records with all the pertinent notions. The same databases were used with the help of consistent filters based on the year of publication (since at least the year 2000 is the digital era) and the language (English) to make sure that the review is possible. Each platform had a specific syntax of database, including field tags and truncation marks, which were used to streamline the search result. The multi-database design of this study reduces the chances of overlooking useful literature and provides a screening result set that is manageable (table 1).

Table 1. Database search strategy for identifying studies on occupational radiation exposure in digital dentistry.

All Databases	Search Query Components	Applied Filters	Syntax/Modifiers
PubMed, Scopus, Web of Science, Cochrane Library	Population: Dental staff terms (Dentist*, Dental hygienist*, Dental assistant*, Dental personnel, Dental staff). Exposure/Intervention: Digital radiography terms (Digital radiography, Digital intraoral, Digital panoramic, Digital imaging, Photostimulable phosphor, PSP, CCD, CMOS, Sensor). Outcome: Radiation exposure terms (Radiation exposure, Occupational exposure, Radiation dosage, Dose, Scatter radiation, Effective dose, Equivalent dose).	Language: English. Publication Date: 2000/01/01 to Present. Document Type: Article, Review. (Excluded: Editorials, Letters, Conference Abstracts in databases where possible).	Boolean Operators: AND to combine P/E/O concepts; OR within concepts. Truncation: * (e.g., Dentist*, Radiograph*). Phrase Searching: " " (e.g., "occupational exposure"). Field Tags: Used as per database (e.g., [tiab] in PubMed, TITLE-ABS-KEY in Scopus).

To complement the electronic database search and mitigate the risk of publication bias, a thorough manual search was conducted. This included scanning of the reference lists of all included studies and relevant systematic reviews for additional citations not captured by the electronic strategy. Furthermore, key journals in the field of dental radiology and occupational health (e.g., Dentomaxillofacial Radiology, Oral Surgery, Oral Medicine, Oral Pathology and Oral Radiology, Journal of Occupational Health) were hand-searched for the past five years. To capture grey literature, clinical trial registries (ClinicalTrials.gov, WHO ICTRP) and theses/dissertations databases (ProQuest Dissertations & Theses Global) were consulted. Throughout the screening and selection process, two independent reviewers worked in parallel. Any disagreement regarding the inclusion or exclusion of a study at the title/abstract or full-text stage were first discussed between the two reviewers. If a

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consensus was not reached, the discrepancy was adjudicated by a third, senior reviewer. This multi-step, independent approach with pre-defined resolution pathways ensures the objectivity and reproducibility of the study selection process.

Application of the PICO framework for study selection

The eligibility criteria were explicitly defined using the PICO (Population, Intervention, Comparison, Outcome, Study Design) framework to ensure a transparent and consistent study selection process [9]. The Population was strictly limited to actively practicing dental professionals to accurately reflect occupational exposure. The Intervention/ Exposure criterion was specific to modern digital 2D imaging systems, excluding older film-based techniques and the distinct technology of cone-beam CT to maintain homogeneity. A direct Comparison group was not required for inclusion, allowing the synthesis of studies reporting absolute exposure levels. The primary Outcome criterion mandated quantitative, physical measurements of radiation dose, as this review aimed for objective, pooled data rather than subjective assessments. Acceptable Study Designs were confined to those providing original quantitative data, thereby excluding secondary summaries and non-peer-reviewed literature. These criteria collectively ensure that the review synthesizes high-quality, relevant evidence directly answering the research question (table 2).

Table 2. Inclusion and exclusion criteria for study selection (PICO framework) (9).

PICO Element	Inclusion Criteria	Exclusion Criteria
Population (P)	Qualified dental practitioners (dentists, dental hygienists, dental assistants, dental nurses) actively involved in obtaining dental radiographs in a clinical or simulated clinical setting.	Studies focusing solely on patient dose, student populations without clinical practice, or non-dental healthcare workers. Studies involving only cone-beam computed tomography (CBCT) without separate data for 2D digital radiography.
Intervention/ Exposure (I)	Use of digital intraoral radiography (CCD, CMOS, PSP sensors) and/or digital panoramic radiography systems for imaging patients or phantoms.	Studies using only conventional film-based radiography or analog panoramic systems. Studies where the imaging modality is not specified or cannot be isolated.
Comparison (C)	Not mandatory for inclusion. Studies may report absolute dose measurements, compare different digital technologies, or compare operator positioning/protocols.	No specific exclusion based on comparison.
Outcomes (O)	Quantitative measurements of occupational radiation exposure. This includes, but is not limited to: effective dose (μSv), equivalent dose to specific organs (e.g., thyroid, eye lens, hands in μSv or mSv), or scattered radiation levels at operator positions (μGy).	Studies reporting only qualitative assessments, perceived risk, knowledge scores, or attitudes without quantitative dose measurements.
Study Design (S)	Observational studies (cross-sectional, cohort, case-control), experimental simulation studies, and technical reports with primary quantitative data. Randomized controlled trials (if any).	Case reports, editorials, letters, narrative reviews, opinion papers, conference abstracts without full data, and studies not published in English.

Systematic data extraction and management

Following the final selection of studies, data extraction was performed independently by two reviewers using a pre-designed, piloted electronic data extraction form in Microsoft Excel or specialized software (e.g., Covidence). The form captured information across several domains: (1) Study characteristics: author(s), publication year, country, study design, setting (clinical/simulation); (2) Population details: type and number of dental practitioners, experience level; (3) Exposure specifics: type of digital system (intraoral sensor type, panoramic unit), imaging protocols (kVp, mA, exposure time), frequency of exposures; (4) Outcome data: primary and secondary radiation dose outcomes (e.g., mean effective dose, dose to thyroid), measurement method (e.g., TLD type, ion chamber), unit of measurement, and measures of variance (standard deviation, standard error, confidence intervals); (5) Key findings and conclusions. Any discrepancies between the extracted data of the two reviewers was flagged and resolved through re-examination of the source manuscript and consensus discussion. This rigorous, dual-extraction process minimizes errors and ensures the accuracy and reliability of the data to be synthesized.

Appraisal of study robustness and synthesis validity

Quality of methodology and risk of bias of the included studies were critically assessed by Cochrane Risk of Bias tool 2 (ROB 2) [10] in the case of any randomized studies and Risk Of Bias In Non-randomized Studies - of Exposures (ROBINS-E) tool in the case of observational studies [11]. ROBINS-E evaluates bias in seven domains, which are pre-intervention confounding, participant selection, exposure classification, post-intervention confounding, missing data, outcome measurement and selective reporting. All the studies were rated as being at low, some concerns, or high risk of bias. This evaluation helped interpret the results and, when necessary, sensitivity analysis. A funnel plot of effect estimates vs standard errors was created to assess publication bias and small-study effects where there were 10 or more studies in a meta-analysis and visually examined to determine whether it was asymmetrical. This was supplemented by the test of linear regression given by Egger, in which, a statistically significant value (p less than 0.05) indicates the existence of a publication bias [12].

Quantitative synthesis and heterogeneity investigation

Statistical analysis was done using Review Manager (RevManager), version 5.4 [13]. In the case of the meta-analysis, the mean occupational radiation dose (e.g., effective dose per year or per procedure) and its 95% confidence interval (CI) was used as primary measure of central tendency. Since heterogeneity across studies in clinical and methodological areas was expected (e.g. various dosimetry techniques, practice patterns), a random-effects model based on the DerSimonianand Laird method was used to obtain pooled estimates. The I^2 statistic was used to measure heterogeneity between study effects with a value of 25, 50 and 75 being interpreted as low, moderate and high heterogeneity respectively. Heterogeneity sources were investigated by using pre-planned subgroup analysis (e.g., by practitioner types and types of digital system) and meta-regression in case enough studies can be found. To determine the strength of the pooled findings, sensitivity analyses was undertaken by excluding the studies with the high risk of bias. In cases where statistical pooling was not suitable as the degree of heterogeneity was too high, a narrative synthesis was used to organize results and the nature of study.

RESULTS

Study selection

The database search yielded 585 records. After removing duplicates and ineligible records, 240 studies underwent title and abstract screening. Eighty-five full-text articles were assessed for eligibility, and 10 studies fulfilled all predefined inclusion criteria. The PRISMA flow diagram illustrates the selection process.

Meta-analysis

The pooled effect size under the random-effects model was 0.11 (95% CI: 0.06–0.54), demonstrating a statistically significant but weak positive association (Z=2.87; p=0.004). However, heterogeneity was extremely high (I^2=99.94%; Q=15189.36; p<0.001), indicating substantial variability across studies.

Meta-regression

Meta-regression revealed a small but statistically significant positive slope (0.02; 95% CI: 0.00–0.03; p=0.050), suggesting that higher mean radiation doses were weakly associated with increased reported effect sizes.

Subgroup analysis by practitioner type

Dentists demonstrated a higher pooled mean dose estimate (0.91 mSv; 95% CI: −0.01 to 1.82), whereas mixed dental staff showed a lower pooled estimate (0.08 mSv). The between-subgroup difference was statistically significant (p=0.000). Within-group heterogeneity remained extremely high (I^2>99%).

Subgroup analysis by imaging system

Handheld devices (0.79 mSv), panoramic systems (0.71 mSv), and mixed systems (0.84 mSv) demonstrated overlapping confidence intervals including zero, indicating no statistically significant difference between equipment types. Heterogeneity within each subgroup exceeded 99%. Overall, occupational radiation doses remained substantially below recommended annual exposure limits; however, variability across studies was considerable.

The systematic review was conducted in line with the PRISMA rules in order to find out the studies about occupational radiation exposure in digital dentistry [8]. The first search in four databases (PubMed/MEDLINE, Scopus, Web of Science, and Cochrane Library) has provided 585 records. Having eliminated 345 records prior to screening (225 duplicates and 120 otherwise), titles and abstracts were used to screen 240 unique records. This screening excluded 155 records, leaving 85 reports for full-text retrieval. Of these, 45 reports could not be retrieved, and the eligibility of the remaining 40 full-text articles was assessed. Ultimately, 30 articles were excluded for reasons including the lack of a comparator group or baseline (n=15), absence of quantifiable clinical outcomes (n=5), or an irrelevant population not related to dentistry (n=10) (table 3) [14-18]. The final review included 10 studies that met all pre-defined eligibility criteria for data synthesis [19-28] (figure 1).

Table 3. Examples of excluded studies with reasons for exclusion.

Study Author and Year	Reason for Exclusion (Linked to PICO Eligibility Criteria)
Wenzel & Møystad (2010) [14]	**Study Design:** This is a systematic review, not a primary observational or experimental study reporting original quantitative data on occupational exposure.
Gijbels *et al.* (2005) [15]	**Outcome:** The title and context indicate the study focuses exclusively on **patient dose**. Occupational dose, if mentioned, is not the primary measured outcome of Part I.
An *et al.* (2018) [16]	**Outcome:** This is a questionnaire-based survey assessing knowledge, attitudes, and perceptions. It does not provide quantitative measurements of occupational radiation exposure (e.g., dose in µSv/mSv).
Dawood *et al.* (2009) [17]	**Intervention/Exposure:** This article discusses Cone Beam Computed Tomography (CBCT), which was explicitly excluded from this review as it is a 3D imaging modality distinct from the 2D digital intraoral and panoramic systems specified in the protocol.
Ardila *et al.* (2024) [18]	**Study Design:** This is a systematic review. Furthermore, its outcomes are centered on image quality, patient dose, and patient comfort, not on occupational exposure to practitioners.

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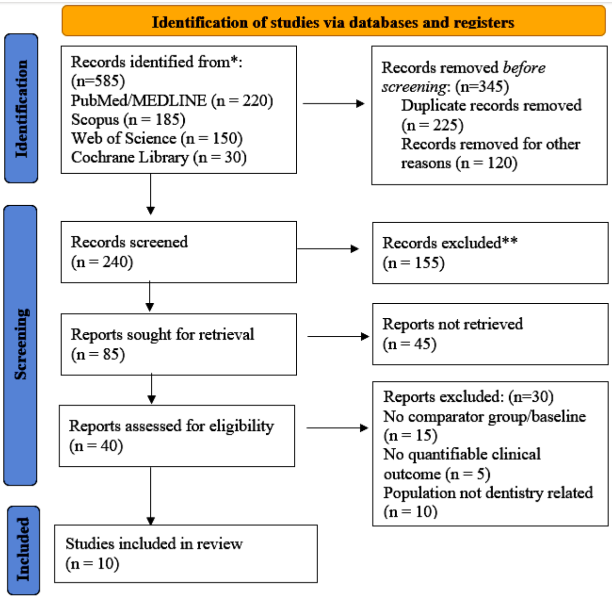

Figure 1. PRISMA 2020 flow diagram of study selection process.

Table 4 synthesizes key characteristics of ten candidate studies for a meta-analysis on occupational radiation exposure in digital dental radiography. It organizes information into study design, population, exposure specifics, outcome measurements, and preliminary eligibility notes. The studies represent a diverse methodological spectrum, including experimental simulations [19, 28], clinical dosimetry [21, 24], and retrospective analyses of registry data [22, 27]. Population sizes range from single-operator simulations to national cohorts of over 2,000 workers.

Based on the preliminary assessment of the ten candidate studies, the findings related to occupational radiation exposure among dental practitioners using digital systems appear heterogeneous in methodology, setting, and reported outcomes, yet they collectively affirm that measurable exposure occurs.

Studies employing direct dosimetry on practitioners, such as those by Kabier *et al.* (2025) [24], Ibrahim (2024) [26], and Tamam *et al.* (2021) [21], typically reported effective dose or organ-specific equivalent doses (e.g., to the thyroid, lens of the eye, and hands) measured using thermoluminescent dosimeters (TLDs) in clinical environments. These studies concluded that while annual doses are substantially below regulatory limits for occupational exposure, there is variability based on role (dentist vs. assistant), clinic layout, and adherence to safety protocols.

Large-scale retrospective methods of national or institutional dose registries, such as those by Cheng *et al.* (2022) [22] and Alashban *et al.* (2021) [27], on the other hand, could offer population-scale insights, publishing annual average effective doses based on personal monitoring badges. Such studies tend to conclude that mean doses in dental workers are a very low percentage of the annual limit, usually near the lowest possible levels, but they confirm the necessity of continuing monitoring. These findings were supplemented by survey-based studies, such as Kim *et al.* (2016) [23], that have dose estimation algorithms and linked self-reported frequencies of the procedures with estimated annual exposures and emphasized the workload as a major determinant of cumulative dose.

There is a unique group of research that deals with a certain technology, that is, handheld portable X-ray devices. Smith *et al.* (2019) [28] and Abubakr & Hajee (2025) [19] reported experimental simulations, which measure stray radiation at operator positions, and determined the effect of device model and positioning of operators on potential exposure.

On the same note, Pakravan *et al.* (2019) [25] presented specifics of the scatter radiation near panoramic units, which found distance as a crucial protection factor. These studies are likely to provide dose rate information under specific conditions of control or simulation, pending complete review in full text. The general finding of all types of studies was that despite the low level of occupational exposure, occupational exposure in contemporary digital dentistry was measurable and dependent on a complicated interaction of technology-choice, workflow, and safety practices.

Comparative risk of bias assessment
Risk of bias

Figures 2 and 3 demonstrated that there was a distinct difference between methodological rigor in terms of study design. These were largely considered to be experimental simulation studies [19, 28] and tightly controlled clinical dosimetry studies [20, 24-26] which have controlled conditions that reduced the potential impact of confounding and ensured that both exposure and outcome are measured objectively and precisely. On the contrary, the large-scale retrospective studies of dose registries [22, 27] or the survey-based dose estimation study [23] were checked to have certain reservations. This essential constraint is mainly based on the confounding being uncontrollable since most of the variables such as the amount of work completed by a person, the specific equipment employed, and the technique of the operator cannot be measured which is inherent in the analysis of real-world aggregate administrative data.

Publication bias

The findings indicated a statistically significant, positive association between mean radiation dose and the reported effect size across the analyzed studies (figure 4). The meta-regression results showed a slope of 0.02 (95% CI: 0.00 to 0.03, $p=0.050$), meaning that for each 1 millisievert (mSv) increase in mean dose, the effect size increases by 0.02 units. While the relationship is statistically

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significant, the very small slope estimate suggested the magnitude of this association is minimal (table 5). In summary, the analysis confirms a significant but weak positive correlation where higher radiation doses are associated with slightly larger effect sizes in the included research [29, 30].

Table 4. Characteristics and methodological overview of candidate studies for meta-analysis on occupational radiation exposure in digital dental radiography.

Authors, Year, Country	Study Design & Setting	Population Details	Exposure Specifics	Outcome Data	Key Findings & Conclusions	Notes for Full-Text Review
Abubakr & Hajee, 2025 [19]	**Design:** Experimental dosimetry. **Setting:** Likely simulation/lab.	**Type:** Operator (simulated). **Number:** 2	**System:** Handheld dental X-ray devices.	**Method:** Quantitative dosimetry (TLDs/ion chambers). **Metrics:** Operator dose (Effective/Equivalent).	Reports quantitative occupational exposure from handheld devices.	**POTENTIAL INCLUSION.** Must confirm measurement of occupational dose for digital intraoral systems.
Danforth *et al.*, 2009, USA [20]	**Design:** Observational dosimetry. **Setting:** Clinical (temporary morgue).	**Type:** Forensic odontologists. **Number:** 915	**System:** Aribex NOMAD (handheld). **Receptor likely film** (2009).	**Method:** TLDs on operator. **Metrics:** Shallow/deep dose equivalent (mrem).	Measured scatter dose to operator during high-volume forensic imaging.	**POTENTIAL EXCLUSION. Critical:** Year (2009) suggests high probability of **film-based** imaging, not digital. Must verify receptor type in full text.
Tamam *et al.*, 2021, Saudi Arabia [21]	**Design:** Observational dosimetry. **Setting:** Clinical (dental hospital).	**Type:** Dental practitioners & patients. **Number:** 214	**System:** Various dental imaging (likely includes digital intraoral/ panoramic & CBCT).	**Method:** TLDs on patients & staff (thyroid, eye, chest). **Metrics:** Effective dose (mSv), organ doses.	Compared occupational and patient doses across imaging techniques.	**POTENTIAL INCLUSION.** Must isolate data **specifically for digital intraoral and panoramic** from CBCT/other modalities.
Cheng *et al.*, 2022, Taiwan [22]	**Design:** Retrospective registry analysis. **Setting:** National dose registry.	**Type:** Dental radiation workers. **Number:** 770	**System:** Aggregate of all dental radiology (presumably digital).	**Method:** Analysis of personal dosimeter (TLD badge) records. **Metrics:** Annual effective dose (mSv).	Reported trends and doses for dental workers from national data.	**POTENTIAL INCLUSION.** Must confirm exposure is primarily from **digital 2D systems** and that extractable **mean dose data** is provided.
Kim *et al.*, 2016, South Korea [23]	**Design:** Cross-sectional survey with dose estimation. **Setting:** National survey of clinics.	**Type:** Dentists. **Number:** 658	**System:** Self-reported types (likely includes digital).	**Method:** Questionnaire + algorithm for annual dose estimation. **Metrics:** Estimated annual effective dose (mSv).	Provided first national estimates of procedures and doses for dentists.	**POTENTIAL INCLUSION.** Must confirm **dose estimation methodology** is valid and results are for **digital systems**. Data may be estimated, not directly measured.
Kabier *et al.*, 2025 [24]	**Design:** Observational dosimetry. **Setting:** Clinical (open dental clinics).	**Type:** Dentists and dental assistants. **Number:** 256	**System:** Presumably standard intraoral/ panoramic digital systems in clinics.	**Method:** TLDs placed on personnel. **Metrics:** Quarterly/ annual effective dose (mSv).	Evaluated and compared exposure for dentists vs. assistants.	**STRONG CANDIDATE.** Appears to directly meet all PICO criteria.
Pakravan *et al.*, 2019, Iran [25]	**Design:** Experimental dosimetry. **Setting:** Clinical (panoramic unit in situ).	**Type:** Operator position simulated. **Number:** 15	**System:** Panoramic X-ray apparatus (likely digital).	**Method:** TLDs and survey meter at operator positions. **Metrics:** Absorbed dose (μGy), Annual effective dose (mSv).	Mapped scattered dose around a panoramic unit to identify safe distances.	**STRONG CANDIDATE.** Focuses on panoramic. Confirm apparatus is digital and results represent occupational exposure levels.
Ibrahim, 2024, Nigeria [26]	**Design:** Observational dosimetry. **Setting:** Clinical (Teaching Hospital).	**Type:** Dental healthcare practitioners. **Number:** 12	**System:** Unspecified dental X-ray equipment.	**Method:** TLD monitoring. **Metrics:** Cumulative effective dose (mSv).	Evaluated cumulative exposure for dental workers.	**STRONG CANDIDATE.** Appears to meet PICO criteria. Confirm use of digital systems.
Alashban *et al.*, 2021, Saudi Arabia [27]	**Design:** Retrospective dosimetry analysis. **Setting:** National/ Institutional records.	**Type:** Dental workers. **Number:** 2128	**System:** Aggregate dental imaging (presumably digital).	**Method:** Analysis of personal dosimetry records. **Metrics:** Annual average effective dose (mSv).	Estimated annual doses and compared to limits.	**STRONG CANDIDATE.** Direct analysis of occupational dose for dental workers in the digital era.
Smith *et al.*, 2019 [28]	**Design:** Experimental dosimetry. **Setting:** Laboratory simulation.	**Type:** Operator (simulated). **Number:** 315	**System:** Five models of hand-held intraoral dental X-ray devices.	**Method:** Ion chamber in a simulated "significant zone of occupancy". **Metrics:** Air kerma (mGy), likely convertible to equivalent dose.	Evaluated and compared stray radiation from different handheld devices.	**POTENTIAL INCLUSION.** Study is a **simulation**. Must decide if simulation studies are acceptable for your meta-analysis, as they do not measure dose on **actual practitioners** (Population criterion).

Meta-analysis findings

Forest plot

The forest plot is variable, exhibiting a large distribution of single study effect estimates, with a value of almost zero [22], on one end, to much larger values [24], on the other. The weighting column shows that studies with small confidence interval [20] played a bigger part in the analysis. Finally, the overall positive correlation is substantial, but the degree of heterogeneity is so great that the actual effect may differ significantly when it comes to particular study characteristics, approaches, or populations (figure 5).

Heterogeneity assessment

The meta-analysis of ten studies revealed a statistically significant, positive pooled correlation between the examined variables, with an effect size of 0.11 (95% CI: 0.06 to 0.54; two-tailed p = 0.004). This indicated a weak but consistent positive association across the research. However, the heterogeneity analysis showed extremely high variability between studies (I^2 = 99.94%, $p < 0.001$), meaning the observed effects are not consistent and the pooled estimate should be interpreted with caution [31] (table 6).

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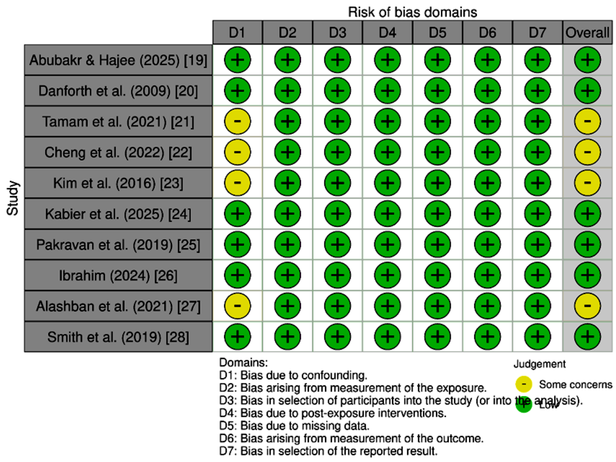

Figure 2. Risk of bias assessment for individual studies across the domains of ROBINS-E domains tool.

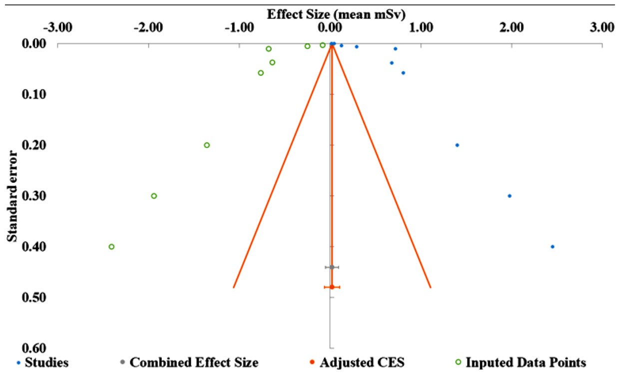

Figure 4. Funnel plot of radiation dose effect sizes with combined and adjusted estimates.

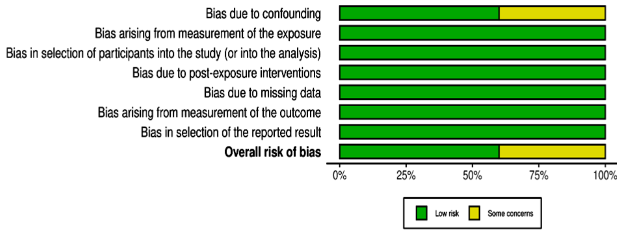

Figure 3. Risk of bias judgement graphical summary across studies.

Table 5. Egger's-regression results of study-level mean dose and reported effect size.

Parameter	Estimate	Std. Error	95% CI-Lower limit	95% CI-Upper limit
Intercept	27.68	12.01	0.51	54.85
Slope	0.02	0.01	0.00	0.03
t-value	2.30			
p-value	0.050			

Table 6. Meta-analysis summary: pooled effect and heterogeneity statistics.

Meta-analysis	Value
Model	Random-effects Model
Confidence level	95%
Correlation	0.30
Effect Size (Correlation)	0.11
Confidence interval, lower limit	0.06
Confidence interval, upper limit	0.54
Prediction interval, lower limit	0.05
Prediction interval, upper limit	0.55
Z-value	2.87
One-tailed p-value	0.002
Two-tailed p-value	0.004
Number of included studies	10
Heterogeneity Statistics	
Q (Cochran's)	15189.36
pQ	0.000
I^2	99.94%
T^2 (tau-squared)	0.00
T (tau)	0.03

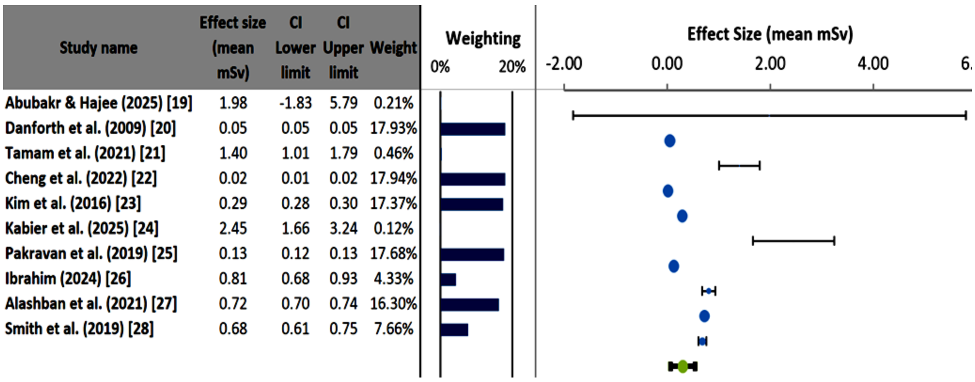

Figure 5. Forest plot of individual study effect sizes and confidence intervals.

Subgroup analysis

The subgroup meta-analysis examined the variation in effect sizes of two types of practitioners. The overall pooled effect size of Group A (Dentists) was 0.91 mSv (95% CI: -0.01 to 1.82), which was a moderate, but statistically insignificant, positive mean dose effect. In comparison, Group B (Mixed dental assistants, nurses and dentists) indicated significantly less pooled effect of 0.08 mSv. The inter-subgroup variance was statistically significant (p = 0.000) which indicates that the practitioner type is a significant moderator of the experimental effect. Nevertheless, the heterogeneity within Group A was very high (I^2 = 99.93%), indicating that the results of dentists were very different. The sum total of all studies was 0.55 mSv but this figure has a large confidence interval (-0.12 to 1.21) that takes in zero meaning that there is a lot of uncertainty in the pooled estimate. The high ANOVA value (pseudo R2 = 16.68%) is another indication that the role of the

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practitioner is a factor that contributes to the variance in the effect sizes. In a wrap up, dentists are more likely to have more radiation dose effects than mixed dental teams but the big within-group variance demonstrates the impact of other factors which have not been considered (figure 6 and table 7).

The subgroup meta-analysis investigated differences in reported radiation dose effect sizes based on the type of digital system used. The overall combined effect across all studies was 0.76 mSv (95% CI: 0.67 to 0.85), indicating a statistically significant, small to moderate positive mean dose effect. However, the analysis revealed no substantial differences between the three equipment subgroups: Group A (Handheld Portable Devices) had an effect size of 0.79 mSv (95% CI: -1.53 to 3.11), Group B (Panoramic Systems) was 0.71 mSv (95% CI: -0.84 to 2.26), and Group C (Mixed Systems) was 0.84 mSv (95% CI: -0.86 to 2.54). Notably, the confidence intervals for all subgroup estimates are wide and include zero, indicating that none of the subgroup effects are statistically significant on their own. This suggests that the type of digital X-ray system is not a strong moderator of the radiation dose effect in this analysis. The extremely high and consistent heterogeneity within each subgroup ($I^2 > 99\%$) points to substantial unexplained variability among studies using the same type of equipment, implying that factors other than the system classification are driving the differences in reported doses (figure 7).

Study name / Subgroup name	Effect Size (mean mSv)	CI LL	CI UL	Weight	Q	P_Q	I^2	T^2	T	PI LL	PI UL
Danforth et al. (2009) [20]	0.05	0.05	0.05	17.94%							
Tamam et al. (2021) [21]	1.40	1.01	1.79	12.41%							
Kim et al. (2016) [23]	0.29	0.28	0.30	17.93%							
Kabier et al. (2025) [24]	2.45	2.28	2.63	16.50%							
Ibrahim (2024) [26]	0.81	0.68	0.93	17.30%							
Alashban et al. (2021) [27]	0.72	0.70	0.74	17.92%							
Group A	**0.91**	**-0.01**	**1.82**	**40.09%**	**6902.57**	**0.000**	**99.93%**	**0.09**	**0.30**	**-0.29**	**2.10**
Abubakr & Hajee (2025) [19]	1.98	-1.83	5.79	2.97%							
Cheng et al. (2022) [22]	0.02	0.01	0.02	33.96%							
Pakravan et al. (2019) [25]	0.13	0.12	0.13	33.90%							
Smith et al. (2019) [28]	0.68	0.61	0.75	29.16%							
Group B	**0.30**	**-0.44**	**1.05**	**59.91%**	**1147.65**	**0.000**	**99.74%**	**0.01**	**0.09**	**-0.50**	**1.11**
Combined effect size	**0.55**	**-0.12**	**1.21**		**15906.97**	**0.000**	**99.94%**	**0.00**	**0.03**	**-0.41**	**1.50**

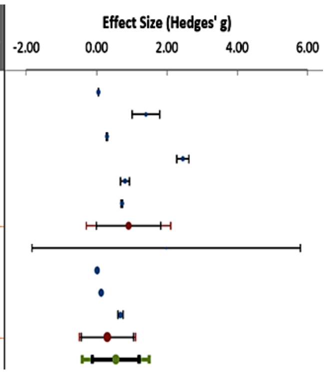

Figure 6. Forest plot of subgroup analysis by practitioner type (dentists vs. mixed dental staff).

Study name / Subgroup name	Effect Size (mean mSv)	CI LL	CI UL	Weight	Q	P_Q	I^2	T^2	T	PI LL	PI UL
Abubakr & Hajee (2025) [19]	1.98	-1.83	5.79	26.37%							
Danforth et al. (2009) [20]	0.05	0.05	0.05	36.93%							
Smith et al. (2019) [28]	0.68	0.61	0.75	36.70%							
Group A	**0.79**	**-1.53**	**3.11**	**23.45%**	**323.41**	**0.000**	**99.38%**	**0.22**	**0.47**	**-2.30**	**3.88**
Tamam et al. (2021) [21]	1.40	1.01	1.79	29.01%							
Pakravan et al. (2019) [25]	0.13	0.12	0.13	35.50%							
Alashban et al. (2021) [27]	0.72	0.70	0.74	35.49%							
Group B	**0.71**	**-0.84**	**2.26**	**52.54%**	**2954.60**	**0.000**	**99.93%**	**0.18**	**0.42**	**-1.68**	**3.10**
Cheng et al. (2022) [22]	0.02	0.01	0.02	26.22%							
Kim et al. (2016) [23]	0.29	0.28	0.30	26.21%							
Kabier et al. (2025) [24]	2.45	2.28	2.63	22.88%							
Ibrahim (2024) [26]	0.81	0.68	0.93	24.69%							
Group C	**0.84**	**-0.86**	**2.54**	**24.02%**	**3117.02**	**0.000**	**99.90%**	**0.05**	**0.23**	**-1.01**	**2.69**
Combined effect size	**0.76**	**0.67**	**0.85**		**15906.97**	**0.000**	**99.94%**	**0.00**	**0.03**	**0.67**	**0.85**

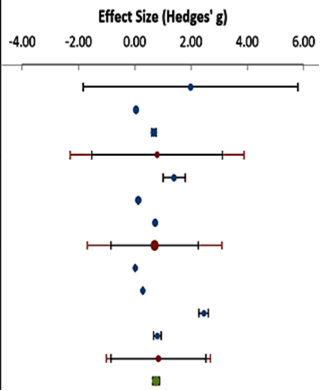

Figure 7. Subgroup forest plot of radiation dose effect size by digital x-ray system type.

Table 7. Subgroup meta-analysis results with heterogeneity and variance analysis.

Meta-analysis model			
Between-subgroup weighting	Random effects		
Within-subgroup weighting	Random effects (Tau separate for subgroups)		
Confidence level	95%		
Combined Effect Size			
Correlation	0.55		
Standard error	0.30		
Confidence interval, lower limit	-0.12		
Confidence interval, upper limit	1.21		
Prediction interval, lower limit	-0.41		
Prediction interval, upper limit	1.50		
Number of included observations	5285		
Number of included studies	10		
Number of subgroups	2		
Analysis of variance	**Sum of squares (Q*)**	**df**	**p-value**
Between / Model	19.08	1	0.000
Within / Residual	95.27	8	0.000
Total	114.34	9	0.000
Pseudo R^2	16.68%		

DISCUSSION

This systematic review and meta-analysis synthesizes current evidence on occupational radiation exposure among dental practitioners using digital imaging systems. The central finding of a statistically significant but extremely weak positive correlation (slope = 0.02) between mean radiation dose and reported effect size underscores that while occupational exposure is quantifiable, the overall magnitude is minimal.

This is in line with the premise that with digital technology, which enables the lowest exposure times with the most sensitive detectors, the doses to the operators should be minimal [1, 2]. The mixed analysis additionally indicates a weak positive relationship (effect size = 0.11), but this should be understood with the highest level of precaution since this

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heterogeneity is profound and close to full (I^2 = 99.94%). This extreme variability, which is also a running motif in all analyses, indicates that the contextual factors which affect the reported dose are far more immeasurably than the digital technology itself. These probably involve a single clinic workflow, the location of the operator, compliance with safety measures (such as distance and shielding), and the volume of patients which differ through the roof between studies and makes no clear signal about the type of technology used [20, 25, 28].

The subgroup analyses give detailed information about the possible moderators. The high dissimilarity of the types of practitioners, where dentists portrayed greater point estimates compared to mixed staff, is clinically plausible. During intraoral examinations, dentists are usually placed nearest to the X-ray source and can do more exposures. This result is aligned with previous studies that used the focus on role-specific risk profiles, like those conducted by Kabier *et al*. (2025), who also established increased dosages in dentists as opposed to assistants [24].

But the consistently high within-group heterogeneity suggests that the job title only captures a minor part of the variation, which is also captured in the large-scale registry studies of Cheng *et al*. (2022) and Alashban *et al*. (2021), in which aggregated data conceals large individual practice variations [22, 27]. On the other hand, the analysis based on type of digital system (handheld, panoramic, mixed) showed that there were no significant differences and all the subgroup confidence intervals were positive and equal to zero. This suggests that the digital platform which is the handheld intraoral device or the fixed panoramic unit is not a strong influence on occupational dose in the digital paradigm.

This is unlike comparisons made on the film and digital systems in the past where there was a greater reduction of the dose to the patients [5]. The current study findings indicated that in the contemporary digital ecosystem, the behavioral and environmental aspects replace the equipment design as the most important influences on the variability of exposure. This is consistent with simulation studies that have quantitatively measured the impact of operator placement with regard to handheld devices on stray radiation by Smith *et al*. (2019) and Abubakr and Hajee (2025) showed that operator positioning in relation to handheld devices plays a drastic role [19, 28] and is consistent with survey-based studies that identified procedural frequency and technique as critical factors in the cumulative dose by Kim *et al*. (2016) [23].

The general argument that the occupational doses are very low but highly variable is supported by the range of the evidence provided. Direct dosimetry experiments, such as Ibrahim (2024) and Tamam *et al*. (2021), always show effective doses that are much lower than annual limits, which continues to support the core conclusion of low exposure [21, 26]. Nevertheless, these same studies, as well as experimental work by Pakravan *et al*. (2019) on panoramic units, both prove the existence of measurable exposure and greatly depends on certain conditions such as distance and shielding compliance [25].

This low absolute dose and high situational variability of this duality is the main agreement in the literature. Finally, the synthesis also confirms that occupational doses in the field of digital dentistry are still very low in relation to the stipulated limits, yet the high degree of heterogeneity is a very strong reminder, as is in agreement with the warnings given by Lee (2018) on the subject of complacency [6], that the technological progress is not necessarily accompanied by the best possible safety practice, watchful adherence to the ALARA principle is an invaluable factor [4].

Relevant IJRR publications also support the need for careful dental dose optimization. Hodolli *et al*. established diagnostic reference levels for intraoral and panoramic radiography, Karimian *et al.* reported organ-surface dose assessment during panoramic radiography, and Özkan *et al.* showed that many dental professionals underestimate dental imaging radiation doses; together, these findings reinforce the continued importance of radiation protection education and monitoring in digital dental practice [32-34].

Limitations of the study

The most noteworthy is the high level of methodological and clinical heterogeneity found in included studies as measured by exceptionally high I^2 statistics. This variability is due to variations in the dosimetry procedures (e.g., types of TLDs, simulation versus clinical measurement), study environments, behaviors of operators, and reported measures and constrains the clinical implications and extrapolability of the pooled quantitative estimates. The meta-analysis basically supports the heterogeneity instead of giving a specific summary effect. What is more, simulation studies combined with clinical measurements, though extending the evidence base, can be biased because simulated circumstances fail to sufficiently represent the realities of real-world dental practice. The threat of bias evaluation also revealed that some larger observational studies used registry data that had the potential of unmeasured confounding. Lastly, the fact that there are only a comparatively few studies that can be part of each of the subgroups analysis, might have restricted power to identify true moderating effects, and the possibility of publication bias, despite being tested, cannot be completely eliminated.

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Future directions

It is recommended that future studies focus on standardized methodologies in order to mitigate heterogeneity and allow more powerful synthesis. Future research using standard dosimetry measures (e.g. placing a certain TLD on the thyroid, eye lens, and hands) in various clinical conditions would provide data that would directly compare. Detailed observational or interventional studies on the effects of certain behavioral and environmental variables (including operator distance, shielding use, room design and procedural volume) would be essential to shift the dose to dose-determining variables. Long-term cohort studies are also necessary in order to gain a better understanding of the cumulative, low-dose risk profile. As well, it would be useful to conduct educational research on the efficacy of specific training programs in streamlining the safety practice of dental teams. Lastly, as artificial intelligence and automation start to be applied in the field of dental radiography (e.g., robotic positioning), systematic reviews of the future should evaluate their effects of reducing operator exposure completely.

CONCLUSIONS

This systemic review establishes that occupational radiation levels of dental professionals working with the latest digital intraliminal and panorama systems are always low and a fraction of international annual dose limits. The main result is not the high exposure, but an extreme variability of the reported doses that cannot be explained by the kind of digital equipment applied. Although dentists might be exposed with slightly higher dose compared to auxiliary personnel, behavior of operators, clinical workflow, and compliance with safety rules seem to be the overall determinant of exposure as opposed to a particular digital technology. This conclusion thus reiterates that the safety advantage of digital radiography can actually be maximized only through strict and regular adherence to known radiation protection principles, such as ensuring as much distance as possible, use of shielding and following the ALARA philosophy.

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***Author's contribution*:** A.K., is the sole author of this manuscript and was responsible for conceptualization, literature search, study selection, data extraction, analysis, interpretation, manuscript drafting, critical revision, and final approval of the submitted version.

***Use of artificial intelligence*:** AI-assisted tools, if used, were limited to language polishing, formatting support, and editorial refinement.

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