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DEVELOPMENT AND VALIDATION OF A STANDARDIZED PHANTOM-BASED PROTOCOL FOR QUANTIFYING RADIATION DOSE REDUCTION USING LEAD-FREE APRONS IN DIGITAL INTRAORAL RADIOGRAPHY: A COMPARISON ACROSS CMOS SENSORS AND RECTANGULAR COLLIMATION

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Abstract:

Objectives: The purpose of this research is to create and test a reliable method to measure how lead-free aprons reduce radiation in digital dental X-rays.

Materials and Methods:

The clinical setting were simulated employing a standardized adult dental phantom that mimicked the mandibular and maxillary features. Two distinct CMOS detectors had been employed for obtaining intraoral digital imaging according to both round and rectangular collimation conditions. Lead-free protective aprons were positioned over the phantom during selected exposures and a standardized dosimeter has been employed. Each exposure configuration was performed five times to assure similarity and predictability.

Results:

At all measured anatomical regions, the utilization of free of lead aprons exhibited a noticeable decrease in the exposure to radiation, varying from 35% to 50%. Rectangle collimation observed an extra 15–20% reduction in exposure in contrast to round collimation. Thyroid exposure dropped by as much as 57% when combined preventative approaches were employed. For measuring radiation dosage reduction approaches, the phantom-based methodology appeared to be trustworthy and predictable. The primary determinant that decreased radiation was discovered to be rectangle collimation. The type

of CMOS sensor did not significantly affect radiation dose ($p = 0.23$), indicating that shielding and beam restriction played a more critical role than detector selection.

Conclusion:

Lead-free aprons offered further safeguards, but rectangular collimation demonstrated to be the primary consideration for minimizing exposure. These outcomes emphasize the important role of tailoring the procedures for imaging through precise radiation limiting and independently verified shielding approaches.

Keywords:

Radiation protection, CMOS sensors, intraoral imagery, lead-free aprons, phantom dosimetry, and rectangular collimation

Introduction:

In-oral imaging is still vital for routine dental procedures. Limiting the risk of radiation continues to be an important priority, particularly concerning sensitive areas like the thyroid and salivary glands, notwithstanding advancements in technology for digital imaging. Compliance to ALARA principles still entails meticulous utilization of beam constraint and precautionary shielding, irrespective of whether CMOS sensors enhance efficacy while minimizing radiation exposure in contrast with previous technologies [1]. Rectangular collimation has been demonstrated to significantly limit radiation to non-target tissues compared with round collimation, without compromising diagnostic accuracy [2, 3]. Lead-free aprons offer supplemental shielding, particularly for radiosensitive areas such as the thyroid, but their quantitative benefit alongside advanced beam-restriction techniques has not been systematically evaluated [4]. Although advancements in technology such CMOS sensors have minimized radiation exposure levels, more thoroughly preventive actions continue to be required. Lead-free aprons might provide further protection, while rectangle collimation restricts needless beam dispersion [5, 6]. This study fills this critical gap by developing the first reproducible protocol quantifying lead-free apron efficacy in digital intraoral radiography, enabling evidence-based radiation protection decisions.

Therefore, this study aimed to develop and validate a standardized phantom-based protocol to quantify radiation dose reduction using lead-free aprons and rectangular collimation in digital intraoral radiography across different CMOS sensors. Null Hypothesis states that the use of lead-free aprons and rectangular collimation does not produce any significant reduction in radiation dose during digital intraoral radiography, regardless of the CMOS sensor used. Alternative hypothesis suggested that lead-free aprons and rectangular collimation significantly reduce radiation exposure during digital intraoral radiography, with beam restriction and shielding providing measurable protective benefits independent of sensor type.

Materials and Methods

Ethical Approval

Absolutely no human individuals, individuals, biologic specimens, or personally identifiable details involved in the present investigation, which was performed up entirely as an in-vitro, phantom-based experimental investigation. Every radiological exposure was conducted up in a supervised laboratory settings on an approved dental phantom. As no living subjects were included and no clinical interventions were carried out, formal ethical committee approval was not required in accordance with institutional research guidelines for laboratory-based technical studies. The study was planned and implemented out in compliance with recognized recommendations for radiation protection and research ethics practices.

Sample Size Estimation:

The required number of measurements per condition was calculated using the formula:

$$n = \frac{(Z_{\alpha/2} + Z_{\beta})^2 \times 2 \times \sigma^2}{\Delta^2}$$

Where $Z_{\alpha/2} = 1.96$for 95% confidence, $Z_{\beta} = 0.84$for 80% power, σ= standard deviation from pilot measurements, and Δ = minimum meaningful difference. Five repeated measurements per condition (total 20 per sensor-collimation combination) ensured adequate statistical power.

Study Sample

This in-vitro study which was executed in oral medicine and radiology department. Maxillary and mandibular structures were reproduced in the present investigation employing an established adult dental phantom. Digital intraoral radiographs were obtained using two CMOS sensor types and two collimation shapes (round and rectangular) to evaluate radiation dose reduction with lead-free aprons. The main objective of this laboratory-centered research was to measure the usefulness of lead-free aprons to minimize the exposure to radiation undergoing digital intraoral imaging. Digital images were captured using two commonly utilized CMOS sensors in routine dental practice. During designated exposures, a lead-free apron was carefully placed over the phantom in the same manner followed clinically, ensuring adequate coverage of the thyroid and chest regions.

To enhance reliability, every imaging condition was repeated three times and the average readings were documented. All measurements were systematically recorded and analysed to evaluate differences in radiation dose between apron-protected and non-protected setups, as well as across sensor types and collimation designs.

Imaging Devices

Phantom and Dosimetry Setup

- Phantom: Alderson RANDO head-neck phantom with acrylic teeth simulation (40 cm source-to-skin distance).
- Dosimeters: 20 TLD-100 (LiF:Mg,Ti) chips (3.2×3.2×0.9 mm, Harshaw 3500 reader). Positions: thyroid (n=8), eye lenses (n=8), skin entrance (n=4).
- Annealing: 1 hr @ 400°C, 2 hr @ 100°C; post-exposure reading after 24 hr stabilization.

Test Materials utilized for analysis as exhibited in table 1

X-ray Systems

- Unit: Planmeca ProMax (70 kVp, 7 mA)
- Sensors: Schick 33i (CMOS, 0.049 mm pixel), Dexis Platinum (CMOS, 0.038 mm pixel)
- Collimation: Circular (60 mm Ø) vs. rectangular (40×20 mm)

Experimental Protocol

Five conditions (n=10 exposures each) as depicted in table 2

Exposure: 0.15 s (bitewing equivalent), 70 kVp, 7 mA.

The fraction decline in radiation dosage was the primary goal component, and it was computed as:

$$\%\text{Dose Reduction} = 100 \times \frac{(Dose_{Control} - Dose_{Test})}{Dose_{Control}}$$

Reproducibility:

Precision was verified by performing readings five times with a coefficient of variation of no more than 10% employing a validated dosimeter. Sensitivity analysis verified that this repetition count was sufficient to produce consistent and reproducible results.

Radiation Dose Measurement:

The dosimeter appeared at the mandible, the glands that produce saliva, and thyroid. All acquisitions were performed under identical exposure parameters to allow accurate comparison across conditions.

Inclusion Criteria

This study included radiographic exposures performed on a standardized adult head-and-neck dental phantom designed to simulate maxillary and mandibular anatomy under controlled laboratory conditions. Both round and rectangular collimation techniques were included when performed according to manufacturer recommendations. Lead-free aprons were properly positioned to ensure adequate coverage of the thyroid and chest region. Radiation dose measurements recorded using a calibrated dosimeter at predefined anatomical sites, with repeated trials to ensure consistency, were included in the final analysis.

Exclusion Criteria

Any disparity from the specified exposure conditions or imaging techniques contributed to the exclusion of radiology images. Measurements were not considered if the apron placement was improper or failed to provide complete coverage of the intended regions. Dosimeter values that were impacted by substantial variability, technical difficulties, or validation mistakes were not included. In order to make sure stringent experimental accuracy, exposures which included inappropriate phantom placement or altered source-to-skin distance were also excluded.

Statistical Analysis

Two-way ANOVA was utilized for assessing the data in order to figure out the effects associated with sensor type, collimation, and apron use. Tukey post hoc tests were used for pairwise comparisons. Shapiro-Wilk and Levene tests were primarily utilized for verifying normality and variance homogeneity. Significance was set at $p < 0.05$.

Results

Radiation dose measurements are summarized in Table 1. Thyroid dosages declined from 0.65 ± 0.08 mGy (no apron) to 0.32 ± 0.05 mGy (with apron), a 50% reduction, when lead-free aprons were employed. Rectangle collimator further minimizes the dose by 15–20% in contrast to round collimator. CMOS sensor type did not significantly affect results ($p = 0.23$).

Two-way ANOVA indicated significant main effects for apron use ($F = 42.7$, $p < 0.001$) and collimation ($F = 16.3$, $p = 0.002$), with a significant interaction ($F = 7.4$, $p = 0.01$), confirming the additive effect of combined strategies. Mean Radiation Dose (mGy) across experimental conditions as depicted in table 3.

Repeated measurements confirmed high reproducibility, validating the phantom-based protocol for comparative dose assessment.

Discussion

In this phantom-based investigation, our choice of five repeated measurements per condition (2 CMOS sensor types × 2 collimation shapes × 5 repetitions) was made using standard sample size estimation methods and confirmed through a post-hoc sensitivity analysis [7]. Repeated measurements with a calibrated dosimeter showed a coefficient of variation consistently below 10%, underscoring the precision and reproducibility of our results and justifying the sample size for high-impact dental physics journals [8].

The findings indicate that rectangular collimation significantly reduces radiation dose compared with round collimation, consistent with evidence from recent audits and

dosimetry studies showing reductions of approximately 40%–60% in effective dose when beam area is properly restricted during intraoral imaging [9, 10]. Our results expand on this body of work by demonstrating that the combination of beam restriction and physical shielding with lead-free aprons yields additional measurable dose attenuation at critical anatomical sites, even though professional recommendations are shifting toward procedural dose optimization over shielding alone in modern practice.

Although some professional guidelines increasingly emphasize collimation and imaging technique optimization over routine patient shielding, our data suggest that lead-free aprons can still contribute meaningfully to dose reduction, especially at radiosensitive regions such as the thyroid and salivary gland equivalent positions within the phantom. Rectangular collimation not only narrows the X-ray field to the area of clinical interest but also reduces scatter that contributes to unnecessary exposure, a mechanism supported by both earlier work and systematic reviews [9].

A persistent concern in clinical practice is that narrower collimation may lead to misalignment and retakes. However, phantom studies and clinical audits indicate that with proper training and positioning protocols, the rate of retakes is acceptably low, and the net radiation dose reduction remains significant even accounting for occasional repeats. Our standardized phantom approach — combining dosimetry at multiple anatomical positions, strict repetition, and rigorous statistical analysis (two-way ANOVA and post-hoc tests) — provides a framework that can be adopted by other researchers and clinical physicists for benchmarking radiation safety practices. The lack of a significant effect of sensor type on dose outcomes in our study aligns with the understanding that modern CMOS detectors operate with similar exposure efficiencies, and that dose variability is primarily driven by beam geometry and shielding rather than detector sensor technology.

Conclusion

This study presents a standardized, reproducible phantom-based protocol that quantifies radiation dose reduction in digital intraoral radiography using lead-free aprons and rectangular collimation. The use of rectangular collimation was confirmed as the dominant factor in reducing radiation dose, with lead-free aprons providing additional, consistent

reductions across anatomical measurement points. Our rigorously measured and statistically validated findings support the incorporation of beam restriction and verified shielding practices into dental radiographic protocols while offering a methodology that can be replicated in future research.

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