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Artificial Intelligence in Pediatric Endodontics: Development of Consensus Guidelines for Working Length Determination Using a Delphi Method

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ABSTRACT

Background: Artificial intelligence (AI) is emerging in endodontics as a promising adjunct, with its widespread applications in radiographic interpretation, anatomical landmark identification, and working length determination. Although preliminary evidence suggests that AI may enhance diagnostic accuracy and clinical efficiency, its application in primary teeth remains limited owing to the unique anatomical characteristics associated with physiological root resorption. Currently, no evidence-based clinical recommendations or consensus guidelines exist regarding the use of AI for working length determination in pediatric endodontics. Aim: To develop expert consensus recommendations on the role of artificial intelligence in working length determination of primary teeth using a modified Delphi methodology. Materials and Methods: Three-round modified Delphi study was carried out with an international multidisciplinary panel of experts in the fields of pediatric dentistry, endodontics, dental radiology, artificial intelligence, and digital dentistry. The consensus statements have been formulated after a thorough examination of the literature at hand and they have been refined after rounds of anonymous questionnaires. Participants rated each statement on a 9-point Likert scale. Consensus was predefined as a median agreement score of ≥7, an interquartile range (IQR) ≤2, and at least 75% agreement among panel members. The level of consensus was assessed using descriptive statistics such as median scores, IQRs and percentage agreement. Results: From 42 invited experts, 35 participated in Round 1, whereas 32 completed all three Delphi rounds. The initial 58 statements were refined to 60, of which 56 (93.3%) achieved final consensus. Expert agreement progressively increased across rounds (Kendall's W: 0.48, 0.67, and 0.81), with high internal consistency (Cronbach's $\alpha = 0.91$). The strongest consensus supported AI can be used as a clinical decision-support tool, its integration with electronic apex locators. It also suggested pediatric-specific validation before clinical implementation, appropriate ethical and regulatory oversight, and incorporation of AI education into dental training. Conclusions: As AI continues to transform pediatric endodontic dental diagnostics, expert consensus is essential for safe, ethical, and evidence-informed adaptation. This Delphi study generates recommendations which are anticipated to serve as an important foundation for future clinical guidelines,

validation studies, and the development of AI-assisted technologies for working length determination in primary teeth.

INTRODUCTION

Pulpectomy is the time-honoured treatment modality for retaining infected or necrotic primary teeth until their normal physiological exfoliation, thereby preserving arch integrity, masticatory function, aesthetics, speech development, and the normal eruption pathway of the permanent successor.[1-3] Among the various stages of pulpectomy, accurate determination of the working length (WL) remains one of the most critical determinants of treatment success.[4-6] Working length is defined as the distance from a reproducible coronal reference point to the point at which canal cleaning, shaping, and obturation should terminate.[7] Accurate WL determination facilitates complete debridement of the root canal system while minimizing the risk of over-instrumentation or under-preparation, both of which may adversely affect clinical outcomes and compromise the developing permanent tooth germ.[4-6]

Determining the working length in primary teeth is considerably more challenging than in permanent dentition because of the unique anatomical and physiological characteristics of the primary root canal system. Progressive physiological root resorption, irregular apical morphology, accessory canals, canal curvature, and the close proximity of the permanent successor contribute to significant variability in the location of the apical terminus. In addition, behavioral management challenges in young children often limit the number of radiographs that can be obtained during treatment, further complicating accurate working length determination.[2,5,6]

Conventionally, WL has been established using tactile sensation, radiographic techniques, and electronic apex locators (EALs). [2,6]Although EALs significantly improves measurement accuracy and reduced dependence on multiple radiographs, no single technique consistently overcomes the anatomical variability associated with primary teeth.[8,9] For this reason, clinicians frequently combine multiple diagnostic methods and rely on individual clinical judgement to determine the final working length, introducing variability in treatment approaches.[8-10]

Recent advances in digital dentistry have accelerated use of Artificial Intelligence (AI) into clinical practice. AI technologies, including machine learning, deep learning, and convolutional neural networks, have demonstrated promising performance in various endodontic applications, including automated tooth segmentation, detection of periapical lesions, identification of root fractures, assessment of canal morphology, and radiographic interpretation.[11,12] Experimental studies have also suggested that AI-assisted systems may accurately identify apical landmarks and estimate working length using digital radiographs and cone-beam computed tomography. However, the majority of available evidence has been generated using permanent teeth, while studies involving primary teeth remain scarce and largely limited to preliminary investigations.[13]

Despite the growing interest in AI-assisted endodontics, its implementation in pediatric dentistry remains unclear. Important questions regarding its clinical indications, reliability of WL in the presence of physiological root resorption, integration with electronic apex locators, ethical considerations, regulatory requirements, clinician responsibility, and the level of evidence required before routine clinical adaptation. At present, no consensus guidelines exist regarding the appropriate role of AI in determining WL in primary teeth. The absence of standardized recommendations or consensus may lead to inconsistent clinical practice, variable adoption of emerging technologies, and uncertainty among clinicians regarding the safe and effective integration of AI into pediatric endodontic care.

When evidence is limited with rapidly evolving technologies, structured expert consensus methods provide an effective approach for developing basic preliminary recommendations and identifying priorities for future research. It is an established technique, the Delphi technique, that systematically gathers and refines expert opinion by a sequence of anonymous, iterative questionnaires using controlled feedback, facilitating the convergence to a consensus with minimal dominance of individuals or group bias.[14] Modified Delphi studies have been widely used in medicine and dentistry to establish clinical recommendations in areas where strong evidence is lacking or evolving.

Consequently, the current research will provide expert consensus recommendations on the use of AI in WL determination of primary teeth under a modified Delphi approach. The present study aims to find areas of agreement regarding the possible clinical uses, its advantages, limitations, implementation, ethical issues and future research priorities of AI-assisted determination of the working length in pediatric endodontics. These consensus statements are discussed to offer initial direction to clinicians, researchers, educators, and technology developers and help in the responsible adoption of AI in pediatric endodontic practice.

MATERIALS AND METHODS

Study Design

This **modified Delphi study conducted** to develop expert consensus recommendations regarding the application of AI in WL determination for primary teeth. Ethical approval was obtained from the Institutional Ethics Committee before commencing the study. To reduce bias participant anonymity was maintained throughout all Delphi rounds to minimize response bias and prevent the influence of dominant individuals

Development of Initial Statements

After reviewing literature an initial pool of consensus statements was developed: Artificial intelligence in dentistry, Artificial intelligence in endodontics, Working length determination, Electronic apex locators, Digital radiography, Pediatric endodontics, Clinical decision-support systems were reviewed. These included systematic reviews, randomised controlled trials, observational studies, narrative reviews, professional guidelines, and expert opinions indexed in PubMed, Scopus, Web of Science, and Embase.

Based on the available evidence

the research team formulated approximately **40–60 preliminary statements**, which organized into the Clinical need for AI, Diagnostic applications, Integration with conventional working length techniques, Clinical implementation, Ethical and legal considerations, Education and training, Research priorities. The preliminary questionnaire went through face and content validation by an independent group of pediatric endodontists before distribution to the expert panel.

Expert Panel Selection

It was done through purposive sampling in which eligible participants met at least one of the following criteria which include, Specialist in Pediatric Dentistry or Endodontics or Oral and maxillo facial Radiologist with a minimum of five years of clinical or academic experience, Faculty member affiliated with an accredited dental institution, Author of peer-reviewed publications related to pediatric endodontics, artificial intelligence, digital dentistry, or dental imaging, Researcher with demonstrated expertise in artificial intelligence or machine learning applications in dentistry

Delphi Procedure

It was divided into three rounds, which included:

Round 1: Participants received an anonymous online questionnaire containing the preliminary consensus statements. Each statement was rated using a **9-point Likert scale**, where:1–3 = Disagree, 4–6 = Neutral or uncertain, 7–9 = Agree.

Also, written comments, suggestions for modifications, identification of ambiguities, proposals for additional statements, and recommendations for new domains were also taken into note. Responses from Round 1 were reviewed, and statements were revised based on participant feedback.

Round 2: All participants were once again given the revised questionnaire. For each statement, participants received: Their previous score, Group median score, Percentage agreement, Anonymous summary of participant comments. Statements failing to achieve predefined consensus were modified or retained for subsequent evaluation.

Round 3: A final round was conducted for statements that remained inconclusive after Round 2.

Participants again read the summarized group responses and give final ratings. By the end of Round 3, any statement that passed the predetermined consensus criteria were incorporated into the final recommendations.

DEFINITION OF CONSENSUS

Consensus was established using predefined criteria:

Median score ≥7

Interquartile range (IQR) ≤2

At least three-quarters of respondents who scored the statement between 7 and 9.

Statements not meeting these criteria after the third Delphi round were considered to have failed to reach consensus and were not included in the final recommendations.

Data Analysis

The statistical analysis was conducted with IBM SPSS Statistics (IBM Corp., Armonk, NY, USA). Participant characteristics and questionnaire responses were summarized using descriptive statistics.

For each statement, the following was calculated:

Median score

Interquartile range (IQR)

Percentage agreement

Frequency distribution of responses

The agreement among experts in the Delphi rounds was evaluated by Cronbach's alpha and Kendall's coefficient of concordance (W). The descriptive analysis of changes in agreement between consecutive rounds was also analyzed to test convergence to consensus.

RESULTS

A total of 42 experts were invited to participate in this modified Delphi study. Among them, 35 professionals accepted to take part and passed Round 1 (response rate: 83.3%). Round 2 (94.3% retention) and Round 3 (97.0% retention) had 33 and 32 experts, respectively, which led to a final completion rate of 91.4%.

The panel of experts consisted of dentists of various specialties, 20 pediatric dentists (57.1%), 8 endodontists (22.9%), 4 oral and maxillofacial radiologists (11.4%), and 3 artificial intelligence and digital dentistry researchers (8.6%). The median clinical or academic experience was 12 years.

Table 1 summarizes the characteristics of the participants.

Delphi Process

A literature review identified 58 preliminary statements across six different thematic domains. Figure 1 shows the Delphi process.

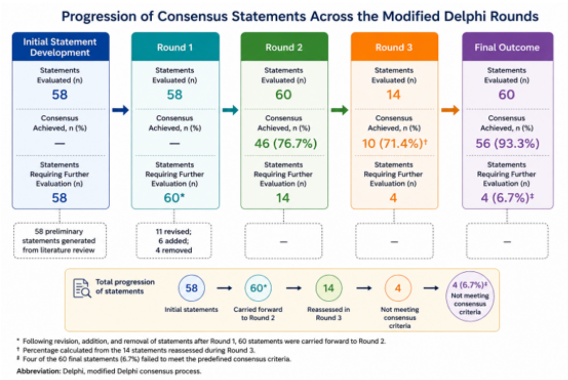

Figure 1. Figure 1: Progression of consensus statements across the modified delphi rounds

Following Round 1: 11 statements were revised, 6 new were suggested by participants and 4 statements were removed because of duplication or ambiguity.

As a result, Round 2 consisted of 60 statements.

Following Round 2: 46 statements (76.7% consensus) were reached, 14 statements needed additional consideration. In comparison, in Round 3, consensus was reached on an extra 10 statements. In total, 56 out of 60 statements (93.3%) met the predetermined consensus criteria, and 4 statements (6.7) did not reach consensus. (Figure 2)

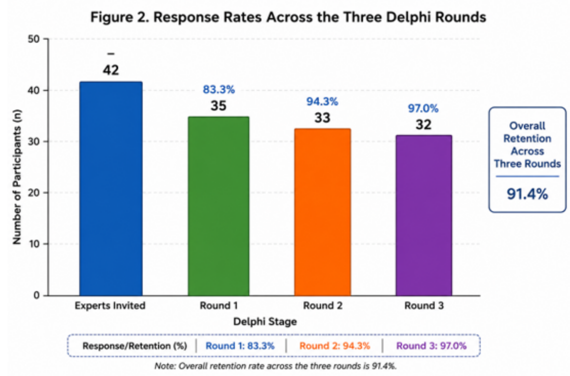

Figure 2. Figure 2: Response rates across Delphi rounds.

Agreement Between Experts

Agreement among experts improved progressively throughout the Delphi process.

Kendall's coefficient of concordance (W) increased from:

Round 1: W = 0.48

Round 2: W = 0.67

Round 3: W = 0.81

indicating substantial convergence of expert opinion.

The final questionnaire demonstrated excellent internal consistency with a **Cronbach's alpha of 0.91**. (Table 2)

Final Consensus Recommendations

A total of **56 consensus recommendations** were established. The five highest-ranked recommendations were:

1. AI is to be used as a clinical decision-support tool and not to substitute clinicians (100% agreement).

2. AI must supplement electronic apex locators in working length determination (100% agreement).

3. Before routine clinical use, pediatric-specific validation studies are needed (100% agreement).

4. Ethical governance and regulatory approval are essential before implementation (97% agreement).

5. AI education should be incorporated into pediatric dental curricula (97% agreement). (Table 3, figure 3)

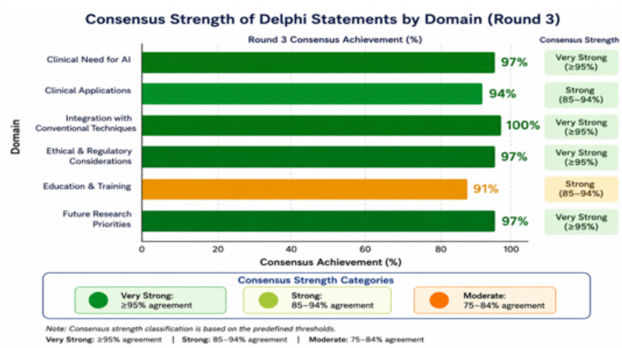

Figure 3. Fig 3: Consensus strength of delphi statements by domain

The complete list of consensus statements and corresponding agreement scores is depicted in Table 4.

Based on the responses final Proposed AI-Assisted Workflow for Working Length Determination in Primary Teeth was depicted in Figure 4.

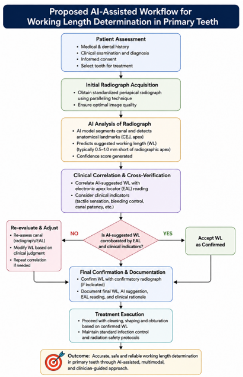

Figure 4. Figure 4– Proposed AI-Assisted Workflow for Working Length Determination in Primary Teeth

DISCUSSION

The present modified Delphi study aimed to establish expert consensus regarding the application of AI in WL determination for primary teeth. With the rapid advancement of AI technologies in dentistry, there is increasing interest in their potential to improve diagnostic precision and clinical decision-making. However, evidence supporting their application in pediatric endodontics remains limited, and standardized recommendations are lacking. The modified Delphi approach enabled the development of consensus-based recommendations by systematically synthesizing expert opinion in an area where high-quality clinical evidence is still evolving. [14,15]

One of the principal findings in this study was the strong consensus about AI should currently function as a **clinical decision-support tool rather than an autonomous diagnostic system**. Experts consistently agreed that AI has the potential to improve the accuracy, reproducibility, and efficiency of WL determination while preserving clinician oversight. This observation is consistent with recent reviews that note that AI is most useful when used to supplement clinician performance, and not to substitute the role of clinical judgement and behaviour in pediatric endodontics, where anatomy, behaviour, and clinical judgement play an important role in influencing treatment outcomes.[11,12,13]

The panel also showed a high level of agreement on the integration of AI with traditional techniques, especially electronic apex locators (EALs) and radiographic evaluation. Accurate WL determination in primary teeth remains challenging because of physiological root resorption, accessory canals, root curvature, and proximity to the developing permanent successor.[16] Although EALs have demonstrated high accuracy in primary teeth, they are not infallible, especially in teeth with advanced physiological resorption.[17,18] For these reasons, experts supported a multimodal diagnostic approach in which AI complements, rather than replaces, conventional techniques.

Another important consensus finding was that AI algorithms intended for pediatric endodontics must be trained and validated using **primary tooth-specific datasets**. Existing dental AI systems have been trained on images of permanent dentition, which are very different in morphology, physiological resorption patterns, pulp chamber size, and root morphology in pediatric patients.[11] As a result, direct extrapolation of these algorithms to children may lower diagnostic accuracy and clinical validity. Recent reviews of AI uses in dentistry have also expressed similar concerns, noting the importance of representative datasets and extraneous validation prior to clinical use. [11,13]

The Delphi panel also came to a significant consensus concerning ethical and regulatory issues of AI implementation. The participants highlighted that patient privacy, data safety, transparency of algorithms, and regulatory control should be regarded as essential conditions to make regular clinical adaptation. These recommendations can be supported by the World Health Organization recommendations on ethics and governance of artificial intelligence in health, which proposed transparency, accountability, explainability, and continuous human control over AI-assisted healthcare systems.[19] These have also been proposed in dental artificial intelligence literature to help introduce artificial intelligence into clinical practice responsibly.

Researchers suggested the introduction of AI-related skills into undergraduate dental education and lifelong education. Concordance in this area, however, was relatively less than in clinical implementation, perhaps due to the varying institutional infrastructure, faculty experience, and existing educational exposure. As past studies have shown, dental professionals are likely to recognize the importance of AI education, even though the systematic introduction of the technology into the curriculum remains low in the world.[20] The development of dental literacy on AI in future practitioners will be essential to the adequate interpretation of algorithm output and safe clinical application.

The panel also outlined a number of future research priorities. Researchers supported multicentre prospective clinical validation studies before the routine application of AI-assisted WL determination. In addition to its diagnostic accuracy, future studies should determine clinical outcomes, operator performance, treatment time, cost-effectiveness, patient safety, and user acceptance. These recommendations are consistent with previous studies in which more general appeals have been made to more robust prospective validation and standardized reporting before the mass deployment of AI in healthcare. [21,22]

The modified Delphi methodology represents a major strength of the present study. The anonymity and repetitiveness of the process reduced the impact of dominant personalities and enabled the experts to re-evaluate their answers in the wake of systematic feedback. The reliability and stability of the consensus is also validated by high response and retention rates in all rounds of the Delphi. Moreover, the involvement of specialists in the fields of pediatric dentistry, endodontics, oral radiology, and digital dentistry made the multidisciplinary opinions applicable to the clinical application of AI.

Nevertheless, certain limitations should be acknowledged. To begin with, Delphi studies are not based on clinical evidence but expert consensus; hence, the recommendations must be viewed as guidance awaiting confirmation by clinical research. Second, the panel does not fully represent global clinical practice. Third, the fast-changing character of AI requires the regular renewal of these recommendations with the emergence of new technologies and more high-quality evidence. Lastly, a number of recommendations relate to emerging AI applications that are yet to be broadly clinically validated in pediatric endodontics.

Overall, this study provides one of the first structured expert consensus frameworks specifically addressing AI-assisted WL determination in primary teeth. These guidelines provide useful advice to clinicians, researchers, software developers, and policymakers and set the priorities of future research. With AI technologies still developing, the cooperation between clinicians, engineers, researchers, and regulatory agencies will be necessary to make sure that these technologies enhance the accuracy of diagnostic results, improve clinical decision-making, and eventually lead to improved outcomes among pediatric patients.

CONCLUSION

This study established consensus on the role of AI in WL determination for primary teeth. The findings support the use of AI as a clinical decision-support tool which is adjunct to conventional methods, while preserving clinician oversight. It also emphasizes the need of AI validation in pediatrics, regulatory standards, and AI education in dental education. These recommendations provide a basis on which AI can be used responsibly in pediatric endodontics and why well-designed prospective clinical trials are needed to confirm its efficacy prior to it becoming a clinical practice.

Table 1. Characteristics of the Expert Panel Participating in the Modified Delphi Study

Variable	Category	n (%)
Total experts invited		42
Experts participating in Round 1		35 (83.3)
Experts completing Round 2		33 (94.3)*
Experts completing Round 3		32 (97.0)*
Specialty	Pediatric Dentistry	20 (57.1)
	Endodontics	8 (22.9)
	Oral and Maxillofacial Radiology	4 (11.4)
	Artificial Intelligence/Digital Dentistry	3 (8.6)
Academic Position	Professor	11 (31.4)
	Associate Professor	10 (28.6)
	Assistant Professor	8 (22.9)
	Consultant/Specialist	6 (17.1)
Years of Professional Experience	5–10 years	6 (17.1)
	11–15 years	9 (25.7)
	16–20 years	8 (22.9)
	>20 years	12 (34.3)
Primary Area of Expertise	Pediatric Endodontics	16 (45.7)

Variable	Category	n (%)
	Clinical Endodontics	8 (22.9)
	Dental Imaging	4 (11.4)
	Artificial Intelligence in Dentistry	3 (8.6)
	Academic Research/Methodology	4 (11.4)

*Percentage calculated based on the number of participants completing the previous Delphi round.

Table 2. Evolution of Expert Consensus Across the Three Delphi Rounds

Statement	Round 1 Agreement (%)	Round 2 Agreement (%)	Round 3 Agreement (%)	Final Status
AI has the potential to improve the accuracy of working length determination in primary teeth.	82	91	97	Consensus
AI should assist in identifying the radiographic apex.	79	88	96	Consensus
AI should assess physiological root resorption before estimating working length.	76	87	94	Consensus
AI should be integrated with electronic apex locators.	86	94	100	Consensus
Radiographic confirmation should remain part of AI-assisted working length determination.	84	91	97	Consensus
Final working length determination should remain the responsibility of the treating clinician.	88	97	100	Consensus
AI systems should undergo clinical validation before routine implementation.	91	97	100	Consensus
AI algorithms should be transparent and explainable.	73	86	94	Consensus
AI education should be included in undergraduate dental curricula.	69	81	91	Consensus
Multicenter clinical validation studies are required before routine clinical adoption.	83	91	97	Consensus
AI should independently determine the final working length without clinician verification.	39	35	31	No Consensus
AI should replace electronic apex locators in routine pediatric endodontics.	48	45	42	No Consensus
AI-generated measurements should be accepted without radiographic confirmation.	33	29	25	No Consensus
AI systems should be permitted to make autonomous clinical decisions.	21	18	16	No Consensus

Agreement (%) represents the proportion of experts assigning a score of **7–9** on the 9-point Likert scale for each statement. **Consensus** was defined as a median score ≥7, an interquartile range (IQR) ≤2, and ≥75% agreement among panel members.

Table 3. Final Consensus Statements on the Role of Artificial Intelligence in Working Length Determination of Primary Teeth

Domain	Consensus Statement	Median (IQR)	Agreement (%)	Consensus Achieved
Clinical Need	AI has the potential to improve the accuracy and consistency of working length determination in primary teeth.	9 (1)	97	Yes
	Physiological root resorption limits the accuracy of conventional working length determination methods.	9 (1)	94	Yes
	AI may reduce operator-dependent variability during working length assessment.	9 (1)	94	Yes
Clinical Applications	AI should assist in identifying the radiographic apex in primary teeth.	9 (1)	96	Yes

Domain	Consensus Statement	Median (IQR)	Agreement (%)	Consensus Achieved
	AI should assess the degree of physiological root resorption before estimating working length.	9 (1)	94	Yes
	AI should provide an estimated working length based on radiographic analysis.	8 (1)	91	Yes
Integration with Conventional Techniques	AI should be used in conjunction with electronic apex locators.	9 (0)	100	Yes
	Radiographic confirmation should remain part of the working length determination process.	9 (1)	97	Yes
	Final clinical judgement should remain the responsibility of the treating clinician.	9 (0)	100	Yes
Safety and Ethics	AI systems should undergo rigorous clinical validation before routine implementation.	9 (0)	100	Yes
	Patient privacy and data security should be ensured when using AI technologies.	9 (1)	97	Yes
	AI algorithms should be transparent and explainable.	8 (1)	94	Yes
	Regulatory approval should precede routine clinical implementation of AI systems.	9 (1)	94	Yes
Education and Training	AI should be incorporated into undergraduate dental education.	8 (2)	91	Yes
	Continuing professional development programmes should include AI training.	9 (1)	94	Yes
Future Research Priorities	Large pediatric-specific datasets are required for AI development.	9 (0)	100	Yes
	Multicenter prospective validation studies should be conducted before routine clinical use.	9 (1)	97	Yes
	AI should be integrated with electronic apex locators for future clinical applications.	9 (1)	94	Yes
	Long-term clinical outcome studies are required to evaluate AI-assisted working length determination.	9 (1)	94	Yes

Consensus criteria: Median score ≥7, Interquartile Range (IQR) ≤2, and ≥75% agreement among participants.

Table 4. Consensus-Based Clinical Recommendations for the Application of Artificial Intelligence in Working Length Determination of Primary Teeth

Recommendation No.	Consensus Recommendation	Strength of Consensus*	Clinical Implication
R1	Artificial intelligence should be used as a **clinical decision-support tool** rather than an autonomous diagnostic system.	Very Strong (100%)	AI should assist, not replace, clinician judgement.
R2	AI-assisted working length estimation should be interpreted in conjunction with **clinical examination, radiographic findings, and electronic apex locator measurements**.	Very Strong (100%)	Multimodal assessment provides greater diagnostic reliability than any single method.
R3	The **final working length** should always be confirmed by the treating clinician.	Very Strong (100%)	Clinical responsibility remains with the operator.
R4	AI systems should undergo **rigorous clinical validation** before routine implementation in pediatric endodontics.	Very Strong (100%)	Validation should include multicenter prospective clinical studies.
R5	AI algorithms should be specifically developed and validated using **primary tooth datasets**, accounting for physiological root resorption.	Very Strong (97%)	Pediatric-specific AI models are likely to perform better than models trained solely on permanent teeth.

Recommendation No.	Consensus Recommendation	Strength of Consensus*	Clinical Implication
R6	AI should assist in identifying the radiographic apex and assessing physiological root resorption.	Very Strong (96%)	AI may improve consistency and reduce operator-dependent variability.
R7	Patient privacy, data security, and regulatory compliance should be ensured before clinical deployment of AI systems.	Very Strong (97%)	AI applications should comply with national and institutional data governance standards.
R8	Dental curricula and continuing professional development programmes should incorporate education on AI-assisted diagnostics.	Strong (94%)	Training will facilitate safe and effective adoption of emerging technologies.
R9	Future research should prioritize prospective multicenter validation studies and cost-effectiveness analyses of AI-assisted working length determination.	Very Strong (97%)	High-quality evidence is required before widespread clinical implementation.
R10	AI should not replace conventional diagnostic methods until sufficient clinical evidence demonstrates comparable or superior performance.	Strong (94%)	AI should currently be considered an adjunct rather than a substitute for established techniques.

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