

DIGITAL TECHNOLOGIES IN DENTISTRY

FROM ROBOT-ASSISTED IMPLANT PLACEMENT TO ARTIFICIAL INTELLIGENCE AIDED DIAGNOSTICS

Ph.D. Thesis

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2026

„Science, my boy, is composed of errors, but errors that it is right to make, for they lead step by step to the truth.”

- Jules Verne, Journey to the Center of the Earth

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1. LIST OF ABBREVIATIONS

AB	Ameloblastoma
AD	Angular Deviation
AI	Artificial intelligence
ApGD	Apical Global Deviation
AR	Augmented Reality
AUC	Area under the Receiver Operating Characteristics curve
A-P	Antero-Posterior
B-L	Bucco-Lingual
B-L AD	Bucco-lingual angular deviation
B-L ApD	Bucco-lingual (medio-lateral) apical deviation
B-L CD	Bucco-lingual (medio-lateral) coronal deviation
CAIS	Computer-assisted Implant Surgery
CBCT	Cone beam computed tomography
CGD	Coronal Global Deviation
CI	Confidence interval
CNN	Convolutional neural network
DC	Dentigerous cyst
dCAIS	dynamic Computer-assisted Implant Surgery
DOR	Diagnostic odds ratio
FG	Fully Guided
FN	False negative
FP	False positive
GRADE	Grades of Recommendation, Assessment, Development, and Evaluation
HAD	Horizontal apical deviation
HCD	Horizontal coronal deviation
HG	Half Guided
IoU	Intersection over union
M-D	Mesio-Distal
M-D AD	Mesio-distal angular deviation
M-D ApD	Mesio-distal (antero-posterior) apical deviation
M-D CD	Mesio-distal (antero-posterior) coronal deviation

M-L	Mesio-Lateral
N	No lesion
NPDC	Nasopalatine duct cyst
NPV	Negative predictive value
OKC	Odontogenic keratocyst
OPG	Orthopantomograph
PG	Pilot Guided
PIRD	Population, Index test, Reference test, Diagnosis of interest
PPV	Positive predictive value
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
QUADAS	Quality Assessment of Diagnostic Accuracy Studies
RC	Radicular cyst
ROC	Receiver operating characteristics
sCAIS	static Computer-assisted Implant Surgery
SD	Standard deviation
SE	Standard error
Se	Sensitivity
Sp	Specificity
TN	True negative
TP	True positive
VA	Vertical distance error in apical surface area
VC	Vertical distance error in coronal surface area

2. STUDENT PROFILE

2.1. Vision and mission statement, specific goals

My vision is a world where innovations are swiftly integrated into everyday dental practice. From robots or augmented reality (AR) to artificial intelligence (AI)- driven diagnostics, all tools enhance the quality of dental care, thereby quality of life.

My mission is to explore the usage and reliability of these methods. My specific goal is to evaluate the accuracy of currently available implant placement techniques and to assess AI-assisted diagnostic tools used for identifying odontogenic cysts and ameloblastomas (ABs).



2.2. Scientometrics

Number of all publications:	6
Cumulative IF:	23.1
Av IF/publication:	3.85
Ranking (SCImago):	D1: 4, Q1: 1, Q2: 1
Number of publications related to the subject of the thesis:	2
Cumulative IF:	8.1
Av IF/publication:	4.05
Ranking (Sci Mago):	D1: 1 Q2: 1
Number of citations on Google Scholar:	187
Number of citations on MTMT (independent):	133
H-index:	4

The detailed bibliography of the student can be found on page 97.

2.3. Future plans

In the future, I aspire to become a specialist in dento-alveolar surgery. I plan to further develop my research on dental implantology, specifically focusing on the learning curve associated with AR-based implant placement. Additionally, I aim to examine the accuracy of AI tools in classifying different implant brands.

3. SUMMARY OF THE THESIS

Recent advancements in digital technologies are transforming the field of dentistry. Innovative techniques, such as AR tools or robots, have been shown to achieve greater implant placement accuracy, which is crucial for the longevity of implants and provides a great aid in complicated cases. The definitive diagnosis of odontogenic cysts and ABs can be established by histologic examination, which requires an invasive procedure. AI algorithms can potentially detect and classify these lesions on routine panoramic radiographs (OPGs).

Study I evaluated the *in vitro* accuracy of currently available implant placement modalities. Study II assessed the performance of AI in classifying, detecting, and segmenting odontogenic cysts and ABs in panoramic radiographs. Study I indicated that fully guided (FG) static computer-assisted implant surgery (sCAIS) achieved the highest accuracy, while freehand implant placement was the least precise.

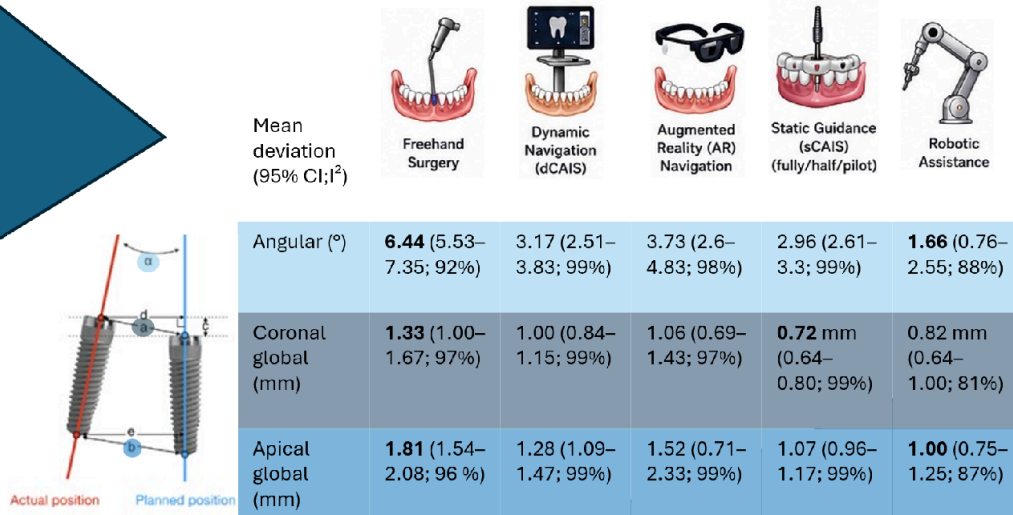
Study II demonstrated high specificity (Sp) but suboptimal sensitivity (Se) for lesion classification.

These findings address significant knowledge gaps. Study I highlights opportunities to improve implant placement accuracy, ultimately improving patients' quality of life. Study II suggests the potential for AI-assisted, rapid, and universally available non-invasive diagnostics in the future.

4. GRAPHICAL ABSTRACT

Digital Technologies in Modern Dentistry

Implant placement



Cyst diagnostics

Panoramic radiograph



AI algorithm

Classification
Detection
Segmentation

Diagnosis

Histopathological diagnosis

The gold standard



Ameloblastoma (AB)
Dentigerous cyst (DC)
Odontogenic keratocyst (OKC)
Radicular cyst (RC)

Lesion type	Classification sensitivity mean (95% CI; I ²)	Classification specificity mean (95% CI; I ²)
AB	0.44 (0.2310–0.6429; 79%)	0.99 (0.9736–1.0000; 0%)
DC	0.88 (0.7828–0.9749; 93%)	0.95 (0.9116–0.9917; 90%)
OKC	0.76 (0.6999–0.8262; 14%)	0.9 (0.8683–0.9298; 8%)
RC	0.91 (0.8051–1.0000; 89%)	0.97 (0.9431–1.0000; 79%)
No lesion	0.97 (0.9284–1.0000; 46%)	0.92 (0.8385–1.0000; 95%)

5. INTRODUCTION

5.1. Overview of the topic

Ever-increasing digital innovations are radically changing the field of dentistry. Therapeutic approaches such as computer-assisted surgery and dental robots have emerged. AI algorithms were developed for diagnostics, personalized treatment planning and risk analysis (1).

These novel techniques can only be integrated into clinical practice if sufficient evidence is available regarding their accuracy and reliability, and potential pitfalls.

This dissertation examines two key areas of improvement: computer-assisted implant surgery (CAIS) and AI-driven radiographic diagnosis of odontogenic cysts and ABs.

5.1.1. What is the topic?

Study I evaluated the *in vitro* accuracy of various implant placement modalities, including conventional freehand implant placement, as well as novel approaches in clinical use like static CAIS (sCAIS) or dynamic CAIS (dCAIS), and cutting-edge techniques with yet scarce practical experience: AR-assisted CAIS, and robot-assisted implant placement.

Convolutional neural networks (CNNs) achieved notable diagnostic accuracy in caries diagnostics (2), periodontology (3) and oral cancer classification and detection (4). Study II investigated their accuracy in the diagnosis of odontogenic cysts and ABs from OPGs.

5.1.2. What is the problem to solve?

5.1.2.1. Study I

In backward planning, implant placement is determined by the prosthetic treatment plan. Surgically, the precise transfer of this virtually planned position to the surgical area is crucial (5, 6).

Freehand implant placement is widely used, yet its accuracy is less reliable, which may lead to iatrogenic damage and biomechanical and esthetic complications. These shortcomings led to the development of computer-assisted approaches (7, 8), which rely on virtual planning through the registration of digital impressions and three-dimensional imaging data (9). To reproduce the planned position, the surgical templates used during

sCAIS guide the instruments of implant bed preparation and implant placement (10). However, its application is impaired in cases of limited mouth opening and is often problematic in the molar region. During implant bed preparation, surgical guides may inhibit drill cooling, thereby causing bone necrosis which in turn can lead to early implant failure (11).

Dynamic navigation systems track the real-time position of the drills and the patient. This information is displayed on a monitor alongside the surgical plan. As dCAIS needs no guides (12), it is suitable for a smaller mouth opening (13, 14). However, as the operator is forced to alternate their attention between the screen and the surgical area while performing dCAIS iatrogenic injuries may occur. (14).

For complete visual control, AR CAIS's virtual retinal displays superimpose the virtual plan on the surgical area (15). Although this technique is still in development, initial results showed promising accuracy (16).

Parallel to this, autonomous and semi-autonomous robotic systems emerged to maximize the accuracy of dental implant placement. Currently, their expenses limit their broader application (17, 18).

5.1.2.2. Study II

Odontogenic cysts manifest in the oral cavity with a reported prevalence of 13.8% (19). As their clinical, radiological, and histopathological characteristics regularly overlap (20), reliable diagnosis is critical, especially in the case of odontogenic keratocysts (OKCs) (10-20% of odontogenic cysts), which show a relatively aggressive growth pattern, recurrence risk, and may occur associated with the Gorlin-Goltz syndrome (up to 5%) (21, 22). They show similar radiographic features to ABs (23), which are benign, yet locally aggressive neoplasms, accounting for 10% of odontogenic tumors. Worldwide, they affect 0.5 per million people a year (24). In rare cases, they may undergo malignant transformation (4).

In the majority of cases, these lesions are asymptomatic and therefore remain undetected until they cause symptoms, including facial asymmetry, tooth displacement, malocclusion or pathological fractures (21, 22).

In spite of their clinical importance, currently, definitive diagnosis can only be gathered through histopathological examination, which is time consuming and involve an

invasive procedure (20).

5.1.3. What is the importance of the topic?

5.1.3.1. Study I

With the rising number of modalities over time, literature and expert opinions are divided regarding the best approach. Previous research mainly focused on freehand implant placement. Literature on sCAIS and conventional dCAIS was often contradictory, while only a few publications described AR and robot-assisted implant placement's accuracy. Thus, a comprehensive analysis was needed to summarize available evidence.

5.1.3.2. Study II

Cysts and ABs are generally distinguishable on routine OPGs.

Due to their ability to analyze spatial information, AI algorithms have the potential to detect (recognize the presence of a particular object), classify (predefine grouping of the detected object), and segment (identify pixels belonging to the detected structure) these lesions. Consequently, this non-invasive, painless diagnostic tool provides a rapid, easily accessible diagnosis to prevent late complications (25).

5.1.4. What would be the impact of our research results?

Until Study I was published, no meta-analysis evaluated the accuracy of robotic CAIS or included the complete spectrum of available implant placement methods.

Thus, this research could provide guidance for professionals regarding the decision-making process on the most appropriate implant placement modality for each individual case. The findings of our *in vitro* evaluation could mean a stepping stone for further clinical investigations.

Study II addressed important knowledge gaps by assessing AI's classification performance for different types of odontogeneous cysts and ABs separately. Our results highlight the need for more evidence on this topic and facilitate the development and later validation of AI diagnostics.

6. OBJECTIVES

6.1. Study I – Advancing accuracy in guided implant placement: A comprehensive meta-analysis

The first study aimed to assess the *in vitro* accuracy of all currently available computer-assisted implant surgery (CAIS) modalities. Additionally, new techniques were evaluated for their potential to achieve clinically acceptable implant placement accuracy, based on evidence from preclinical studies guiding their selection.

6.2. Study II – Artificial Intelligence in the Diagnosis of Odontogenous Cysts and Ameloblastomas—A Systematic Review and Meta-Analysis

We aimed to synthesize all available evidence on classification, detection, and segmentation approaches and verify whether the diagnostic accuracy of AI tools can achieve clinically acceptable levels.

7. METHODS

Studies I. and II. followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (26) and the Cochrane Handbook (27). Study protocols were registered in PROSPERO (registration numbers: CRTN 42022374647 and CRD42024523372).

7.1. Study I – Advancing accuracy in guided implant placement: A comprehensive meta-analysis

7.1.1. Methodology and Protocol

The previously published protocol was modified to provide a more comprehensive analysis. Examination of blocks as models and the evaluation of drilled holes without implants were included. Articles were also accepted if any of our predefined outcomes were assessed. To decrease heterogeneity, populations of animals, cadavers, and dried mandibles were excluded. Only absolute values were used to preserve a consistent distribution of results.

7.1.2. Eligibility Criteria

The study followed the PICO framework. Our population (P) consisted of models undergoing implant placement. Interventions (I) were sCAIS, dCAIS, AR-based CAIS, freehand-, and robot-assisted implant placement. No comparator group (C) was used. The outcome (O) - implant placement accuracy - was defined by several metrics: angular deviation (AD), apical global deviation (ApGD), coronal global deviation (CGD), horizontal apical deviation (HApD), horizontal coronal deviation (HCD), medio-lateral/bucco-lingual (M-L/B-L) apical deviation (ApD), antero-posterior/mesio-distal (A-P/M-D) ApD, M-L/B-L coronal deviation (CD), A-P/M-D CD, vertical distance error in the apical surface area (VA), and vertical distance error in the coronal surface area (VC), B-L AD, and M-D AD.

7.1.3. Information Sources and Search Strategy

MEDLINE (via PubMed), EMBASE, and the Cochrane Central Register of Controlled Trials were systematically searched on April 18, 2023, without filters or restrictions. Selected articles' citations and reference lists were manually inspected. Our search key was illustrated in Table 1.

Search key for PubMed/MEDLINE and Cochrane Central Register of Controlled Trials:
((((dental OR oral) AND (implant OR surgery)) AND (('augmented reality' OR 'augmented reality based-navigation') OR ('navigation system' OR 'Computer-assisted implant surgery' OR 'CAIS' OR 'computer assisted implant placement' OR 'navigated implant surgery')) OR ('Free-hand') OR ('Static computer-assisted' OR 'static navigation' OR static cais OR 'static implant' OR 'static guided') OR ('dynamic computer aided' OR 'dynamic computer guided' OR 'dynamic computer assisted' OR 'Dynamic navigation' OR dynamic cais OR dynamic implant OR 'image guided') OR ('robot-assisted' OR 'robot-assisted' OR robotic)) AND (accuracy OR trueness OR precision OR reliability))
Search key for EMBASE:
(dental OR oral) AND ('implant'/exp OR implant OR 'surgery'/exp OR surgery) AND ('augmented reality'/exp OR 'augmented reality' OR 'augmented reality based-navigation' OR 'navigation system' OR 'computer-assisted implant surgery' OR 'cais' OR 'guided implant' OR 'navigated' OR 'computer assisted implant placement' OR 'free-hand' OR 'freehand' OR 'static computer-assisted' OR 'static navigation' OR 'static cais' OR (static AND cais) OR 'static implant' OR 'static guided' OR 'dynamic computer aided' OR 'dynamic computer guided' OR 'dynamic computer assisted' OR 'dynamic navigation' OR 'dynamic cais' OR (dynamic AND cais) OR 'dynamic implant' OR (dynamic AND ('implant'/exp OR implant)) OR 'navigated implant surgery' OR 'image guided' OR 'robot-assisted' OR robotic) AND ('accuracy'/exp OR accuracy OR trueness OR precision OR reliability)

Table 1. Search key for Study I

7.1.4. Study Selection and Data Extraction

Identified articles were imported into EndNote X9 (Clarivate Analytics, Philadelphia, PA, USA) for reference management. Following duplication removal, articles were evaluated first by title and abstract, and then by full text, by two independent reviewers (A.T. and E.H.). At each step, interrater reliability was assessed by Cohen's kappa coefficients. In case of disagreements, a third independent investigator (M.K.) was consulted. In cases of missing full texts, the study's authors were contacted.

Data were individually collected by two authors (A.T. and E.H.) into a standardized

form (Excel [Microsoft Corporation, Redmond, Washington, United States] data sheet). A third independent investigator (M.K.) resolved disagreements.

We gathered information regarding the first author, year of publication, intervention, number of implants placed, and outcomes. Subgroups based on the guidance level were created for sCAIS: in the pilot guided (PG) group, only pilot drills; in the half guided (HG) group, the entire implant bed preparation; and in the FG group, both drilling and implant placement are performed through a surgical guide (10). If the level of guidance was not shared, the article was included in the overall sCAIS group. Three-dimensional deviations (AD, ApGD, and CGD) were considered our primary outcomes. HApD, HCD, B-L/M- L ApD, M-D/A-P ApD, B-l/M-L CD, M-D/ A-P CD, VA, VC, B-L AD, and M- D AD were the secondary outcomes.

For linear outcomes, the clinically acceptable deviation was set to a maximum of 1.5mm as the literature considered this to be the appropriate peri-implant bone width in the vestibular and oral aspects (28). AD was deemed clinically acceptable if it did not exceed 5°, as Guentsch et al. reported approximately 1.5 mm ApD at 5° AD for a 10-mm-long implant (29).

7.1.5. Risk of Bias and Quality of Evidence Assessment

In vitro studies were assessed by the Quality Assessment Tool For *In vitro* Studies (QUIN Tool) (30). Two authors (A.T. and E.H.) independently evaluated the aims statement, sample size calculation, sampling, methodology, operators, randomization, outcome measurement, details of the outcome evaluator, blinding, statistical analysis, and results demonstration. The "Details of the comparison group" criterion was inapplicable to most studies and therefore was precluded from analysis. Depending on the Sp of the information, each domain received a score of 0 to 2. A score of 0 was given for missing input. If they provided ineligible data, a score of 1 was considered. A score of 2 indicated that the details were specific enough to allow the experiments to be repeated. An independent third author (M.K.) resolved disagreements.

Given the methodological characteristics of the present study, application of the Grades of Recommendation, Assessment, Development, and Evaluation (GRADE) (31) approach for assessing the certainty of evidence was not feasible.

7.1.6. Data Synthesis and Analysis

A random effects model was utilized due to the expected substantial heterogeneity across studies. The study included continuous outcomes without a comparator group; therefore, mean value was considered as the effect size measured with 95% confidence intervals (CI). Sample size, mean, and corresponding standard deviation (SD) data were sought, and pooled mean was calculated using inverse variance weighting method.

Subgroup analyses were conducted for the implantation modalities. We used a Cochran Q test (an omnibus test) (32) for the between-subgroup difference evaluation. For pairwise comparison, the CIs of the subgroups were examined: if the two intervals did not overlap, the difference was considered statistically significant. Our findings are summarized on forest plots.

Prediction intervals (the expected range of the effects of future studies) were applied if the number of studies was sufficiently large and not too heterogeneous.

Higgins and Thompson's I^2 statistics (33) was used to evaluate heterogeneity between the studies. Publication bias was evaluated using funnel plots. Because all included studies reported absolute deviations, resulting in exclusively positive values, conventional funnel plot symmetry could not be expected. Studies with lower standard errors (SEs) were anticipated to cluster near the null line, whereas studies with higher SEs were expected to show greater positive deviations. Consequently, Egger's test (34) was not performed, and funnel plots were inspected qualitatively to identify potentially problematic studies (35). All analyses were conducted in the meta (Schwarzer 2023, v6.2.1) package for basic meta-analysis calculations and plots in R software (R Core Team 2023, v4.3.0) (36). CIs were estimated using the Hartung–Knapp adjustment (37, 38). The heterogeneity variance measure (τ^2) of the means was estimated using restricted maximum likelihood estimator, with CIs derived using the Q-profile method (32, 39). Prediction intervals were calculated based on the t-distribution.

7.2. Study II – Artificial Intelligence in the Diagnosis of Odontogenous Cysts and Ameloblastomas—A Systematic Review and Meta-Analysis

7.2.1. Methodology and Protocol

Minor changes occurred compared to the published protocol: due to missing data, positive predictive value (PPV) and negative predictive value (NPV) could not be evaluated in our meta-analysis. Data available for detection were insufficient for a

meta-analysis, so we could only conduct a systematic review of Se and PPV, and, additionally, average precision (AP) and F1 score. To reflect trends in the studies, sample-size-weighted averages were calculated.

7.2.2. Eligibility Criteria

Eligibility criteria were defined according to the PIRD (Population, Index test, Reference test, Diagnosis of interest) framework. Studies involving patients with panoramic radiographs were enrolled (P). The diagnostic performance of AI (I) was evaluated against histopathological examination (R) for the diagnosis of odontogenic cysts and AB (D). Se, Sp, area under the receiver operating characteristic curve (AUC), and PPV and NPV values were collected.

Studies were eligible if outcome data were reported separately for at least one lesion type supported by histopathological diagnosis. Review articles and alternative imaging modalities, such as cone beam computed tomography (CBCT) or periapical radiography, were excluded.

7.2.3. Information Sources and Search Strategy

The systematic search was conducted in Medline, EMBASE, and Cochrane Central Register of Controlled Trials on 11 January 2026. We used no restrictions or filters. Citations and references were manually screened. The search key is presented in Table 2.

Search key for PubMed/MEDLINE and Cochrane Central Register of Controlled Trials:
(autom* OR algorithm OR (artificial AND intelligence) OR ai OR (neural AND network) OR convolutional OR cnn OR (deep AND learning) OR 'machine learning' OR (computer AND learning) OR ML OR DL) AND (((cyst* OR cyst) AND (dental OR oral OR odonto* OR follicular OR dentigerous OR eruption OR radicular OR periapical OR periodontal OR gingival OR primordial OR keratocyst)) OR ameloblastoma) AND (radiolog* OR imaging OR OP OR x-ray OR panoramic)
Search key for EMBASE:
(autom* OR 'algorithm'/exp OR algorithm OR (artificial AND ('intelligence'/exp OR intelligence)) OR ai OR (neural AND ('network'/exp OR network)) OR convolutional OR cnn OR (deep AND ('learning'/exp OR learning)) OR 'machine learning'/exp OR 'machine learning' OR (('computer'/exp OR computer) AND ('learning'/exp OR learning)) OR ml OR dl) AND ((cyst* OR 'cyst'/exp OR cyst) AND ('dental'/exp OR dental OR oral OR odonto* OR follicular OR dentigerous OR 'eruption'/exp OR eruption OR radicular OR periapical OR periodontal OR gingival OR 'primordial'/exp OR primordial OR 'keratocyst'/exp OR keratocyst) OR 'ameloblastoma'/exp OR ameloblastoma) AND (radiolog* OR 'imaging'/exp OR imaging OR op OR 'x ray'/exp OR 'x ray' OR panoramic)

Table 2. Search strategy for Study II

7.2.4. Study Selection and Data Extraction

Reference management was performed using EndNote X9 (Clarivate Analytics, Philadelphia, PA, USA). After duplicate removal, two reviewers (A.T. and D.T.) independently screened studies based on titles and abstracts, followed by full-text assessment. Interrater agreement was evaluated at both stages using Cohen's kappa coefficient. Discrepancies were resolved by an independent third investigator (M.K.). If full texts could not be retrieved, the corresponding authors were contacted.

Data extraction was conducted separately by two reviewers (A.T. and D.T.) using a standardized form in Microsoft Excel (Microsoft Corporation, Redmond, WA, USA). A third reviewer (M.K.) was consulted in case of disagreements. We contacted authors to clarify missing or ambiguous information.

First author, publication year, lesion type, AI model and architecture, amount of panoramic radiographs per group, and outcomes were extracted from each article. Statistical AI models were categorized according to their mathematical structure. All included studies employed neural networks and deep learning algorithms, which are considered CNNs.

The primary outcomes were Se, Sp, AUC, and PPV and NPV. Where available, we also extracted the numbers or proportions of true-positive (TP), false-positive (FP), true-negative (TN), and false-negative (FN) decisions.

Grouping was based on the lesion types, including AB, radicular cyst (RC), dentigerous cyst (DC), and OKC. As several studies' pools had healthy control radiographs, a separate "no lesion" group (N) was introduced.

7.2.5. Risk of Bias and Quality of Evidence Assessment

Two examiners (A.T. and D.T.) independently performed the assessment using the Quality Assessment of Diagnostic Accuracy Studies (QUADAS-2) tool. Its four domains were patient selection, index test, reference standard, and the flow and timing. Additionally, the first three assessed applicability with the possible ratings of "low," "unclear," or "high" (40). Disagreements were solved by a third independent author (M.K.).

The certainty of the evidence was assessed in accordance with the recommendations of the GRADE Working Group (41) by two reviewers (A.T. and D.T.) separately. For conflicting results, a third independent reviewer (M.K.) was consulted.

7.2.6. Data Synthesis and Analysis

Random-effects meta-analyses were conducted for the classification performance of each lesion type represented by at least 3 studies reporting either the amount of true positives (TPs), true negatives (TNs), false positives (FPs), and false negatives (FNs) or point estimates and intervals for Se and Sp.

A random-intercepts logistic regression model, as recommended by Schwarzer et al. (42) and Stijnen et al. (43), was used to estimate pooled Sp and Se with 95% confidence intervals (CIs). Heterogeneity variance (τ^2) was estimated using the maximum likelihood method, while study-specific CIs were calculated using the Clopper–Pearson method (44).

Forest plots were generated to display individual and pooled estimates of Se and Sp, along with corresponding 95% confidence and prediction regions.

The diagnostic odds ratio (DOR) and its 95% CI were calculated. It reflects the ratio of the odds of a positive test result among diseased individuals to the odds among non-diseased individuals, with higher values indicating superior discriminatory performance. Ranging from 0 to infinity, higher values indicate better performance. It simplifies the comparison of diagnostic performance by combining Se and Sp (45).

Heterogeneity was assessed using I^2 statistics and its CI, obtained from separate univariate analyses.

A pooled random-effect meta-ROC curve with a 95% confidence region was estimated for each lesion type using the nsROC package's non-parametric approach (46), based on the methodology by Martinez-Camblor et al. (47).

Statistical analyses were performed in R (version 4.1.2, R-core team, 2023) (48) using the meta (49) and the lme4 (50) packages, in part based on Freeman et al.'s web tool (51). Statistical analyses followed the recommendations of Harrer et al. (32). For detection performance, predefined standards for meta-analysis were not met. Consequently, results were synthesized descriptively and visualized using summary plots. For PPV, Se, F1-score, and AP, sample size-weighted averages were calculated and plotted for each lesion type to illustrate overall trends across studies.

8. RESULTS

8.1. Study I: Advancing accuracy in guided implant placement: A comprehensive meta-analysis

8.1.1. Study Search and Selection

The systematic search found 5912 studies from which 86 were included (14, 15, 17, 52-134) after the selection. No full text was available for twenty-eight studies (135-162). After full text selection, 20 *in vitro* articles (8, 163-181), four animal or cadaver studies (182-185), and 43 articles of different study designs or unclear outcomes (186-228) were excluded. 1439 references and citations were identified, of which 55 entered full-text selection. 19 studies were eligible (229-247). Six reports could not be retrieved (248-253). Thirty studies in total were excluded: six were not *in vitro* (254-259), and 24 had different or poorly described designs (260-283).

PRISMA 2020 flow diagram for new systematic reviews which included searches of databases, registers and other sources

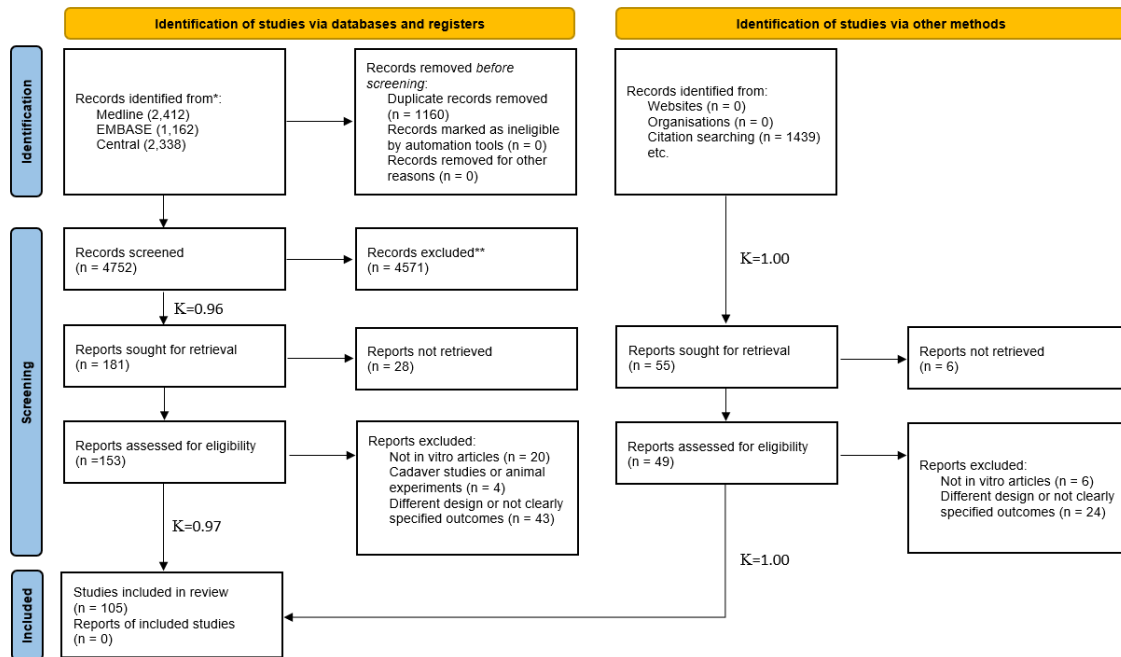


Figure 1. PRISMA flowchart describing Study I's selection process(26).

8.1.2. Description of the Included Studies

This meta-analysis included a total of 105 studies. Freehand implant placement was evaluated by 20 articles, and 32 reported data of dCAIS. AR and robot-assisted implant placement were assessed by 5 articles. The sCAIS group included 79 publications altogether, from which 57 evaluated FG, 9 assessed HG and 12 reported data on PG. 10 studies investigated sCAIS without specifying the guidance level. The detailed baseline characteristics table is available in our article “Advancing accuracy in guided implant placement: A comprehensive meta-analysis: Meta-Analysis evaluation of the accuracy of available implant placement Methods”(284).

8.1.3. Primary Outcomes

8.1.3.1. Angular deviation (AD)

A total of 103 studies were included in the analysis. 19 studies evaluated freehand implant placement (mean 6.44°, 95% CI 5.53–7.35; I² = 92%), five assessed AR (mean 3.73°, 95% CI 2.6–4.83; I² = 98%). dCAIS was investigated by 41 articles (mean 3.17°, 95% CI 2.51–3.83; I² = 99%), and five measured robot-assisted implant placement (mean 1.66°, 95% CI 0.76–2.55; I² = 88%). The overall sCAIS group included 84 studies (mean 2.96°, 95% CI 2.61–3.3; I² = 99%), 11 investigating PG (mean 4.72°,

95% CI 3.45–5.99; $I^2 = 98\%$), nine evaluating HG (mean 3.35°, 95% CI 2.28–4.42; $I^2 = 99\%$), 55 for FG (mean 2.61°, 95% CI 2.27–2.95; $I^2 = 99\%$), and additionally, nine studies which did not clearly specify guidance level.

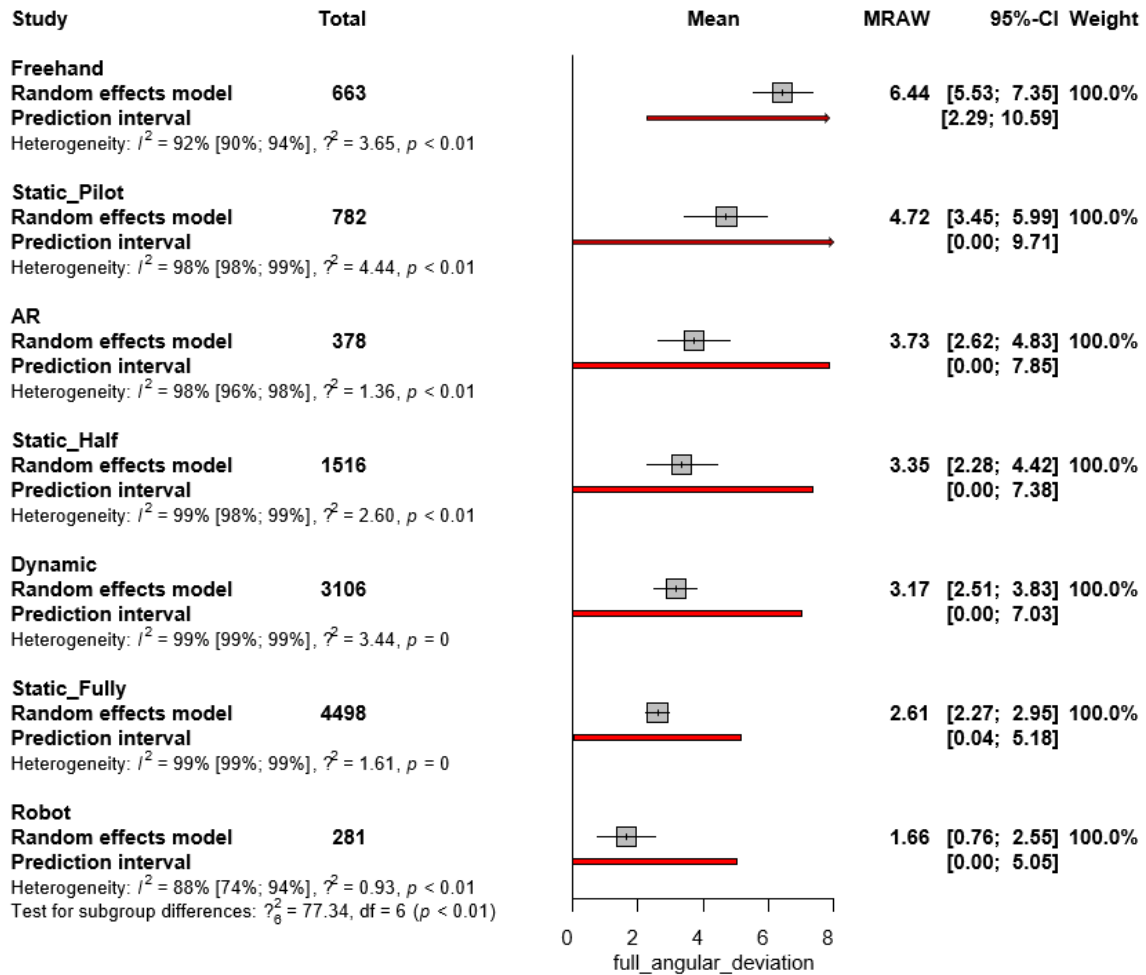


Figure 2. Compact forest plot presenting the AD of various implant placement methods.

Robot-assisted implant placement demonstrated the lowest pooled mean deviation, whereas the freehand approach exhibited the highest. The overall sCAIS group showed significantly higher accuracy than the freehand method but remained less accurate than robotic CAIS.

The 95% CI for freehand implant placement did not overlap with those of the other guidance modalities, except for the PG subgroup, suggesting comparable levels of deviation between these approaches. The PG subgroup demonstrated a tendency for significantly lower accuracy than both the robot-assisted and FG groups, as indicated by

the absence of overlap between their CIs. Similarly, the CI of the AR-guided CAIS group did not overlap with that of the robot-assisted group, suggesting a tendency for significantly greater deviations with AR-guided implant placement.

A maximum AD of 5° was considered clinically acceptable. Among all evaluated approaches, only the freehand group exceeded this threshold based on its pooled mean estimate. Although the pooled mean deviation of the PG subgroup remained below 5°, its 95% CI extended beyond this threshold.

8.1.3.2. Coronal global deviation (CGD)

Seventy-nine articles shared data on CGD: 13 studies for freehand (mean 1.33 mm, 95% CI 1.00–1.67; I2 = 97%), three for AR (mean 1.06 mm, 95% CI 0.69–1.43; I2 = 97%), 22 for dCAIS (mean 1.00 mm, 95% CI 0.84–1.15; I2 = 99%), and four for robots (mean 0.82 mm, 95% CI 0.64–1.00; I2 = 81%). In the sCAIS group (mean 0.72 mm, 95% CI 0.64–0.80; I2 = 99%), seven studies evaluated PG (mean 0.84 mm, 95% CI 0.66–1.03; I2 = 94%), seven assessed HG (mean 0.73 mm, 95% CI 0.49–0.97; I2 = 98%), 44 included FG (mean 0.71 mm, 95% CI 0.61–0.82; I2 = 99%), and eight lacked further description of guidance level.

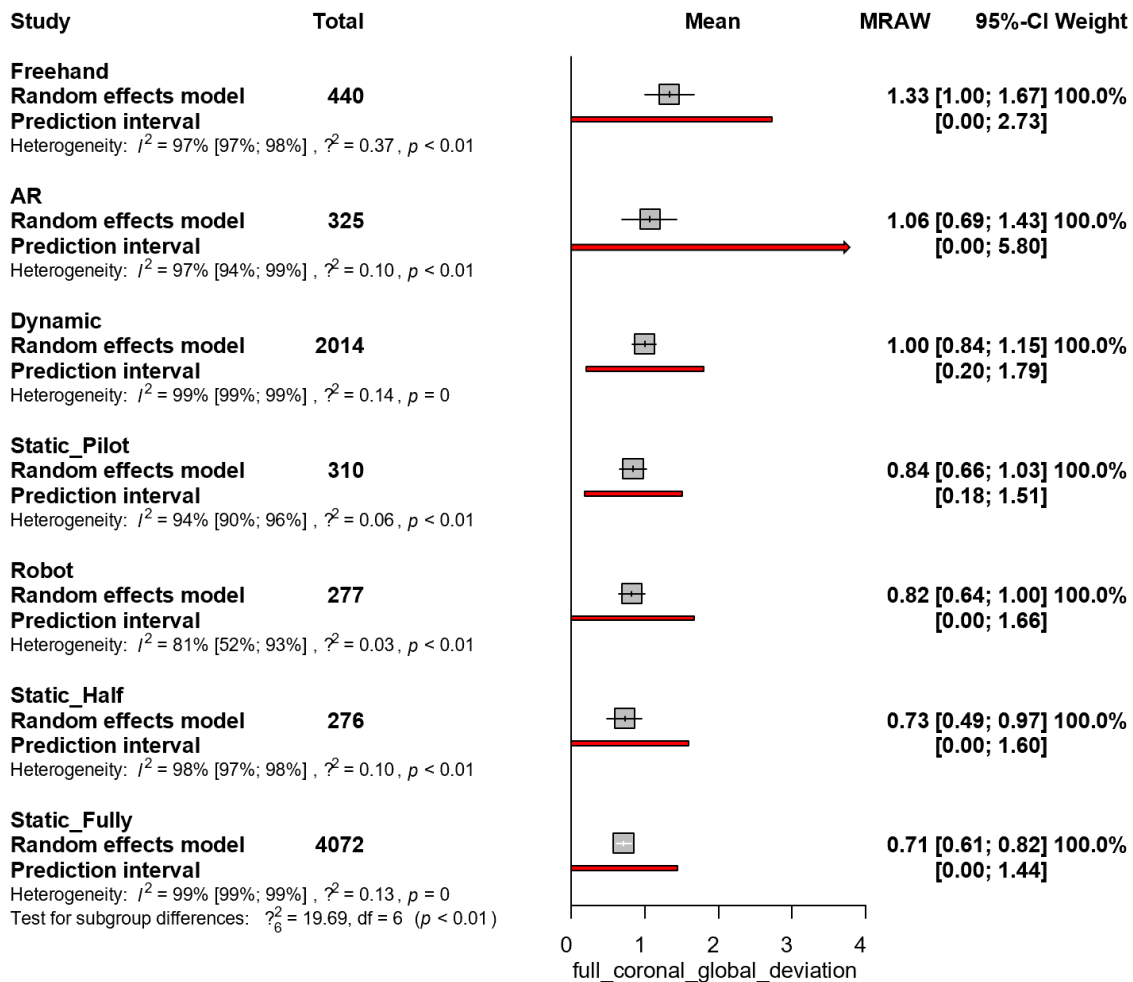


Figure 3. Compact forest plot presenting the CGD of various implant placement methods.

The FG subgroup reached the lowest pooled mean deviation, whereas the freehand group yielded the highest. Both the overall sCAIS and FG subgroups showed a tendency toward greater accuracy compared with the dCAIS and freehand approaches.

HG and FG subgroups tended to produce significantly lower deviations compared to those of the freehand method, as suggested by the non-overlapping CIs.

A maximum deviation of 1.5 mm was considered clinically acceptable. The pooled mean estimates of all evaluated subgroups remained below this threshold. However, the upper bound of the 95% CI for the freehand group exceeded the predefined clinical limit.

8.1.3.3. Apical global deviation (ApGD)

Eighty-four studies evaluated ApGD. 15 articles provided data about freehand (mean 1.81 mm; 95% CI 1.54–2.08; $I^2 = 96\%$), four about AR (mean 1.52 mm, 95% CI 0.71–2.33; $I^2 = 99\%$), 27 about dCAIS (mean 1.28 mm, 95% CI 1.09–1.47; $I^2 = 99\%$), and four about robot-assisted implant placement (mean 1 mm, 95% CI 0.75–1.25; $I^2 = 87\%$). Seventy articles included sCAIS (mean 1.07 mm, 95% CI 0.96–1.17; $I^2 = 99\%$): nine reported on PG (mean 1.39 mm, 95% CI 1.11–1.68; $I^2 = 98\%$), eight on HG (mean 1.11 mm, 95% CI 0.79–1.43; $I^2 = 99\%$), and 45 on FG (mean 1.02 mm, 95% CI 0.90–1.15; $I^2 = 99\%$). Eight studies did not specify the level of guidance.

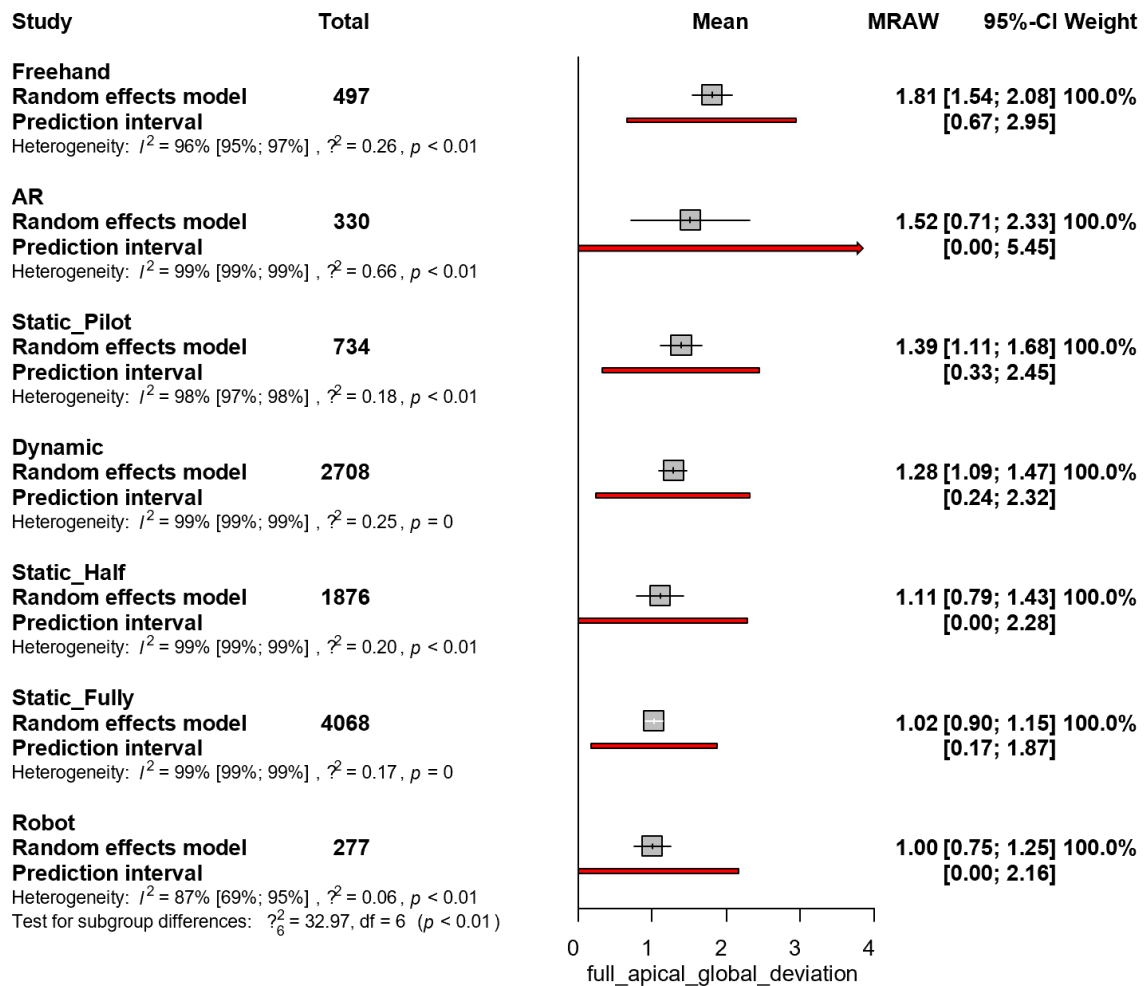


Figure 4. Compact forest plot presenting the AGD of various implant placement methods.

The robot-assisted implant placement subgroup achieved the lowest pooled mean

deviation, whereas the freehand subgroup had the highest. The overall sCAIS group showed a tendency toward greater accuracy than the freehand approach. The CI of freehand implant placement overlapped only with those of the AR and PG subgroups, whereas all other guidance modalities demonstrated a tendency for lower deviations. The robot-assisted subgroup tended to have higher accuracy than the PG method.

A maximum deviation of 1.5 mm was considered clinically acceptable. All pooled mean estimates remained below the predefined threshold. Notably, the upper bound of the 95% CI for the PG subgroup exceeded the limit.

8.1.4. Secondary Outcomes

8.1.4.1. Horizontal Apical Deviation (HAD)

26 articles reported HAD values: four for the freehand method (mean 1.85 mm, 95% CI 1.42–2.27; I²= 81%) and eight for dCAIS (mean 1.30 mm, 95% CI 0.79–1.81; I²= 99%). The sCAIS group (mean 0.95 mm, 95% CI 0.80–1.10; I²= 99%) consisted of four articles about PG (mean 1.28 mm, 95% CI 0.96–1.60; I²= 97%), four about HG (mean 1.02 mm, 95% CI 0.81–1.22; I²= 96%) and 13 about FG (mean 0.82 mm, 95% CI 0.62–1.01; I²= 98%). Regarding AR (mean 1.09 mm, 95% CI 0.95–1.23) and robot-assisted implant placement (mean 0.91 mm, 95% CI 0.43–1.39), only one article was available for each.

The highest pooled mean accuracy was in the FG, and the lowest was in the freehand group. The freehand method tended to achieve significantly lower accuracy than the sCAIS, AR, HG, robot, and FG subgroups. All subgroups except the freehand had lower pooled mean values than the clinically acceptable threshold of 1.5 mm. Also, the upper bounds of the CIs for PG and dCAIS exceeded this limit.

8.1.4.2. Horizontal Coronal Deviation (HCD)

Of the 34 studies, 8 concerned the freehand approach (mean 1.26 mm, 95% CI 0.98–1.53; I²= 98%) and 12 reported on dCAIS (mean 1.07 mm, 95% CI 0.78–1.36; I²= 99%). In sCAIS (mean 0.57 mm, 95% CI 0.48–0.66; I²= 99%), five articles assessed PG (mean 0.83 mm, 95% CI 0.56–1.09; I²= 98%), four evaluated HG (mean 0.67 mm, 95% CI 0.50–0.84; I²= 97%), and 17 examined FG (mean 0.46 mm, 95% CI 0.38–0.54; I²= 98%). Only one article reported HCD regarding AR (mean 1.02 mm, 95% CI 0.91–1.13) and the robot group (mean 0.61 mm, 95% CI 0.44–0.78). Freehand

had the lowest, while FG had the highest accuracy.

The sCAIS group tended to achieve significantly greater accuracy than those by the freehand method, dCAIS, and AR-based CAIS. HG, robot-assisted, and FG CAIS tended towards significantly higher accuracy compared to the freehand group. AR-assisted CAIS showed a tendency to reach significantly higher deviations than those of the HG, robot, and FG groups. Furthermore, FG also tended to show superior precision compared to dCAIS and PG CAIS.

A maximum deviation of 1.5 mm was considered clinically acceptable. All the pooled means fell into this interval; only freehand's CI included higher values.

8.1.4.3. Medio-lateral/Bucco-lingual apical deviation (M-L/B-L ApD)

From 18 studies, three evaluated the freehand method (mean 1.12 mm, 95% CI 0.16–2.07; I²= 92%) and four assessed the dCAIS (mean 0.99 mm, 95% CI 0.70–1.28; I²= 95%). Within the sCAIS (mean 0.55 mm, 95% CI 0.39–0.70; I²= 98%) group, two articles reported deviations on the PG (mean 0.91 mm, 95% CI 0.74–1.07; I²= 68%), two on the HG (mean 0.40 mm, 95% CI 0.17–0.63; I²= 89%) and eight on the FG subgroup (mean 0.54 mm, 95% CI 0.35–0.72; I²= 98%). One article did not specify guidance level.

Freehand method yielded the highest pooled mean value and HG had the lowest. The overall sCAIS group had a tendency for significantly higher accuracy than freehand implant placement. While dCAIS expressed a tendency for significantly greater deviations than that of HG. PG had a tendency for significantly lower accuracy than that of the HG and FG approach. Maximum deviation of 1.5 mm was considered clinically safe, and only freehand implantation's CI included higher values.

8.1.4.4. Antero-posterior/Mesio-distal apical deviation (A-P/M-D AD)

Eighteen studies were included. Three evaluated the freehand method (mean 1.27 mm, 95% CI 0.33–2.22; I²= 95%) and three assessed dCAIS (mean 0.78 mm, 95% CI 0.74–0.82; I²= 0%). Within sCAIS (mean 0.40 mm, 95% CI 0.29–0.51; I²= 96%), three articles published data on PG (mean 0.38 mm, 95% CI 0.28–0.47; I²= 0%), two on HG (0.37 mm, 95% CI 0.04–0.70; I²= 97%), nine on FG (mean 0.42 mm, 95% CI 0.23–0.61; I²= 98%), and one had unclear guidance level.

Freehand implant placement had the lowest accuracy, and HG had the highest. The dCAIS group tended to significantly higher deviations than the sCAIS and its subgroups. The maximum clinically acceptable deviation was considered 1.5 mm, and only the freehand group's CI contained higher deviations.

8.1.4.5. Medio-lateral/Bucco-lingual coronal deviation (M-L/B-L CD)

Eighteen articles were included. Three studies published data on the freehand method (mean 1.22 mm, 95% CI 0.00–2.96; I²= 97%), and four on dCAIS (mean 0.80 mm, 95% CI 0.52–1.08; I²= 97%). From sCAIS (mean 0.31 mm, 95% CI 0.22–0.40; I²= 98%), two studies described PG surgery (mean 0.53 mm, 95% CI 0.36–0.71; I²= 90%), two assessed HG (mean 0.24 mm, 95% CI 0.17–0.30; I²= 72%), seven included FG (mean 0.29 mm, 95% CI 0.19–0.40; I²= 98%) and one study did not specify guidance level.

HG achieved the highest accuracy and freehand had the lowest. The dCAIS group tended to significantly lower accuracy than that of the sCAIS, FG and HG subgroups.

The clinically acceptable accuracy was set to maximum 1.5 mm. Notably, the upper bound of the 95% CI for the freehand group exceeded the limit.

8.1.4.6. Antero-posterior/Mesio-distal coronal deviation (A-P/M-D CD)

Three from eighteen articles assessed the accuracy of freehand implantation (mean 1.04 mm, 95% CI 0.00–2.23; I²= 97%) and three of dCAIS (mean 0.76 mm, 95% CI 0.67–0.85; I²= 62%). In the sCAIS (mean 0.27 mm, 95% CI 0.20–0.34; I²= 96%) group, two studies reported deviations for PG (mean 0.17 mm, 95% CI 0.11–0.22; I²= 52%), two for HG (mean 0.22 mm, 95% CI 0.15–0.28; I²= 66%) and seven for FG (mean 0.29 mm, 95% CI 0.18–0.39; I²= 98%). One article did not describe the guidance level. No articles evaluated the AR and robot groups.

The freehand group yielded the highest pooled deviation and HG CAIS was the most accurate. Both sCAIS and its subgroups tended to significantly higher accuracy compared to dCAIS. The maximum deviation of 1.5 mm was considered clinically acceptable, and only the freehand method's CI contained higher values.

8.1.4.7. Vertical distance error in apical surface area

Forty-two studies were evaluated: seven on freehand (mean 0.45 mm, 95% CI 0.25–0.66; I²= 97%), 19 on dCAIS (mean 0.80, 95% CI 0.60–1.00; I²= 99%), and regarding sCAIS (mean 0.55 mm, 95% CI 0.39–0.71; I²= 99%), four on PG (mean 0.37 mm, 95% CI 0.10–0.64; I²= 99%), five on HG (mean 0.71 mm, 95% CI 0.35–1.07; I²= 100%), 15 on FG (mean 0.50 mm, 95% CI 0.26–0.74; I²= 99%). Three articles had unknown guidance levels. One article evaluated AR (mean 1.08 mm, 95% CI 0.95–1.21) and Robot-assisted implant placement (mean 0.37 mm, 95% CI 0.19–0.55). AR article provided the highest pooled mean, while PG had the lowest. Without the individual AR study, the highest deviation belonged to dCAIS. Apart from the robot-assisted and dCAIS, no significant deviations could be found. All methods expressed clinically acceptable accuracy, as deviations did not reach 1.5 mm.

8.1.4.8. Vertical distance error in coronal surface area

From the total of forty-one studies, eight reported data on the freehand method (mean 0.72 mm, 95% CI 0.15–1.29; I²= 99%) and nine on dCAIS (mean 0.61 mm, 95% CI 0.48–0.73; I²= 97%). Considering sCAIS (mean 0.46 mm, 95% CI 0.34–0.57; I²= 98%), five studies included PG (mean 0.32 mm, 95% CI 0.14–0.50; I²= 92%), four assessed HG (mean 0.50 mm, 95% CI 0.22–0.77; I²= 98%), 18 evaluated FG (mean 0.47 mm, 95% CI 0.29–0.64; I²= 99%) and did not specify the guidance level. No evidence was available on AR CAIS, and only one article reported values for robots (mean 0.38 mm, 95% CI 0.23–0.53).

The highest pooled mean belonged to the freehand and the lowest to the PG groups. No significant between-subgroup difference was found. No pooled mean values surpassed the acceptable accuracy of 1.5 mm.

8.1.4.9. Bucco-lingual angular deviation (B-L AD)

Four studies evaluated this outcome. One article assessed dCAIS (mean 2.86°, 95% CI 2.66–3.06). In the sCAIS (mean 1.28°, 95% CI 0.33–2.23; I²= 97%) group two studies published data on the FG subgroup (mean 1.74°, 95% CI 1.44–2.04; I²= 0%) and one article gave no specific guidance level.

Both sCAIS and FG groups showed a tendency for significantly lower deviations than

the dCAIS group. All deviations remained within the clinically acceptable 5° threshold.

8.1.4.10. Mesio-distal angular deviation (M-D AD)

Four studies reported data for this outcome: one on dCAIS (mean 2.57°, 95% CI 2.39–2.75), two on FG (mean 0.93°, 95% CI 0.59–1.27; I²= 60%) and one on the sCAIS (mean 0.76°, 95% CI 0.39–1.14; I²= 87%) group.

Both sCAIS and FG groups tended for significantly lower deviations compared to dCAIS. None of the subgroups exceeded the clinically acceptable maximum of 5°.

8.1.5. Risk of Bias Assessment

The QUIN tool was used for the assessment. We omitted the "Details of the comparison group" domain, because it was not applicable to the included articles. Medium risk of bias was measured for most articles. The main factors contributing to lower quality scores were insufficient reporting of sample size calculations, randomization methods, and blinding procedures. In addition, operator and assessor reliability were rarely addressed, resulting in maximum of only one score for these domains across most studies.

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Angular Deviation															Angular Deviation															
Study	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Final Score	Overall	Study	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Final Score	Overall	
Kivovics, M. 2022	2	2	2	0	2	1	1	1	1	1	2	2	17	●	Sittikornpaiboon, P. 2021	2	2	2	0	2	1	1	1	1	0	2	2	16	●	
Jiang, W. 2018	2	0	2	0	1	1	0	1	1	1	1	2	12	●	Kim, J. E. 2019	2	1	2	0	1	1	1	1	1	1	1	2	2	15	●
Ma, L. 2019	2	0	1	0	1	1	0	1	0	0	0	2	8	●	Cushen, S. E. 2013	2	1	2	0	2	1	0	1	0	0	1	2	12	●	
Vigh, B. 2013	2	0	2	0	1	1	0	1	0	0	2	2	11	●	Fernández-Gil, Á. 2017	2	0	2	0	1	1	0	1	1	1	1	2	2	13	●
Tao, B. 2022	2	1	2	0	2	1	0	1	1	1	2	2	15	●	Soares, M. M. 2012	2	0	2	0	1	0	0	1	1	0	1	2	10	●	
Cheng, K. J. 2020	2	0	1	0	2	2	0	1	0	1	1	2	12	●	Wang, Z. Y. 2021	2	0	2	0	1	1	0	1	0	0	2	2	11	●	
Feng, Y. 2021	2	0	1	0	2	2	0	1	0	1	1	1	11	●	El Kholy 2018	2	0	2	0	1	1	0	1	0	0	2	2	11	●	
Jorba-García, A. 2019	2	2	2	0	2	1	1	1	1	2	2	2	18	●	El Kholy, K. 2019	2	0	2	0	1	1	0	1	0	0	2	2	11	●	
Chen, C. 2018	2	0	1	0	1	0	0	1	0	0	2	2	9	●	El Kholy, K. 2019	2	0	2	0	1	1	0	1	0	0	2	2	11	●	
Chen, Z. 2022	2	2	2	0	2	1	1	1	1	0	2	2	16	●	Thanasisuebwong, P. 2022	2	1	2	0	2	1	1	1	0	0	2	1	13	●	
Nidkenig, H. J. 2010	2	0	2	0	2	1	0	1	0	1	2	2	13	●	Viegas, V. N. 2010	2	0	1	0	1	0	0	1	0	0	1	1	7	●	
Liang, Y. 2019	2	0	1	0	1	0	2	1	0	0	2	2	11	●	Ahmed, M. F. 2019	2	0	2	0	1	0	1	1	0	0	2	2	11	●	
Wang, X. 2022	2	2	2	0	2	1	1	1	0	0	2	2	15	●	Anunmana, C. 2020	2	1	2	0	2	1	2	1	0	0	2	2	15	●	
Guentsch, A. 2022	2	2	2	0	1	1	0	1	1	1	2	2	15	●	Böse, M. W. H. 2022	2	2	2	0	1	1	2	1	1	1	2	2	17	●	
Guentsch, A. 2020	2	2	2	0	2	1	0	1	1	1	2	1	15	●	Esteve-Pardo, G. 2021	2	0	2	0	2	1	0	1	0	0	2	2	12	●	
Park, S. J. 2017	2	0	2	0	1	1	0	1	0	0	1	1	9	●	Jin, X. 2022	2	0	1	0	1	1	0	1	0	0	2	1	9	●	
Üstek, G. K. 2021	2	1	1	0	1	0	0	1	0	0	1	1	8	●	Kang, S.-H. 2014	2	0	1	0	2	1	0	1	0	0	2	2	12	●	
Franchina, A. 2020	2	0	2	0	1	1	2	1	0	0	2	2	13	●	Lin, C. C. 2020	2	1	1	0	1	1	0	1	0	0	1	2	10	●	
Van de Velde, T. 2008	2	0	2	0	1	1	0	1	0	0	2	2	11	●	Song, Y. W. 2021	2	0	1	0	1	1	1	1	0	0	2	1	10	●	
Pei, X. 2022	2	2	1	0	2	1	1	1	1	1	2	2	16	●	Sun, Y. 2019	2	0	1	0	2	1	1	1	1	1	2	2	14	●	
Guzmán, A. M. 2019	2	0	2	0	1	0	1	1	0	0	2	2	11	●	Thanasisuebwong, P. 2022	2	0	2	0	1	1	2	1	1	1	2	2	15	●	
Schnutenhaus, S. 2021	2	0	2	0	1	1	0	1	1	1	2	2	13	●	Vermeulen, J. 2016	2	0	2	0	1	1	0	1	1	1	2	2	13	●	
Emery, R. W. 2016	2	0	2	0	1	1	0	2	1	2	1	2	14	●	Visuttiwattanakorn, S. 2022	2	1	1	0	2	1	1	1	1	1	2	2	15	●	
Stünkel, R. 2022	2	0	2	0	1	1	0	1	0	0	2	2	11	●	Yi, C. 2022	2	2	1	0	1	1	0	1	0	0	2	2	12	●	
Wang, M. 2022	2	0	2	0	2	1	1	1	0	0	2	2	13	●	Liu, L. 2023	2	0	1	0	1	1	1	1	0	0	2	2	11	●	
Spille, J. 2021	2	0	1	0	1	1	0	1	1	2	2	1	12	●	Toyoshima, T. 2015	2	0	2	0	2	1	0	1	0	0	2	1	11	●	
Zhou, M. 2020	2	0	2	0	1	0	0	1	1	0	2	1	10	●	Pieralli, S. 2020	2	0	2	0	1	1	0	1	0	0	2	2	11	●	
Bi, S. 2022	2	0	1	0	1	0	0	1	0	0	1	2	8	●	Widmann, G. 2016	2	0	2	0	1	1	0	1	0	0	2	2	11	●	
Pellegrino, G. 2020	2	2	1	0	2	1	1	1	1	2	2	2	17	●	Bell, C. K. 2018	2	0	1	0	1	1	0	1	1	0	1	1	9	●	
Feng, Y. 2022	2	0	1	0	2	1	0	1	1	1	2	2	13	●	Brandt, J. 2018	2	0	1	0	1	0	0	1	0	0	2	2	9	●	
Wang, X. Y. 2022	2	2	1	0	1	1	1	1	1	1	2	2	15	●	Talmazov, G. 2020	2	0	2	0	1	1	0	1	0	0	1	2	10	●	
Spille, J. 2022	2	0	1	0	1	1	0	1	0	0	2	2	10	●	Sun, T. M. 2018	2	0	1	0	1	1	0	1	0	0	2	2	10	●	
Sun, T. M. 2019	2	2	2	0	1	2	0	1	0	0	2	1	13	●	Ketabi, A. R. 2021	2	0	2	0	1	1	0	1	0	0	2	2	11	●	
Lin, C. C. 2020	2	1	2	0	2	1	0	1	0	0	2	2	13	●	Pellegrino, G. 2022	2	1	1	0	1	1	1	1	1	1	2	2	14	●	
Dreiseidler, T. 2009	2	0	2	0	1	0	0	1	0	0	2	2	10	●	Schulz, M. C. 2019	2	0	2	0	1	1	0	1	1	0	2	2	12	●	
Rungcharassaeng, K. 2015	2	0	2	0	1	1	1	1	0	0	1	2	11	●	Horwitz, J. 2009	2	0	1	0	1	0	0	1	1	0	2	2	10	●	
D'haese, R. 2021	2	0	2	0	1	0	0	1	0	0	2	2	10	●	Vasak, C. 2013	2	0	2	0	1	1	0	1	1	0	2	2	12	●	
Nagata, K. 2021	2	0	1	0	1	1	0	1	0	0	2	2	10	●	Zheng, G. 2008	1	0	1	0	1	0	0	1	0	0	1	1	6	●	
Widmann, G. 2015	2	0	2	0	1	0	0	1	0	0	1	2	9	●	Tan, P. L. B.	2	1	1	0	2	1	1	1	1	2	1	2	15	●	
Zhou, M. 2021	2	0	2	0	1	0	0	1	0	0	2	2	10	●	Peng, Y. T. 2017	1	0	1	0	1	0	0	1	0	0	2	2	8	●	
Somogyi-Garss, E. 2014	2	0	2	0	1	1	0	1	1	0	2	2	12	●	Chen, J. 2023	2	1	1	0	2	1	1	1	2	1	2	2	16	●	
Chang, R. J. 2018	2	0	1	0	1	0	0	1	1	0	2	2	10	●	Dulla, F. A., 2023	2	0	2	0	1	1	1	1	1	0	1	2	12	●	
Sarment, D. P. 2008	2	0	2	0	1	1	0	1	2	0	1	1	11	●	Giellisch, M., 2023	2	0	2	0	1	0	0	1	0	0	2	2	10	●	
Kauffmann, P. 2018	2	0	2	0	1	1	0	1	0	0	2	2	11	●	Guentsch, A. 2023	2	1	2	0	2	1	0	2	0	1	2	2	15	●	
Abduo, J. 2020	2	1	2	0	2	1	0	1	0	0	2	2	13	●	Otaghsara, S. S. T. 2023	2	2	2	0	2	1	0	1	1	0	2	2	15	●	
Abduo, J. 2021	2	1	1	0	1	1	0	1	0	0	2	2	11	●	Raabe, C. 2023	2	1	2	0	2	1	0	1	1	0	2	2	14	●	
Gjelvold, B. 2018	2	0	2	0	1	1	0	1	0	0	2	2	11	●	Raabe, C. 2023	2	1	2	0	1	1	1	1	1	0	2	2	14	●	
Turbush, S. K. 2012	2	1	2	0	1	1	0	1	0	0	2	1	11	●	Schulz, M. C. 2023	2	0	1	0	1	1	1	1	0	0	2	2	11	●	
Pettersson, A. 2014	2	0	2	0	2	2	0	1	0	0	2	2	13	●	Wei, T. 2023	2	2	2	0	1	1	1	1	1	2	2	2	17	●	
van Groningen, L. 2016	2	0	1	0	1	0	0	1	0	0	2	2	9	●	Kessler, A. 2021	2	0	2	0	2	1	0	1	1	0	2	2	13	●	
Thangwarawut, P. 2022	2	0	2	0	1	0	0	1	1	0	2	2	11	●	Schneider, D. 2021	2	1	1	0	1	1	1	0	0	0	2	2	12	●	
															Kim, S. G. 2015	2	0	2	0	1	1	0	1	0	0	1	2	10	●	

b

Coronal Global Deviation														Apical Global Deviation															
Study	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Final Score	Overall	Study	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Final Score	Overall
Kivovics, M. 2022	2	2	2	0	2	1	1	1	1	1	2	2	17	●	Kivovics, M. 2022	2	2	2	0	2	1	1	1	1	1	2	2	17	●
Viegh, B. 2013	2	0	2	0	1	1	0	1	0	0	2	2	11	●	Ma, L. 2019	2	0	1	0	1	1	0	1	0	0	0	2	8	●
Tao, B. 2022	2	1	2	0	2	1	0	1	1	1	2	2	15	●	Viegh, B. 2013	2	0	2	0	1	1	0	1	0	0	2	2	11	●
Cheng, K. J. 2020	2	0	1	0	2	2	0	1	0	1	1	2	12	●	Tao, B. 2022	2	1	2	0	2	1	0	1	1	1	2	2	15	●
Feng, Y. 2021	2	0	1	0	2	2	0	1	0	1	1	1	11	●	Cheng, K. J. 2020	2	0	1	0	2	2	0	1	0	1	1	2	12	●
Jorba-García, A. 2019	2	2	2	0	2	1	1	1	1	2	2	2	18	●	Feng, Y. 2021	2	0	1	0	2	2	0	1	0	1	1	1	11	●
Chen, C. 2018	2	0	1	0	1	0	0	1	0	0	2	2	9	●	Jorba-García, A. 2019	2	2	2	0	2	1	1	1	1	2	2	2	18	●
Chen, Z. 2022	2	2	2	0	2	1	1	1	1	0	2	2	16	●	Chen, C. 2018	2	0	1	0	1	0	0	1	0	0	2	2	9	●
Liang, Y. 2019	2	0	1	0	1	0	2	1	0	0	2	2	11	●	Chen, Z. 2022	2	2	2	0	2	1	1	1	1	0	2	2	16	●
Guentsch, A. 2022	2	2	2	0	1	1	0	1	1	1	2	2	15	●	Liang, Y. 2019	2	0	1	0	1	0	2	1	0	0	2	2	11	●
Guentsch, A. 2020	2	2	2	0	2	1	0	1	1	1	2	1	15	●	Wang, X. 2022	2	2	2	0	2	1	1	1	0	0	2	2	15	●
Park, S. J. 2017	2	0	2	0	1	1	0	1	0	0	1	1	9	●	Guentsch, A. 2022	2	2	2	0	1	1	0	1	1	1	2	2	15	●
Franchina, A. 2020	2	0	2	0	1	1	2	1	0	0	2	2	13	●	Guentsch, A. 2020	2	2	2	0	2	1	0	1	1	1	2	2	15	●
Vande Velde, T. 2008	2	0	2	0	1	1	0	1	0	0	2	2	11	●	Park, S. J. 2017	2	0	2	0	1	1	0	1	0	0	1	1	9	●
Pei, X. 2022	2	2	1	0	2	1	1	1	1	1	2	2	16	●	Üsteki, G. K. 2021	2	1	1	0	1	0	0	1	0	0	1	1	8	●
Guemán, A. M. 2019	2	0	2	0	1	0	1	1	0	0	2	2	11	●	Franchina, A. 2020	2	0	2	0	1	1	2	1	0	0	2	2	13	●
Schmutenhäus, S. 2021	2	0	2	0	1	1	0	1	1	1	2	2	13	●	Pei, X. 2022	2	2	1	0	2	1	1	1	1	1	2	2	16	●
Emery, R. W. 2016	2	0	2	0	1	1	0	2	1	2	1	2	14	●	Guemán, A. M. 2019	2	0	2	0	1	0	1	1	0	0	2	2	11	●
Stünkel, R. 2022	2	0	2	0	1	1	0	1	0	0	2	2	11	●	Schmutenhäus, S. 2021	2	0	2	0	1	1	0	1	1	1	2	2	13	●
Wang, M. 2022	2	0	2	0	2	1	1	1	0	0	2	2	13	●	Emery, R. W. 2016	2	0	2	0	1	1	0	2	1	2	1	2	14	●
Spille, J. 2021	2	0	1	0	1	1	0	1	1	2	2	1	12	●	Stünkel, R. 2022	2	0	2	0	1	1	0	1	0	0	2	2	11	●
Zhou, M. 2020	2	0	2	0	1	0	0	1	1	0	2	1	10	●	Wang, M. 2022	2	0	2	0	2	1	1	1	0	0	2	2	13	●
Bi, S. 2022	2	0	1	0	1	0	0	1	0	0	1	2	8	●	Spille, J. 2021	2	0	1	0	1	1	0	1	1	2	2	1	12	●
Pellegrino, G. 2020	2	2	1	0	2	1	1	1	1	2	2	2	17	●	Zhou, M. 2020	2	0	2	0	1	0	0	1	1	0	2	1	10	●
Feng, Y. 2022	2	0	1	0	2	1	0	1	1	1	2	2	13	●	Bi, S. 2022	2	0	1	0	1	0	0	1	0	0	1	2	8	●
Wang, X. Y. 2022	2	2	1	0	1	1	1	1	1	1	2	2	15	●	Pellegrino, G. 2020	2	2	1	0	2	1	1	1	1	2	2	2	17	●
Lin, C. C. 2020	2	1	2	0	2	1	0	1	0	0	2	2	13	●	Feng, Y. 2022	2	0	1	0	2	1	0	1	1	1	2	2	13	●
Rungcharasaeeng, K. 2015	2	0	2	0	1	1	1	0	0	1	2	2	11	●	Wang, X. Y. 2022	2	2	1	0	1	1	1	1	1	1	2	2	15	●
D'haese, R. 2021	2	0	2	0	1	0	0	1	0	0	2	2	10	●	Sun, T. M. 2019	2	2	2	0	1	2	0	1	0	0	2	2	13	●
Nagata, K. 2021	2	0	1	0	1	1	0	1	0	0	2	2	10	●	Lin, C. C. 2020	2	1	2	0	2	1	0	1	0	0	2	2	13	●
Widmann, G. 2015	2	0	2	0	1	0	0	1	0	0	1	2	9	●	Rungcharasaeeng, K. 2015	2	0	2	0	1	1	1	1	0	0	1	2	11	●
Zhou, M. 2021	2	0	2	0	1	0	0	1	0	0	2	2	10	●	D'haese, R. 2021	2	0	2	0	1	0	0	1	0	0	2	2	10	●
Chang, R. J. 2018	2	0	1	0	1	0	0	1	1	0	2	2	10	●	Nagata, K. 2021	2	0	1	0	1	1	0	1	0	0	2	2	10	●
Sarmant, D. P. 2003	2	0	2	0	1	1	0	1	2	0	1	1	11	●	Widmann, G. 2015	2	0	2	0	1	0	0	1	0	0	1	2	9	●
Gjelvold, B. 2018	2	0	2	0	1	1	0	1	0	0	2	2	11	●	Zhou, M. 2021	2	0	2	0	1	0	0	1	0	0	2	2	10	●
Turbush, S. K. 2012	2	1	2	0	1	1	0	1	0	0	2	1	11	●	Somayaji-García, E. 2014	2	0	2	0	1	1	0	1	1	0	2	2	12	●
Pettersson, A. 2014	2	0	2	0	2	2	0	1	0	0	2	2	13	●	Cheng, R. J. 2018	2	0	1	0	1	0	0	1	1	0	2	2	10	●
van Groningen, L. 2016	2	0	1	0	1	0	0	1	0	0	2	2	9	●	Sarmant, D. P. 2003	2	0	2	0	1	1	0	1	2	0	1	1	11	●
Thangwarawut, P. 2022	2	0	2	0	1	0	0	1	1	0	2	2	11	●	Gjelvold, B. 2018	2	0	2	0	1	1	0	1	0	0	2	2	11	●
Sittikornpaiboon, P. 2021	2	2	2	0	2	1	1	1	1	0	2	2	16	●	Turbush, S. K. 2012	2	1	2	0	1	1	0	1	0	0	2	2	11	●
Henprasert, P. 2020	2	2	2	0	2	1	1	1	2	0	2	2	17	●	Pettersson, A. 2014	2	0	2	0	2	2	0	1	0	0	2	2	13	●
Kim, J. E. 2019	2	1	2	0	1	1	1	1	1	1	2	2	15	●	vanGroningen, L. 2016	2	0	1	0	1	0	0	1	0	0	2	2	9	●
Fernández-Gil, Á. 2017	2	0	2	0	1	1	0	1	1	1	2	2	13	●	Thangwarawut, P. 2022	2	0	2	0	1	0	0	1	1	0	2	2	11	●
Soares, M. M. 2012	2	0	2	0	1	0	0	1	1	0	1	2	10	●	Sittikornpaiboon, P. 2021	2	2	2	0	2	1	1	1	1	0	2	2	16	●
Wang, Z. Y. 2021	2	0	2	0	1	1	0	1	0	0	2	2	11	●	Henprasert, P. 2020	2	2	2	0	2	1	1	1	2	0	2	2	17	●
El Kholy 2018	2	0	2	0	1	1	0	1	0	0	2	2	11	●	Kim, J. E. 2019	2	1	2	0	1	1	1	1	1	1	2	2	15	●
El Kholy, K. 2019	2	0	2	0	1	1	0	1	0	0	2	2	11	●	Fernández-Gil, Á. 2017	2	0	2	0	1	1	0	1	1	1	2	2	13	●
El Kholy, K. 2019	2	0	2	0	1	1	0	1	0	0	2	2	11	●	Soares, M. M. 2012	2	0	2	0	1	0	0	1	1	0	1	2	10	●
Thanasisuebwong, P. 2022	2	1	2	0	2	1	1	1	0	0	2	2	13	●	Wang, Z. Y. 2021	2	0	2	0	1	1	0	1	0	0	2	2	11	●
Viegas, V. N. 2010	2	0	1	0	1	0	0	1	0	0	1	1	7	●	El Kholy 2018	2	0	2	0	1	1	0	1	0	0	2	2	11	●
Ahmed, M. F. 2019	2	0	2	0	1	0	1	1	0	0	2	2	11	●	El Kholy, K. 2019	2	0	2	0	1	1	0	1	0	0	2	2	11	●
Anunmana, C. 2020	2	1	2	0	2	1	2	1	0	0	2	2	15	●	El Kholy, K. 2019	2	0	2	0	1	1	0	1	0	0	2	2	11	●
Esteve-Pardo, G. 2021	2	0	2	0	2	1	0	1	0	0	2	2	12	●	Thanasisuebwong, P. 2022	2	1	2	0	2	1	1	1	0	0	2	2	13	●
Lin, C. C. 2020	2	1	1	0	1	1	0	1	0	0	1	2	10	●	Viegas, V. N. 2010	2	0	1	0	1	0	0	1	0	0	1	1	7	●
Song, Y. W. 2021	2	0	1	0	1	1	1	1	0	0	2	1	10	●	Ahmed, M. F. 2019	2	0	2	0	1	0	1	1	0	0	2	2	11	●
Sun, Y. 2019	2	0	1	0	2	1	1	1	1	1	1	2	14	●	Anunmana, C. 2020	2	1	2	0	2	1	2	1	0	0	2	2	15	●
Thanasisuebwong, P. 2022	2	0	2	0	1	1	2	1	1	1	2	2	15	●	Böse, M. W. H. 2022	2	2	2	0	1	1	2	1	1	1	2	2	17	●
Visuttiwattanakorn, S. 2022	2	1	1	0	2	1																							

Operator details, Q7: Randomization, Q8: Method of measurement of outcome, Q9: Outcome assessor details, Q10: Blinding, Q11: Statistical analysis, Q12: Presentation of results

8.1.6. Publication Bias

Funnel plots were generated to evaluate potential small-study effects for all outcomes, with the pooled mean used as the effect estimate and the SE as the measure of precision. In most plots, the studies were sparse on the left side of the funnel, which may indicate the underrepresentation of small sample sizes studies and non-significant results. However, this asymmetry may also be explained by other factors, including the substantial heterogeneity among the included studies and the lack of randomization. Furthermore, deviations were absolute value and the scale itself was asymmetrical. Theoretically, all the results could range from zero to positive infinity.

Substantial heterogeneity was observed across all analyses. This is likely attributable to differences in study characteristics, including operator experience, implant systems, materials, software platforms, and other methodological factors.

8.2. Study II: Artificial Intelligence in the Diagnosis of Odontogenous Cysts and Ameloblastomas—A Systematic Review and Meta-Analysis

8.2.1. Study Search and Selection

5664 articles were identified by systematic search. Following the elimination of duplicates, 4,808 articles underwent title and abstract screening, of which 33 were considered potentially eligible. After the full-text assessment 11 articles met the inclusion criteria (285-295). Twenty articles were excluded due to their study designs (296-315) and two more due to the absence of histopathological confirmation (316, 317). 499 additional citations and references were assessed for eligibility, from which 21 were sought for retrieval. The full texts of seven reports could not be retrieved (318-324) and 12 had unsuitable designs (325-336). Finally, two additional studies could be included in our review (337, 338)(Figure 6).

Among the included studies, seven reported either CIs or sufficient contingency table data (TP, TN, FP, FN), enabling quantitative synthesis of classification performance. Owing to insufficient data for meta-analysis, outcomes related to detection and segmentation were evaluated descriptively within the systematic review.

PRISMA 2020 flow diagram for new systematic reviews which included searches of databases, registers and other sources

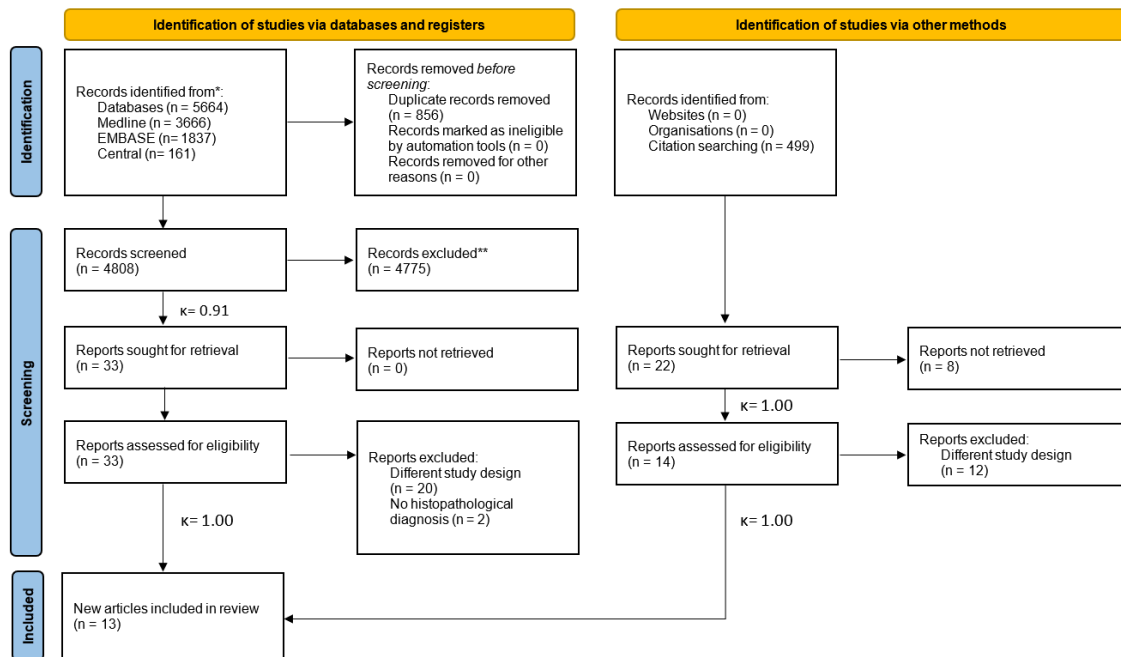


Figure 6. PRISMA flowchart describing Study II's selection process (26).

8.2.2. Description of the Included Studies

Characteristics of included studies are illustrated in Table 3.

Baseline Characteristics Table														
No.	Publication data		DOI	Radio graph	AI type	AI system	Augmentation			Lesions included	Trained	Validated	Tested	Classification/ Detection/Seg- mentation
	First Author	Year					Method	System	"Without augmentation" data					
1	Yang, H.	2020	10.3390/jcm9061839	OPG	CNN	Yolo	Images were horizontally and vertically flipped (in the range of 10°), translated, and scaled.	Pytorch 1.2.0 (PyTorch Foundation)	no	DC, OKC, AB, N	1248 images, 16224 after augmentation	174	181	Classification
2	Kwon, O.	2020	10.1259%2Fdmfr.20200185	OPG	CNN	modified Yolo v3	Images were flipped horizontally, rotated by 1° and -1°, and their grayscale was transformed by γ correction ($\gamma = 0.8, 1, 1.2$).	MATLAB (MathWorks, Natick, MA)	yes	DC, RC, OKC, AB, N	946 images, increased by 12-fold after augmentation	N/A	256	Classification
														Detection
3	Ariji, Y.	2019	10.1016/j.joooo.2019.05.014	OPG	CNN	DetectNet	No augmentation described			AB, OKC, DC, RC, simple bone cyst	210	N/A	Testing dataset 1: 50; testing dataset 2: 25	Classification
														Detection
4	Yu, D.	2022	10.1038/s41598-022-05913-5	OPG	CNN	MoCoV2 was used for classification, Unet28 was used for segmentation	Horizontal flipping, cut-and-pasting, and patch-covering	N/A	no	DC, RC, AB, OKC, N	10616 before augmentation	477	289	Classification
														Detection
														Segmentation
5	Ver Berne, J.	2023	10.1016/j.jdent.2023.104581	OPG	CNN	MobileNetV2 was used for classification, Yolo v3 was used for detection	Optical distortion, horizontal flip, random gamma noise, multiplicative noise, random tone curve, sharpening the edges, and Gaussian noise.	Albumentations augmentation library in Python	no	RC, granuloma, positive control (radio lucent lesion), negative control (no pathology)	Stratified k-fold cross validation was used to randomly split the augmented dataset into training and validation sets in a 10-fold manner	67	Classification	
													21	Detection
6	Kise, Y.	2023	10.5624/isd.20220133	OPG	CNN	DetectNet	No augmentation described			AB, OKC, DC, RC, Stafne cyst	200	50	60	Classification
														Detection
7	Lee, H. S.	2023	10.1016/j.joooo.2023.09.012	OPG	CNN	EfficientDet	Rotation (-30° to 30°); width, and height shift (-20% to 20%) in the horizontal and vertical axes and zooming (0% to 20%).	N/A	no	RC, NDPC, N	967	121	121	Classification

8	Lee, J.H.	2019	10.1111/odi.13223	OPG	CNN	CNN derived from GoogleNet/Inception v3	horizontal and vertical flipping Rotation (in the range of 20°), width and height shifting (in the range of 0.2), shearing (in the range of 0.5), and zooming (in the range of 0.8-1.2).	N/A	no	OKC, DC, RC	684 (68400 after augmentation)	228 (22800 after augmentation)	228	Classification
9	Watanabe, H.	2021	10.1007/s11282-020-00485-4	OPG	CNN	DetectNet	No augmentation described			RC, other	330	71	106	Classification Detection
10	Kang, J.	2024	10.1038/s41598-024-52929-0	OPG	DOLNet FPN	DOLNet	Horizontal and vertical flipping (probabilities of 0.5 each), rotations (up to 5°), and color jittering in [0, 1] for the brightness, contrast, and saturation, and in [0, 0.5] for the hue.	LesionMix	no	AB, OKC, DC, N	The split ratio of the datasets for training, validation, and test was 0.75:0.10:0.15.			Classification Detection
11	Sivasundaram, S.	2021	10.1002/jima.22625	OPG	CNN	modified LeNet	Left shifting and right shifting	N/A	no	DC, odontogenic cyst, RC, N	Threefold cross-validation: the model was trained using twofold and testing is done on the remaining fold. 1171 images were used for testing and the remaining 2342 images were used for training.			Classification Segmentation
12	Sim, S.Y.	2024	10.3390/diagnostics14111144	OPG	CNN	Inception-ResNet-V2	Rotation (-10°-10°) and translation (-5-5 pixels horizontally and vertically).	N/A	no	OKC, SBC	163	41	41	Classification
13	Rašić, M.	2024	10.3390/diagnostics14131443	OPG	CNN	Yolo v8m and Yolo v8l	Translation, scaling, horizontal flipping, rotation, and mosaic augmentation.	N/A	yes	RC, N	The dataset was divided into 3:1:1 subsets for training, testing and validation.			Detection

Table 3. Baseline characteristics table for Study II

8.2.3. Meta-Analysis - Classification

8.2.3.1. Sensitivity (Se)

Two studies evaluated the classification of ABs, yielding a pooled mean estimate of 0.4369 (95% CI: 0.2310–0.6429; $I^2 = 79\%$). Four studies provided data for DC, OKC, and N, resulting in pooled mean estimates of 0.8788 (95% CI: 0.7828–0.9749; $I^2 = 93\%$), 0.7630 (95% CI: 0.6999–0.8262; $I^2 = 14\%$), and 0.9726 (95% CI: 0.9284–1.0000; $I^2 = 46\%$), respectively. Five studies were included in the analysis of RC, yielding a pooled mean estimate of 0.9054 (95% CI: 0.8051–1.0000; $I^2 = 89\%$).

Results for AB, RC, and DC were statistically significant. Each value was clinically significant, apart from the AB group.

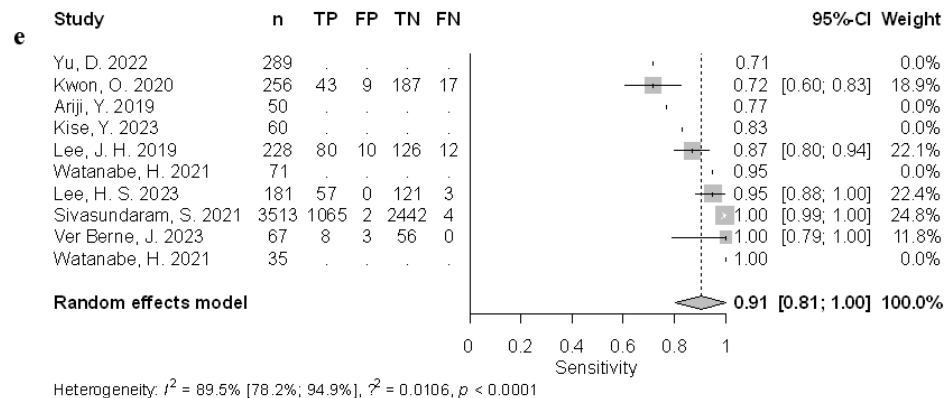
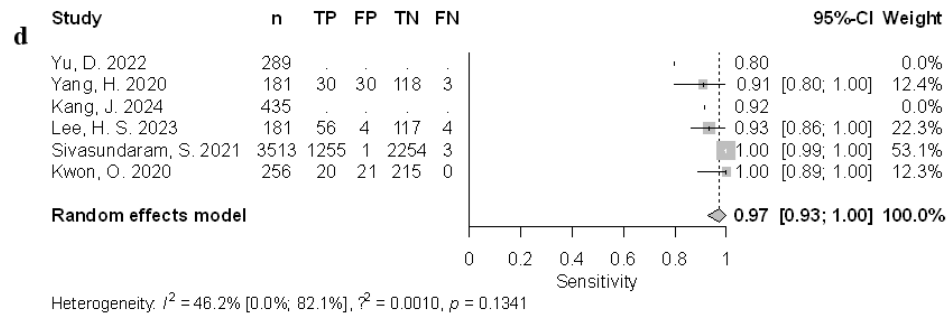
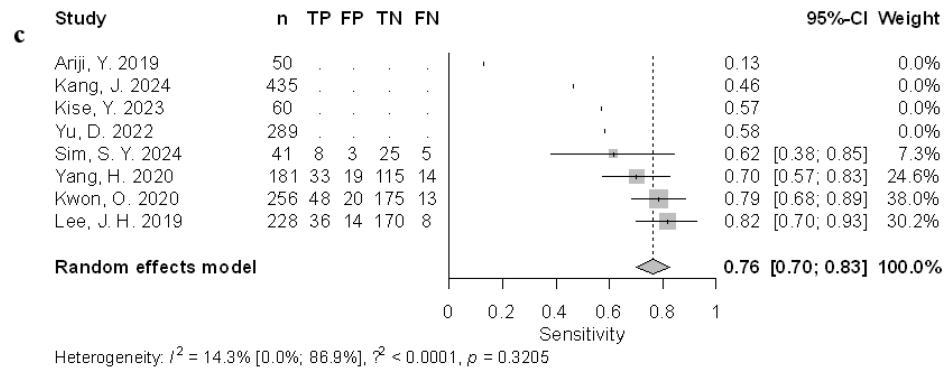
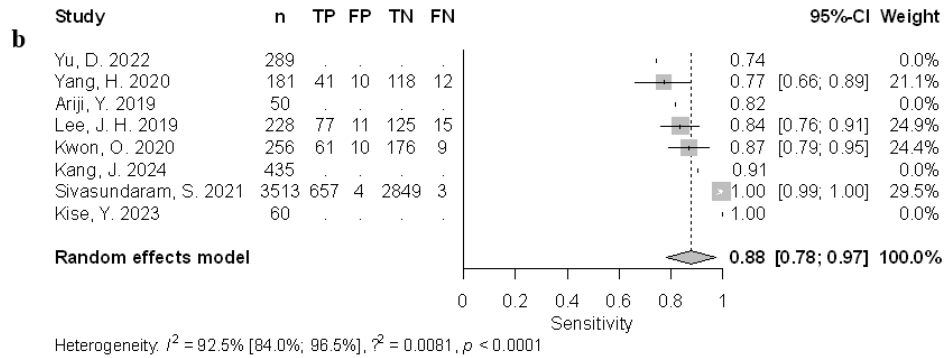
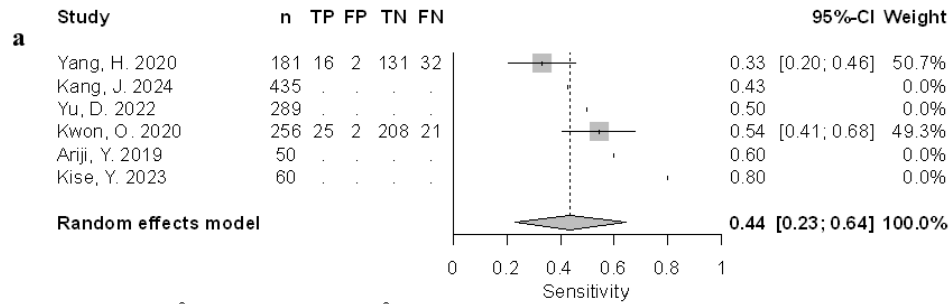


Figure 7. Forest plots illustrating the Se results for the a) AB, b) DC, c) OKC, d) N and e) RC groups.

8.2.3.2. Specificity (Sp)

Two studies reported data for AB, yielding a pooled mean estimate of 0.9889 (95% CI: 0.9736–1.0000; $I^2 = 0\%$). Four studies provided data for DC, OKC, and N, resulting in pooled mean estimates of 0.9516 (95% CI: 0.9116–0.9917; $I^2 = 90\%$), 0.8991 (95% CI: 0.8683–0.9298; $I^2 = 8\%$), and 0.9226 (95% CI: 0.8385–1.0000; $I^2 = 95\%$), respectively. Five studies were included in the analysis of RC, yielding a pooled mean estimate of 0.9724 (95% CI: 0.9431–1.0000; $I^2 = 79\%$). Statistically significant results were observed for DC, N, and RC. All lesion types had clinically relevant values.

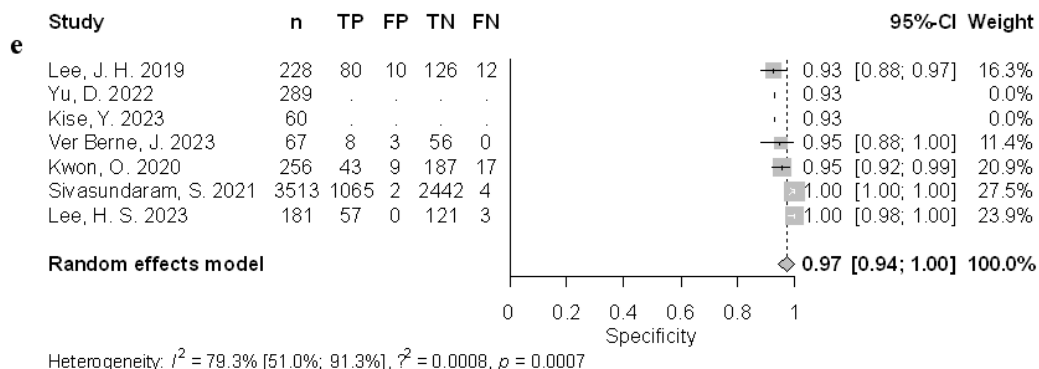
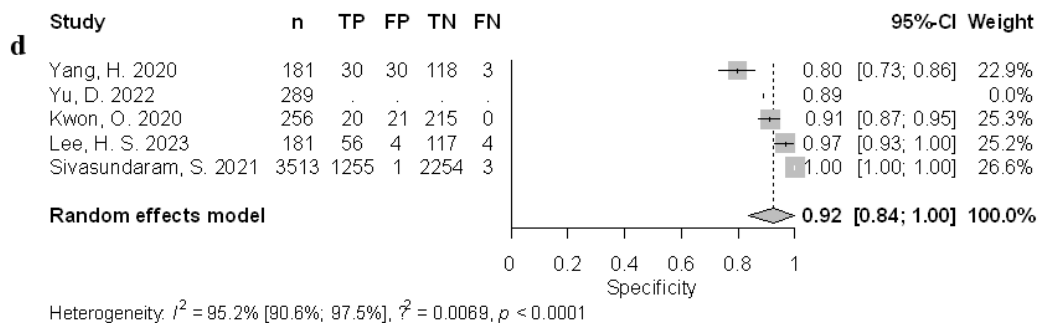
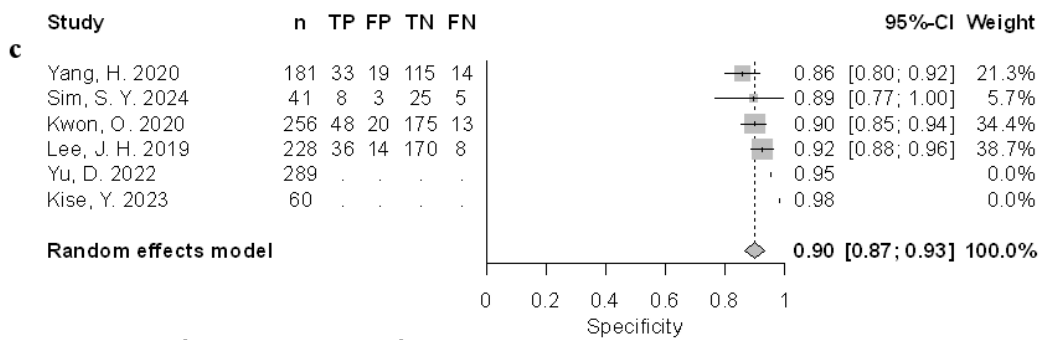
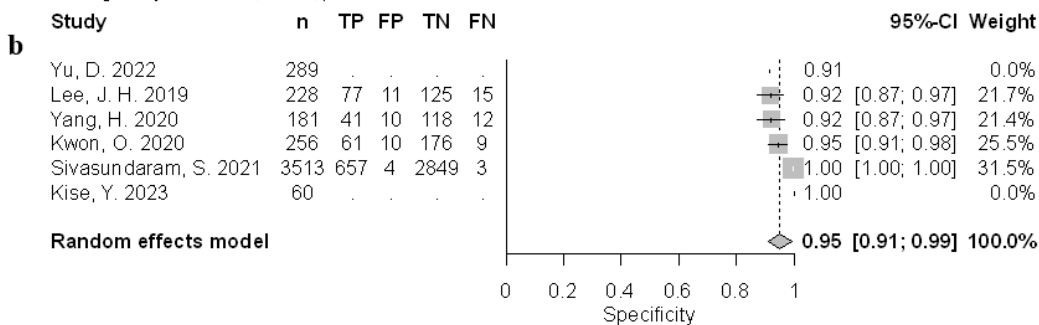
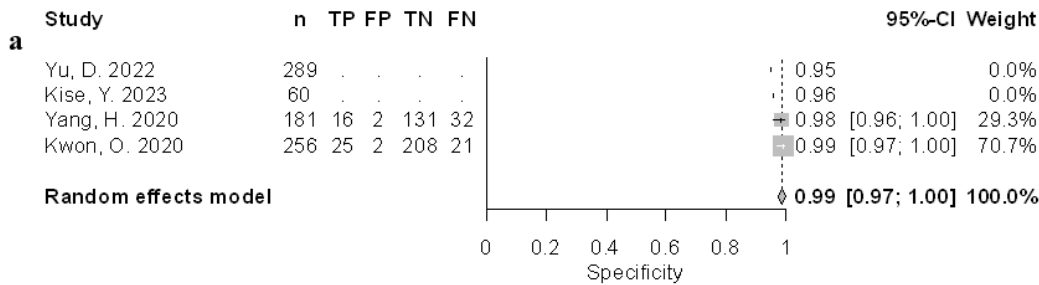


Figure 8. Forest plots illustrating the Sp results for the a) AB, b) DC, c) OKC, d) N and e) RC groups.

8.2.3.3. Diagnostic Odds Ratio (DOR)

The two studies evaluating AB yielded a pooled estimate of 63.89 (95% CI: 0.01–298,254.07; $I^2 = 32\%$). Four studies contributed data to DC, OKC, and N, resulting in pooled DORs of 441.20 (95% CI: 0.90–215,309.42; $I^2 = 97\%$), 25.86 (95% CI: 9.13–73.26; $I^2 = 46\%$), and 1,508.02 (95% CI: 1.38–1,648,837.33; $I^2 = 95\%$). Five studies were included in the RC group, with a pooled DOR of 1,044.55 (95% CI: 11.13–98,063.24; $I^2 = 96\%$). Results for DC, N, and RC were statistically significant.

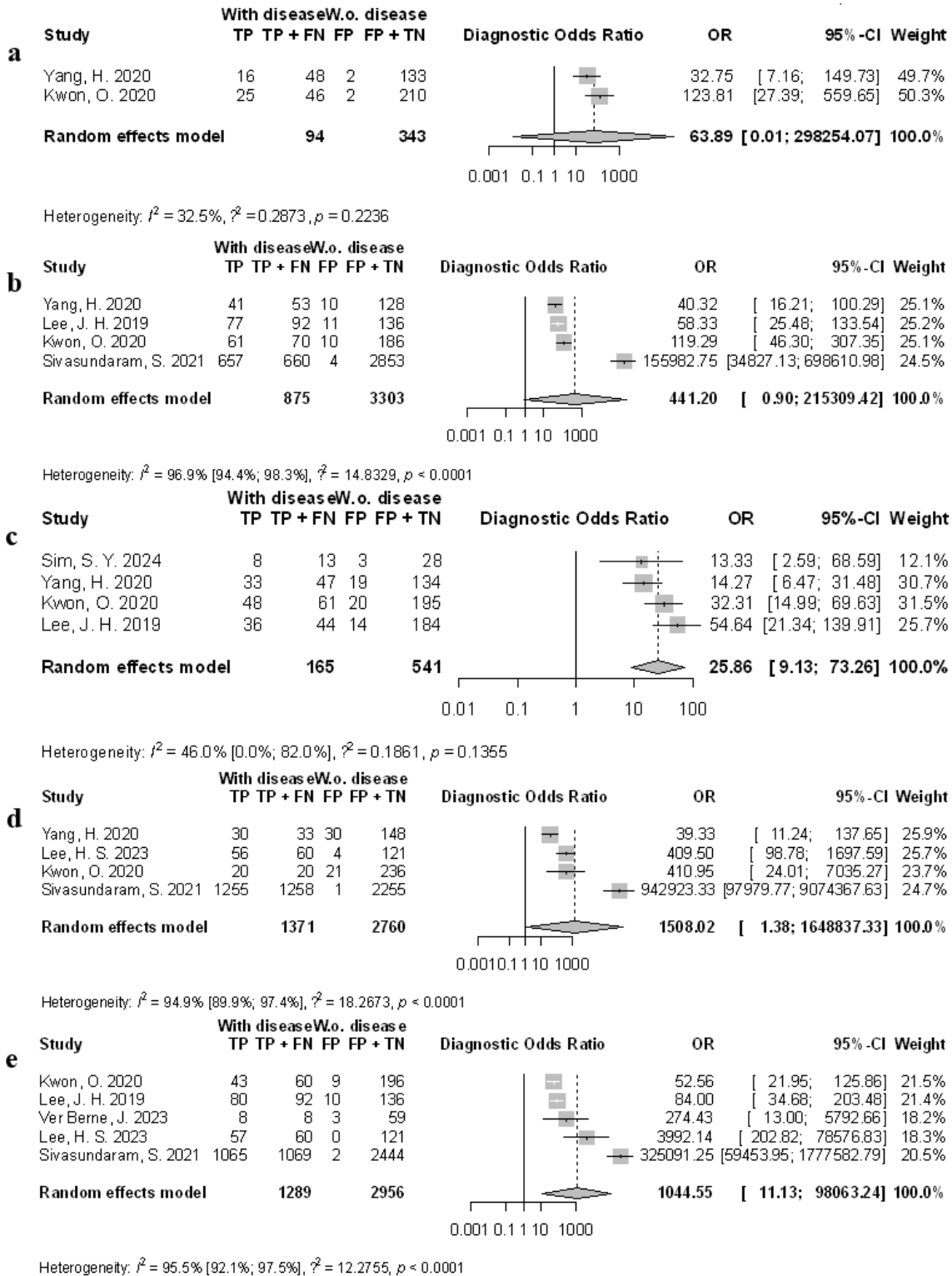


Figure 9. Forest plots illustrating the DOR results for the a) AB, b) DC, c) OKC, d) N and e) RC groups.

8.2.3.4. Area Under the Curve (AUC)

Receiver operating characteristic (ROC) curves were generated for all lesion categories. The highest AUC was observed for RC (0.959), followed by N (0.930), DC (0.901), OKC (0.823), and AB (0.714).

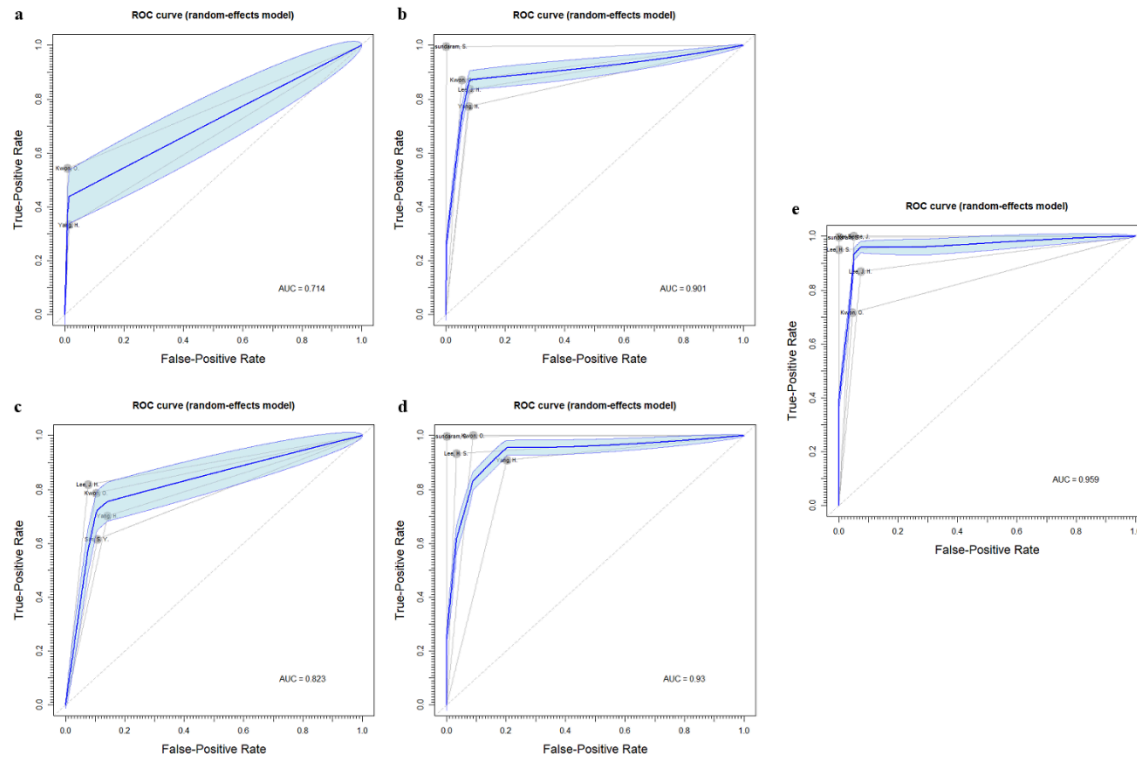


Figure 10. ROC curves of the a) AB, b) DC, c) OKC, d) N and e) RC groups.

8.2.4. Systematic review

8.2.4.1. Detection

8.2.4.1.1. Positive Predictive Value

Four studies reported PPV values. For the detection of DC, RC, OKC, AB lesions and N images, Kwon et al. measured an overall PPV of 0.78 (287). Yu et al. reported values of 0.6132 for DC, 0.575 for RC, 0.5119 for OKC, and 0.4988 for AB, with a total PPV of 0.5497 (295). Watanabe et al. evaluated two datasets. In the first one, the PPV of RC was 0.886. A pooled DC, OKC, and nasopalatine duct cyst (NPDC) group was also reported, with a PPV of 0.933. The overall value was 0.898. In the second dataset, PPV for RC was 0.87, and for the pooled group, it was 1; thus, the overall PPV was 0.9 (293). Rašić et al. reported a PPV of 0.858 for RC (290). Based on these findings, the sample-size-weighted averages were 0.4988 for AB, 0.6900 for DC, 0.96 for OKC, and

0.83 for RC, with an overall weighted PPV of 0.7.

8.2.4.1.2. Sensitivity (Se)

Seven studies reported Se values. Investigating DC, RC, OKC, and AB detection performance, Kwon et al. found a total Se of 0.74 (287). Arijji et al. calculated 0.71 Se for AB, 1 for OKC, 0.88 for DC, and 0.81 for RC (285). Yu et al. measured a Se of 0.7236 for DC, 0.6349 for RC, 0.5112 for AB, and 0.6337 for OKC. The overall Se was 0.6259 (295). Kise et al. reported values of 0.71 for AB, 0.88 for OKC, 1 for DC, 0.75 for RC, and 0.92 for Stafne bone cysts, resulting in a total Se of 0.87 (286). In the first and second datasets of Watanabe et al., Se was 0.78 and 0.8 for RC detection, while 0.667 and 0.7 for a pooled DC, OKC, and NPDC group. Total values were 0.746 and 0.771 (293). Se values of 0.893 for AB, 0.814 for OKC, and 0.917 for DC were published by Kang et al. (337). Rašić et al. estimated a Se of 0.667 for RC (290). Our calculated sample size weighted averages were 0.82 for AB, 0.88 for DC, 0.83 for OKC, 0.71 for RC, and 0.71 altogether.

8.2.4.1.3. F1 Score

Of the two available articles, Kwon et al. used images containing DC, RC, OKC, and AB lesions, as well as normal radiographs. An overall F1 score of 0.76 was estimated (287). Watanabe et al. conducted their evaluation in two groups. The F1 scores were 0.83 for RC and 0.778 for a pooled DC, OKC, and NPDC group, with a total mean of 0.815 in the first data set. In the other set, F1 was 0.833 for RC and 0.824 for the pooled group, yielding an overall value of 0.831 (293). The sample-size-weighted averages we calculated from these data were 0.79 for DC, 0.79 for OKC, 0.83 for RC, and 0.78 overall.

8.2.4.1.4. Average Precision

Three studies assessed AP. Measures described by Kwon et al. were 0.91 for DC, 0.79 for RC, 0.67 for OKC, and 0.78 for AB. The pooled mean was 0.79 with 0.12 SD (287). Yu et al. reported 0.7202 for DC, 0.6954 for RC, 0.6543 for AB, and 0.6432 for OKC and presented a pooled mean of 0.6783 (295). Ver Berne et al. shared 0.83 AP for RC. They also investigated periapical granulomas, with an AP of 0.74 (292). Our estimated sample size weighted averages were as follows: 0.76 for AB, 0.84 for DC, 0.67 for OKC, 0.77 for RC, and a total mean of 0.73.

8.2.4.2. Segmentation- Systematic review

Two research papers were available about segmentation performance. Yu et al. utilized a DL CNN system, achieving Se of 0.7327 for DC, 0.6751 for RC, 0.5135 for AB, and 0.6422 for OKC, with an average of 0.6409 across all groups. The Sp values were 0.7142 for DC, 0.7253 for RC, and 0.689 for OKC, resulting in an overall mean Sp of 0.7064. Pixel accuracy was 0.7132 for DC, 0.6843 for RC, 0.6725 for AB, and 0.6542 for OKC, yielding a total average of 0.6811. The intersection over union (IoU) was also assessed: 0.7326 for DC, 0.7234 for RC, 0.6754 for AB, and 0.7023 for OKC, resulting in a mean of 0.7084 (295). The modified LeNet CNN described by Sivasundaram et al. achieved a Se of 0.987 for DC, 0.989 for RC, 0.988 for the “odontogenic cyst” group, and 0.988 overall. It achieved a Sp of 0.987 for DC, 0.989 for RC, 0.988 for “odontogenic cyst”, and 0.988 overall. Pixel accuracy measurements resulted in 0.985 for DC, 0.976 for RC, 0.984 for “odontogenic cyst,” and 0.985 altogether. The NPV was 0.976 for DC, 0.978 for RC, 0.971 for “odontogenic cyst”, and 0.9783 overall. The PPV was 0.976 for DC, 0.971 for RC, 0.971 for “odontogenic cyst”, and 0.972 in total. IoU calculations resulted in 0.973 for DC, 0.981 for RC, 0.976 for “odontogenic cyst,” and an overall value of 0.976. The dice similarity coefficient (DSC) was 0.987 for DC, 0.976 for RC, 0.989 for odontogenic cyst, and 0.9804 overall (338).

8.2.5. Risk of Bias Assessment

Risk of bias was assessed using the QUADAS-2 tool. Overall, most studies were judged to have a low risk of bias in the “index test,” “reference standard,” and “flow and timing” domains. In the “patient selection” domain, seven studies were rated as low risk, five as unclear, and one as high risk (338). Only one study was classified as high risk in the “index test” (288) and “flow and timing” (337) domains. Regarding applicability concerns, no studies were judged to have a high risk in any domain. In the “index test” and “reference standard”, only one study was assessed as having unclear risk, whereas all studies were rated as low concern in the “patient selection” domain.

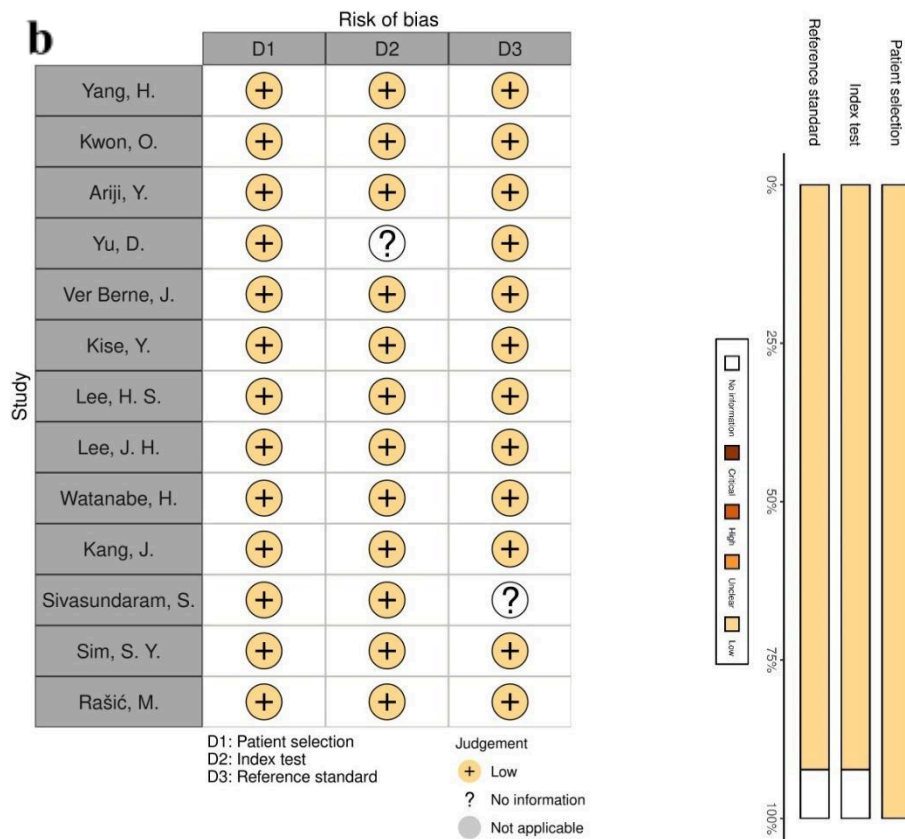
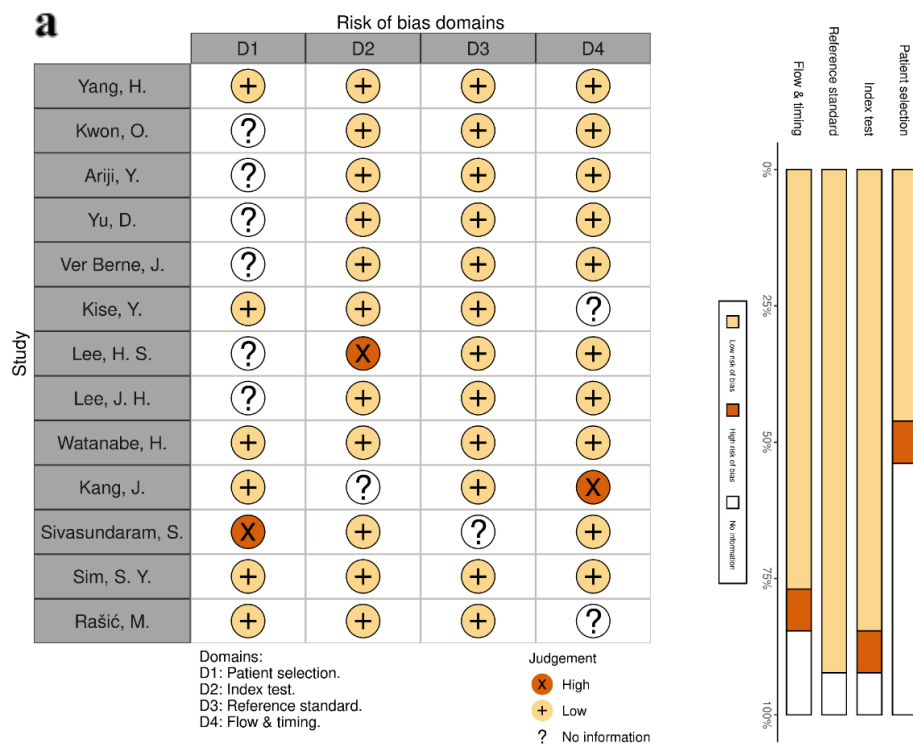


Figure 11. QUADAS-2 tool **a)** risk of bias graph, and **b)** applicability concerns graph.

8.2.6. Quality of Evidence, Publication Bias

Certainty of evidence was rated moderate for most studies. The only exception was AB, where the lack of a large effect contributed to the “very low” rating. Risk of bias and “indirectness” were generally not considered serious. “Inconsistency” and “imprecision” tended to be serious. Additional factors influencing the certainty ratings included the absence of detected publication bias and, the presence of a large magnitude of effect.

Publication bias was assessed using funnel plots, which appeared largely symmetrical and therefore suggested a low risk of publication bias. Nevertheless, these findings should be interpreted with caution because of the limited number of studies included in the analysis. Substantial heterogeneity was observed across all lesion types, apart from OKC. This heterogeneity is likely attributable to differences in the AI models evaluated, as well as variations in training strategies, image augmentation techniques, and study methodologies.

9. DISCUSSION

9.1. Summary of Findings, International Comparisons (including all studies)

Study I investigated the *in vitro* accuracy of currently available implant placement approaches. Our findings indicated that FG sCAIS, HG sCAIS, and robot-assisted implant placement were the most reliable clinically. Among all evaluated techniques, FG sCAIS showed the lowest deviations across the five outcomes (CGD, HAD, HCD, B-L AD, and M-D AD), making it the most accurate approach overall. HG achieved the highest accuracy for one-dimensional parameters (B-L ApD, M-D ApD, B-L CD, and M-D CD), whereas for VA and VC, the PG approach was superior. Altogether, sCAIS exhibited the greatest precision in CGD, HCD, B-L ApD, M-D ApD, B-L CD, M-D CD, B-L AD, and M-D AD.

Robot-assisted implant placement achieved the lowest AD and ApGD values while maintaining high accuracy across most outcomes. Despite still being in a developmental stage, all deviations were within the clinically acceptable range. Our results were consistent with those of Bolding et al. (18).

While we detected no statistically significant differences between FG and HG, in the previous meta-analysis by Bover-Ramos et al., FG was significantly more accurate than HG for AD, HAD, and HCD (339). Another quantitative analysis by Gargallo-Albiol et al. highlighted significant differences in HCD, HAD, and AD, favoring FG. For the HCD outcome, FG performed significantly better than the freehand method as well (340). In neither study did differences in vertical deviations of FG and HG reach statistical significance (339, 340). Contrasts to our findings may be attributed to the fact that these articles synthesized clinical studies.

The present analysis demonstrated significantly lower deviations for FG in outcomes AD and HCD and for the HG CAIS in the B-L ApD compared to those of the PG approach. The meta-analysis of randomized trials by Putra et al. remained consistent with our findings: FG CAIS was significantly more accurate than PG across all primary outcomes (341). Likewise, Tattan et al. observed significantly lower AD values for FG implant placement compared with a combination of HG and PG. However, no significant difference was observed in ApGD or CGD (342).

Except for ApGD, AR-based CAIS yielded clinically acceptable deviations. The report by Pellegrino et al. supports this conclusion by demonstrating two clinical cases (343).

Mai et al. found that AR-based CAIS precision was comparable to sCAIS, and was superior to dCAIS and the freehand approach (16). On the contrary, our pooled dCAIS means were lower (except for HAD and HCD) than those of AR, but the differences were not significant. Differing sample size and inclusion criteria may explain this.

Conventional dCAIS achieved clinically acceptable accuracy across all evaluated outcomes except HAD. While the findings of Schnutenhaus et al. were consistent with those of the present study (344), lower deviations appeared in Jorba-García et al.'s meta-analysis of 14 *in vitro* studies. This discrepancy may be related to the larger number of included studies in the present analysis and the division of static guidance modalities (345).

FG sCAIS demonstrated significantly higher accuracy than dCAIS regarding CGD, HCD, B-L ApD, M-D ApD, B-L CD, M-D CD, B-L AD, and M-D AD. For the remaining outcomes, no significant differences could be observed. Although previous *in vitro* studies advocated dCAIS over sCAIS, their performance was comparable under clinical conditions (345). Varying study designs, experimental settings, subgroups, and sample sizes may lead to such contradictory results. Similarly, Wang et al. reported no significant differences *in vivo* between the two techniques. (346).

Apart from the VA outcome, freehand implant placement tended to be the least accurate, exceeding clinically acceptable thresholds, except for VA and VC. These findings reflect previous reports in the literature. Tattan et al. demonstrated that the freehand method's AD, ApGD, and CGD values significantly exceeded those of FG sCAIS (342). Wang et al. found that dCAIS was significantly superior to freehand implant placement, which, apart from CGD, is consistent with Study I (346).

Study II collected evidence regarding the accuracy of AI diagnostic capabilities on odontogenic cysts and ABs from OPGs. Owing to the limited data available, detection and segmentation performance were introduced by a systematic review.

A meta-analysis was executed for classification. Among the groups, RC and N yielded Se and Sp values over 0.9. DC's Sp also surpassed this threshold, while its mean Se, along with the Se and Sp values of OKC, approached 0.9. Data for AB classification regarding Se and Sp originated from two studies, which allowed only a limited evaluation, resulting in high Sp (exceeding 0.9) and a relatively low Se.

Defining a universal minimum threshold for clinically acceptable Se and Sp remains challenging (349). According to Power et al., the sum of Se and Sp in an adequate diagnostic test is 1.5 at worst. In this aspect, a value of 2 represents perfect performance, and 1 indicates no diagnostic utility (350). In this regard, AI was effective in every group except AB (350).

According to the narrative of Leeflang et al., the diagnostic performance should be comparable or superior to that of the alternatives (349). In our case, diagnostics by human examiners remain the only noninvasive option. Yang et al. reported that AI's performance was at least comparable to that of expert dentists (294). Cardoso et al. assessed the classification accuracy of observers with varying levels of experience in OPG interpretation, yielding mean Se and Sp values of 0.6133 and 0.86 for AB, 0.84 and 0.88 for DC, and 0.6267 and 0.80 for OKC. Compared with these findings, the AI diagnostics in the present study were superior across all lesion groups and outcomes, apart from AB Se (351).

Several studies could not be included in the quantitative synthesis because they shared no confusion matrices or CIs. Nevertheless, their findings were generally consistent with the results of the present analysis. To date, no previous meta-analysis has independently evaluated the classification performance of AI for odontogenic cysts and ABs.

The meta-analysis of Shrivastava et al. reported a mean Se of 0.93 (95% CI 0.77–0.98) and Sp of 0.93 (95% CI 0.83–0.97) for the classification of pooled simple bone cysts, Stafne bone cysts, and glandular odontogenic cysts from OPGs. These were consistent with our findings (25). Using a pooled dataset of OKC and AB, Fedato Tobias et al. also reported high diagnostic accuracy (352). Although the current analysis indicated a worse result for AB when pooled with the OKC group, the findings remained consistent.

In all groups, DOR surpassed 1, indicating that AI algorithms performed better than chance. Higher values can be attributed to a greater ability to distinguish between those with and without the given condition. N achieved the highest DOR, followed by RCs, DCs, and ABs, whereas OKCs exhibited the lowest DOR values.

AUC was evaluated using ROC curves. Values between 0.90 and 1.00 indicate “excellent”, between 0.80 and 0.90 indicate “very good”, and between 0.70 and 0.80

indicate “good” diagnostic accuracy, as described by Šimundić et al. (353). Consequently, AI performance in our study was “excellent” for DC, RC, and N, “very good” for OKC, and “good” for AB. However, these findings should be interpreted cautiously due to the limited number of included studies and the clustering of their results in the upper-left region of the plot.

Detection performance was interpreted with Se. For AB, its value ranged from 0.5112 to 0.893; we calculated a sample-size-weighted mean of 0.82. In the OKC group, Se ranged from 0.6337 to 1.00, yielding a weighted mean of 0.83. RCs were detected by Se values ranging from 0.6349 to 0.81, with a weighted mean of 0.71. For DC, Se ranged from 0.7236 to 1.00, resulting in a weighted mean of 0.88. Substantial intra- and inter-subgroup diversity was detected.

In some cases, Se ranged from 0.6337, which is clinically undesirable, to perfect lesion identification with no FN results. Such variability may be caused by differences in training dataset size, AI architecture, or study design. Overall, the highest mean values were observed for DCs, followed by OKCs, ABs, and RCs. Sample-size-weighted means ranged from 0.80 to 0.90, which is considered satisfactory in the literature.

F1-scores ranged from 0.76 to 0.833. Only two studies provided data for this outcome, and they evaluated different lesion pools without providing lesion-specific data. Consequently, direct comparison of these findings was not possible.

Three studies reported AP values. The results were consistent across lesion types, yielding an overall mean AP of 0.73, indicating that development is necessary. These findings are in line with the conclusions of the systematic review by Fedato Tobias et al. (352).

Available evidence regarding segmentation remains limited to two articles. Sivasundaram et al. indicated impressive results for DCs, RCs, and a combined odontogenic cyst group, with both Se and Sp exceeding 0.90 (338). Yu et al. published Se and Sp values exceeding 0.80 for DCs, RCs, ABs, and OKCs (295). IoU measurements demonstrated similar trends across both studies (295, 338).

9.2. Strengths (including all studies)

Both studies followed transparently a rigorous methodology that adhered to PRISMA guidelines (26) and had been previously registered in PROSPERO.

Study I was the first meta-analysis to provide data on robot-assisted implant placement under *in vitro* conditions. Our analysis included all available methods for implant placement and the entire set of outcomes related to accuracy in literature. The sCAIS group was further subdivided by level of guidance for a more comprehensive evaluation. Most groups had large sample sizes.

Study II was the first meta-analysis to evaluate AI diagnostics concerning various odontogenic cyst types and ABs as distinct entities. Subgroups were formed for each diagnosis, and a healthy OPG group was assessed alongside them. All available evidence had been gathered and evaluated on classification, detection, and segmentation performance for these conditions.

9.3. Limitations (including all studies)

In Study I, the number of eligible articles was relatively small, particularly for AR-based and robot-assisted implant placement, due to their early stage of development. This limited data restricted the ability to include control groups.

Owing to the scarcity of *in vivo* investigations, our meta-analysis was conducted entirely with *in vitro*. Consequently, the generalizability of the findings to the more complex clinical environment should be interpreted with caution.

Heterogeneity was generally high, which can be attributed to the great diversity of implant systems, model materials, evaluation software, and study protocols involved.

We included studies with varying levels of operator experience, regardless of whether only drilled holes or placed implants were evaluated. Although this decision enhanced the comprehensiveness of our analysis, it also contributed to the increased heterogeneity values.

Lastly, several included studies exhibited moderate or high risks of bias, due to insufficiently detailed and non-transparent reporting of methodology and outcomes.

Although Study II managed to include the whole spectrum of odontogenic cysts besides ABs, the number of available studies was limited.

In some subgroups, substantial heterogeneity was observed, originating from differences in AI algorithms and methodological factors, such as the amount of training images and augmentation. To solve the latter issue, non-augmented data were preferentially extracted. When separate reporting was unavailable, the augmented group's information, which often represented larger populations, was sought. As a result, augmented data may be overrepresented in the pooled estimates, potentially influencing the overall findings.

Finally, concerns have been raised regarding the applicability of the QUADAS-2 tool for AI. Although an AI-specific extension, QUADAS-AI, has been proposed, it remains under development. Therefore, in concordance with current Cochrane recommendations, QUADAS-2 was utilized for risk of bias assessment (354).

10. CONCLUSIONS

10.1. Study I

Within the limitations of this study, including the *in vitro* nature of all included articles, FG sCAIS demonstrated the highest accuracy across all outcome measures. In contrast, freehand implant placement exhibited the greatest deviations for most assessed parameters. AR-based and robot-assisted implant placement showed considerable potential as future alternatives to conventional techniques. However, further clinical studies are required to validate their performance in routine practice.

10.2. Study II

AI-based diagnostic systems demonstrated high Sp, indicating a strong ability to correctly identify healthy individuals. However, Se values remained suboptimal, suggesting that further improvements are needed to enhance disease detection performance. Although current results are promising, additional evidence is necessary before clinical implementation can be recommended.

11. IMPLICATIONS FOR PRACTICE

11.1. Study I

State-of-the-art technologies, Robot-assisted implant placement, and AR CAIS all achieved promising accuracy. However, each needs further refinement and clinical validation for routine application.

The accuracy of conventional dCAIS and sCAIS modalities supports their clinical use. FG CAIS, which achieved the highest precision across most outcomes, is especially preferable in cases of limited bone volume or in proximity to anatomical structures. When guides are not feasible (e.g., limited mouth opening), dCAIS can serve as a reliable alternative.

As evidence grows, advanced navigation technologies may enhance treatment predictability and patient safety.

11.2. Study II

Translating AI-related scientific advancements into clinical practice is vital to enhance healthcare (355, 356). Professionals need proper education and training on automated diagnostic algorithms to understand their capabilities and limitations.

CNNs have the potential to support routine dental practice by identifying potentially positive radiographs that require specialist review and to serve as a screening tool for odontogenic cysts.

Given their high Sp but variable Se, AI systems should currently serve as adjunctive tools under the clinician's supervision rather than autonomous diagnostic systems. A human–AI collaborative approach may enhance diagnostic accuracy, improve workflow efficiency, and minimize diagnostic mistakes.

12. IMPLICATIONS FOR RESEARCH

12.1. Methodology and Study Design

In both of our studies, we encountered serious issues related to transparency and reporting consistency.

Articles on dental implants should provide comprehensive methodological information, including the number of operators involved and their levels of experience, blinding, randomization, and sample size calculation. A consensus should be reached regarding the nomenclature and definitions of implant placement accuracy outcomes.

Study II highlighted the need for clear details on AI systems, augmentation procedures, and the number of images in training, testing, and validation. AI-specific risk of bias assessment tools (354) and standardized data collection forms should be developed to aid future meta-analyses.

12.2. New Areas

Study I drew attention to the necessity for more clinical articles.

A new focus of research is the impact of experience on AR-assisted implant placement. A significant danger of sCAIS modalities is the obstruction of cooling water. Therefore, developing new guide designs is a promising approach to achieving high-accuracy implant placement under safer conditions.

Concerning the findings of Study II, future research should focus on multimodal AI systems that integrate detection, classification, and segmentation within a single framework, as well as on the ethical, legal, and regulatory considerations. In addition, more high-quality studies are required to evaluate detection and segmentation performance, particularly for lesion types with lower diagnostic accuracy.

13. IMPLICATIONS FOR POLICY MAKERS

13.1. Study I

Policymakers should support initiatives to educate both clinicians and patients about recent advances in implant placement technologies. Professional development programs should be established to supply dental practitioners with the knowledge and skills to use these systems safely and effectively.

Research should be facilitated by funding for required equipment and materials (e.g., implants, dental models, and hardware).

Regulatory and clinical guidelines should be developed to govern the use of AR- and robot-assisted implant placement. Following adequate validation of their safety and cost-effectiveness, these technologies should be considered for integration into publicly funded healthcare systems to improve the quality and predictability of implant treatment.

13.2. Study II

Policymakers should support the development of AI infrastructure, including high-performance computing resources, in both academic and clinical settings to develop, validate, and deploy these diagnostic systems.

International collaborations should be encouraged to establish robust, standardized registers that collect panoramic radiographs with confirmed histopathological diagnoses to train, validate, and test AI algorithms for large-scale studies.

Regulatory, ethical, and legal challenges associated with AI should be addressed to integrate it into routine clinical practice.

Finally, educational programs should emphasize the radiographic diagnosis of odontogenic lesions. Enhancing clinicians' diagnostic competencies alongside AI-based tools may promote a synergistic human–AI approach and improve the accuracy of noninvasive diagnosis.

14. FUTURE PERSPECTIVES

Our future research will concentrate on dental implantology, specifically assessing the learning curve and clinical effectiveness of AR-assisted implant placement. Additionally, we will investigate the diagnostic performance of AI systems in identifying and classifying various dental implant brands. Together, these research directions aim to bridge the gap between dental implantology and AI, to advance the field of digital dentistry.

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15.1. Acknowledgement of AI use

During the preparation of the Graphical Abstract, the author used ChatGPT (GPT-5.5 model, Open AI, San Francisco, California, USA) for the image illustrating different implant placement methods on mandibles. Grammarly (Grammarly Inc., San Francisco, California, USA) was used to check spelling and grammar during manuscript preparation. The author reviewed and revised the image and text and takes full responsibility for the content of this dissertation.

16. BIBLIOGRAPHY

16.1. Publications Related to the Thesis

1. **Takács A**, Hardi E, Golzio Navarro Cavalcante B, Szabó B, Kispélyi IB, Joób-Fancsaly Á, et al. Advancing Accuracy in Guided Implant Placement : A Comprehensive Meta-Analysis: Meta-Analysis evaluation of the accuracy of available implant placement Methods. JOURNAL OF DENTISTRY. 2023;139. D1, IF: 4.8
2. **Takács A**, Tábi D, Golzio Navarro Cavalcante B, Szabó B, Schulze Wenning A, Gerber G, et al. Artificial Intelligence in the Diagnosis of Odontogenous Cysts and Ameloblastomas—A Systematic Review and Meta-Analysis. JOURNAL OF CLINICAL MEDICINE. 2026;15(6). Q2, IF: 3.3

16.2. Publications not Related to the Thesis

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