



Robotic dentistry and autonomous implant placement: an evolutionary review from computer-assisted surgery to artificial intelligence

Odontología robótica y colocación autónoma de implantes: una revisión evolutiva desde la cirugía asistida por computadora hasta la inteligencia artificial

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ABSTRACT

Robotic dentistry has evolved from computer-assisted surgery to autonomous implant placement systems over four decades, and this review traces that trajectory and synthesises the current evidence on accuracy, safety and autonomy. The origins of dental robotics lie in stereotactic neurosurgery and computer-assisted implant planning, which established the principles of image-to-patient registration that the first autonomous implant systems inherited. Between 2018 and 2020 the first autonomous and semi-autonomous implant robots entered clinical use, and between 2021 and 2023 a body of accuracy studies accumulated showing that robotic placement achieves deviations comparable to or smaller than static guides and dynamic navigation. Between 2024 and 2026 the field turned toward higher levels of autonomy and integration with artificial intelligence, while systematic reviews and multicenter studies consolidated the accuracy evidence and identified the barriers to clinical integration. The trajectory shows a consistent pattern: each period added capability without yet resolving the questions of cost, workflow integration and the level of autonomy that is clinically justified, and these remain the open questions that will shape the next stage of the field.

Keywords: robotic surgical procedures; dental implants; artificial intelligence; surgery computer-assisted; autonomy.

RESUMEN

La odontología robótica ha evolucionado desde la cirugía asistida por computadora hasta los sistemas autónomos de colocación de implantes a lo largo de cuatro décadas, y esta revisión traza esa trayectoria y sintetiza la evidencia actual sobre precisión, seguridad y autonomía. El origen de la robótica dental se encuentra en la neurocirugía estereotáctica y en la planificación de implantes asistida por computadora, que establecieron los principios de registro entre imagen y paciente que heredaron los primeros sistemas autónomos de implantes. Entre 2018 y 2020 los primeros robots de implantes autónomos y semiautónomos entraron en uso clínico, y entre 2021 y 2023 se acumuló evidencia de precisión que mostró que la colocación robótica alcanza desviaciones comparables o menores que las guías estáticas y la navegación dinámica. Entre 2024 y 2026 el campo se orientó hacia mayores niveles de autonomía y la integración con inteligencia artificial, mientras las revisiones sistemáticas y los estudios multicéntricos consolidaron la evidencia de precisión e identificaron las barreras para la integración clínica. La trayectoria muestra un patrón consistente: cada período añadió capacidad sin resolver aún las cuestiones de coste, integración del flujo de trabajo y el nivel de autonomía clínicamente justificado, que siguen siendo las preguntas abiertas que darán forma a la siguiente etapa del campo.

Palabras clave: procedimientos quirúrgicos robotizados; implantes dentales; inteligencia artificial; cirugía asistida por computador; autonomía.

INTRODUCTION

The placement of a dental implant is a deceptively demanding surgical task: the clinician must translate a three-dimensional plan onto a patient whose anatomy shifts and whose jaw offers no fixed landmarks, and an error of a few millimetres or a few degrees can damage a nerve, perforate a sinus or compromise the final restoration.

For many decades the accuracy of that translation depended on the clinician's hand, aided first by drilling guides and then by computer navigation, and the gradual automation of the task is the story that robotic dentistry tells. That story matters because implant placement is one of the most common surgical procedures performed anywhere in the world, and because the tools that automate it embody a larger question about how much of surgery can properly be delegated to a machine.

The clinical stakes of placement accuracy are high, and they explain why the field has pursued automation so persistently. An implant placed too close to the inferior alveolar nerve can cause permanent sensory disturbance, a perforation of the maxillary sinus can lead to sinusitis or implant failure, and an implant that emerges at the wrong angle compromises the prosthesis that it supports.

The published accuracy thresholds reflect these risks, and the entire rationale of the guided, navigated and robotic approaches is to keep the placement within them more reliably than a free hand can. The robotic systems are therefore not a luxury of technical enthusiasm but a response to a measurable and consequential source of error, and the trajectory of the field is the history of that response.

The trajectory from computer-assisted surgery to autonomous robots is a natural evolution, not a sudden invention, and it is best understood chronologically. Computer-assisted implant surgery established the pipeline that all later systems inherited: a cone-beam computed tomography scan, a virtual plan, and a registration step that aligns the plan to the patient's actual anatomy.

The surgical guides that this pipeline produced are static and passive; the navigation systems that followed are dynamic and advisory; the robots that followed again are the first to act on the plan themselves. Each successive step in that sequence is a step toward greater autonomy, and the review follows the sequence deliberately because the sequence itself is the argument.

The present moment is a natural point to take stock of this trajectory, because the field has reached a state of technical maturity without yet reaching a state of settled adoption. The robotic systems are commercially available and their accuracy is documented, but their adoption is limited and their clinical and economic justification remains debated, which is precisely the moment at which a chronological review is most useful, because it can distinguish what has been established from what remains open.

The review therefore does not argue for or against the adoption of robotic dentistry; it traces how the field reached its present state and what the evidence supports at each stage, leaving the adoption decision to the reader who must make it.

The objective of this review is to trace the evolution of robotic dentistry from its origins in computer-assisted surgery to autonomous implant placement, and to synthesize the current evidence on the accuracy, safety and autonomy of these systems. Three questions guide the review throughout: what did each period contribute, what evidence supports the current accuracy claims, and what remains genuinely unresolved as the field moves toward greater autonomy.

METHODS

The review was planned and reported following the SANRA items for narrative reviews, and it is deliberately not presented as a systematic review: no PRISMA flow and no claim of exhaustiveness are made. Scopus, PubMed and Crossref were searched and the searches combined terms for robotic, robot-assisted and autonomous with terms for dentistry, dental implant and implant placement, together with additional terms for accuracy and navigation.

Classic works on the history of surgical robotics and on the levels of autonomy were included regardless of year, because the chronological argument requires them, and the core evidence on robotic implant placement was restricted to the 2018-2026 window. Studies were selected for their relevance to the trajectory of the field, prioritising primary accuracy studies and systematic reviews over single case reports, and the synthesis is organised into four distinct periods defined by explicit criteria: the origins of computer-assisted surgery, the first autonomous systems, the period of expansion, and the current state of autonomy and artificial intelligence integration.

The selection favoured studies that reported a quantitative accuracy or clinical outcome over purely descriptive accounts, and single case reports were used only where they marked a genuine milestone in the trajectory rather than as evidence of performance. The reference list is therefore a curated account of the trajectory rather than an exhaustive bibliography, and the reader should understand the selection in that light.

The four periods are defined by explicit criteria rather than by convention, and the criteria are stated so that the organisation can be judged. The origins period runs from the first surgical robot to the articulation of the levels-of-autonomy framework, and it is defined by the absence of a dental robotic system. The first-autonomous-systems period runs from 2018 to 2020 and is defined by the entry of the first implant robots into clinical use.

The expansion period runs from 2021 to 2023 and is defined by the accumulation of primary accuracy studies. The current period runs from 2024 to 2026 and is defined by the consolidation of the evidence in systematic reviews and by the turn toward autonomy and artificial intelligence. These boundaries are approximate, and the milestones near a boundary are assigned to the period that their contribution most closely matches, but the criteria are transparent and the periods are therefore falsifiable rather than arbitrary.

DEVELOPMENT

Origins of computer-assisted surgery (1985-2017)

The origins of robotic dentistry lie outside dentistry, in the stereotactic neurosurgery of the 1980s. Kwoh et al. described in 1988 a robot that positioned a needle for brain biopsy with an accuracy that a human hand could not reliably match, and that demonstration established the principle that a robot can execute a pre-planned trajectory more reproducibly than a surgeon.(1)

The same decade produced the computer-assisted surgery frameworks that later became the implant planning software of dentistry, and by the 2000s the pipeline of scan, plan and guided placement was standard in implant practice. The robotic systems that followed did not invent a new task but automated an existing pipeline, and the conceptual debt to computer-assisted surgery is the reason the chronology begins here rather than with the first dental robot.

The intervening period between 1988 and 2017 is one of consolidation rather than of dental robotics, and it is best understood as the incubation of the tools that the dental field would later assemble into a robotic system.

The surgical robotics field grew around the da Vinci telemanipulation platform in other specialties, and the dental field, working independently, developed the accuracy evidence for static guides and dynamic navigation that would later serve as the benchmark against which the robots were measured.(2,3) The levels-of-autonomy framework articulated by Yang et al. in 2017, which distinguishes teleoperation from shared control from supervised autonomy from full autonomy, provided the vocabulary that the dental field would later use to describe its own systems.(4) By 2017 the groundwork was complete in every respect, and the first autonomous dental implant systems appeared almost immediately after, taking up the tools that the previous three decades had prepared for them.

The accuracy question that the first systems posed is the question that the rest of the literature has spent the subsequent years answering, and it is worth stating in its original form. The static guide and the dynamic navigation system already existed, and their accuracy was documented, so a new robotic system could only justify itself by being at least as accurate, or by offering a workflow or safety advantage that the existing tools did not.

The first systems therefore entered a field that already had a benchmark, and their success or failure was always going to be measured against that benchmark rather than against a free hand. This framing, established between 2018 and 2020, is the framing that the later accuracy studies inherited, and it is why the accuracy evidence is reported throughout this review as a comparison rather than as an absolute figure.

The first autonomous systems (2018-2020)

The first autonomous and semi-autonomous dental implant systems entered clinical use between 2018 and 2020, and their defining feature was that they acted on the plan rather than merely advising the surgeon. The systems of this period were described as guided innovations, and the earliest clinical descriptions framed them as the natural successor to the static guide, execu-

ting the planned osteotomy with a robotic arm under the surgeon's direct supervision rather than through a physical template.(5)

The period is thin in published evidence, because the technology was new and the case series were small, but the accuracy question that would dominate the next period was already posed, and the benchmark of the static guide and the dynamic navigation system was already the standard of comparison.(5)

The distinction between the autonomous and the semi-autonomous systems that appeared in this period is worth drawing precisely, because it persists through the later literature. An autonomous system, in the usage of this field, holds the drill and moves it along the planned trajectory without the surgeon's hand, while the surgeon supervises and can stop the procedure; a semi-autonomous system shares the movement, with the robot constraining the trajectory and the surgeon advancing the drill.

The systems of this period varied in where they drew that line, and the later studies that compare autonomous against semi-autonomous placement are comparing points along a spectrum of shared control rather than two categorically different technologies. This spectrum, rather than a sharp autonomous-nonautonomous divide, is the accurate description of the field, and it is the framework within which the accuracy evidence should be read.

The contribution of this period was less a body of evidence than a proof of feasibility. The systems demonstrated that a robot could hold and move a drill along a planned trajectory, that the registration between the scan and the patient could be achieved reliably intraoperatively, and that the workflow could be completed in a real clinical setting, and these three demonstrations together were the necessary precondition for the accuracy studies that followed. Between 2018 and 2020 the field therefore moved, for the first time, from a pipeline that advised the surgeon to a machine that assisted the surgeon in the placement itself, and the trajectory toward autonomy began in earnest at that point.

The accuracy metrics themselves require a word of explanation, because they are the common currency of this literature and they are easy to misread. The studies measure the deviation between the planned and the placed implant, reporting the error at the implant platform, at the apex and in the angulation, and these three numbers capture different clinical risks: an error at the platform affects the restoration, an error at the apex affects the proximity to vital structures, and an angular error affects both.

The thresholds that define a clinically acceptable placement are not uniform across studies, which is a source of the variability in the reported accuracy, and the review reports the deviations as ranges for that reason. The units are small, on the order of a fraction of a millimetre and a few degrees, and the differences between the robotic and the guided alternatives, while statistically significant in some studies, are small in absolute terms, which is why the clinical translation of those differences is the open question that the accuracy literature has not yet answered.

Expansion and the accuracy evidence (2021-2023)

The period from 2021 to 2023 produced the accuracy evidence that the previous period lacked, and its central, repeatedly confirmed finding is that robotic placement achieves deviations comparable to or smaller than the static guide and the dynamic navigation system. The studies of this period measured the deviation between the planned and the placed implant, and they reported angular and apical deviations that were within the range considered clinically acceptable and, in several comparisons, smaller than the guided alternative.(6-8)

The semi-autonomous systems, in which the robot moves the drill and the surgeon retains supervisory control, were the most studied of the period, and their accuracy was reported across single-tooth, immediate and multi-implant placement scenarios.(6,8) The case series of this period extended the evidence beyond the single tooth to more complex placements, and the comparison of the robotic approach against dynamic navigation became a recurring study design that would carry into the next period.(7)

The comparison designs of this period are the reason the accuracy finding is credible rather than anecdotal. The studies that compared the robotic against the static guide, against the dynamic navigation system, and against freehand placement in the same sample each controlled for the confounding that a single-arm accuracy study cannot, and the consistent ordering of the results, with the robotic approach among the most accurate, is the product of those designs.(6-8)

The studies that reported the human-robot interaction, examining how the division of the task between the surgeon and the machine affected the result, added the further finding that the accuracy depends on that division, which is the seed of the autonomy question that the current

period has foregrounded.(7)The expansion period therefore established not only that the robots are accurate but that their accuracy is a property of the control architecture, and that the design of the control architecture is itself a variable that the field must account for.

The accuracy finding was consistent but its clinical meaning was not yet settled, because the studies of this period were mostly single-centre and the deviation thresholds that define clinical success were not uniform.

The reported deviations, typically on the order of a fraction of a millimetre at the apex and a few degrees of angular deviation, are small in absolute terms and are measured in units that a clinician can readily interpret, but the period's literature had not yet established whether those small differences from the guided alternative translate into any difference in implant survival or complication rates, which is the question that the next period would begin to address.

The expansion period therefore consolidated the technical accuracy claim while leaving the clinical outcome claim deliberately open, and it set the stage for the consolidation and the turn toward autonomy that the current period would bring.

The levels of autonomy deserve a careful statement, because they are the vocabulary through which the current state must be read. The framework distinguishes teleoperation, in which the surgeon directs every movement, from shared control, in which the robot and the surgeon divide the task, from supervised autonomy, in which the robot executes a plan and the surgeon supervises, and from full autonomy, in which the robot acts without human intervention.(4)

The dental implant systems of the current period occupy the supervised-autonomy level, executing the planned osteotomy while the surgeon retains the authority to pause or take over, and this is the level at which the accuracy evidence has been generated. The distinction matters because the clinical and regulatory justification for each level is different, and the question of whether the field should move beyond supervised autonomy is the question that the current period has posed but not answered.

The current state: autonomy and artificial intelligence (2024-2026)

The current period, from 2024 to 2026, is defined by two developments: the consolidation of the accuracy evidence through systematic reviews and multicenter studies, and the turn toward higher levels of autonomy and integration with artificial intelligence. The systematic reviews and umbrella reviews of this period pooled the accuracy studies and reached the conclusion that robotic placement is accurate and, in most comparisons, at least as accurate as the guided alternative.(9-12)

The reviews that compared robotic, navigated and static-guided placement directly found the robotic approach among the most accurate, and the comparisons of robotic against dynamic navigation and against freehand placement reinforced the same conclusion.(13-16)

The accuracy of the autonomous and semi-autonomous systems was reported across immediate placement, edentulous arches, tilted implants and zygomatic implants, extending the evidence beyond the single-tooth case that dominated the earlier periods.(17-20)

The learning-curve and factor studies of the current period add a dimension that the pure accuracy studies omit, and it is a dimension that bears on adoption. The studies that examined how the accuracy of the robotic systems changed with the operator's experience reported a learning curve, and the studies that examined the factors affecting accuracy, such as the implant site, the bone quality and the calibration method, identified the conditions under which the accuracy is robust and those under which it degrades.(21,22)

These findings matter because a tool whose accuracy depends on the operator's experience reintroduces the very variability that the robotic system was meant to remove, and a tool whose accuracy depends on the bone or the site requires the user to know where it is reliable. The factor studies therefore temper the headline accuracy with the conditions under which it holds, and they are the part of the current evidence that a clinician deciding on adoption should weight most heavily.

The turn toward autonomy and artificial intelligence is the more consequential development, and it is where the trajectory points. The systems of this period are described in the language of autonomy levels, with the task-autonomous systems that execute a planned osteotomy under supervision distinguished from the semi-autonomous systems that share the task with the surgeon, and the learning-curve and factor studies examined in detail how the human and the machine divide the work between them.(21,22)

The integration with artificial intelligence is the frontier, with embodied intelligence and vision-free robots proposed as the next concrete step, and the reviews of this period frame the trajectory explicitly and without ambiguity as one toward ever greater autonomy.(23-25)

The barriers to clinical integration, which the literature of this period now names explicitly rather than implying, are cost, workflow disruption and the unresolved question of how much autonomy is clinically justified, and these barriers rather than the accuracy are the field's current limit.(26)

The artificial intelligence layer that the current period has begun to add is distinct from the robotics layer, and the two should not be conflated. The robotic system executes a plan; the artificial intelligence layer proposes the plan, recognises the anatomy or adapts the plan to the intraoperative conditions, and the embodied-intelligence and vision-free proposals describe systems in which the perception and the decision are themselves automated rather than the movement alone.(23,24)

The trajectory from computer-assisted surgery to supervised-autonomous robotics is therefore followed by a second trajectory, from robotic execution to artificial perception and decision, and the current period is the meeting point of the two. The barriers named in the literature, the cost, the workflow and the clinical justification, apply to both layers, and the unresolved questions of autonomy apply to the artificial intelligence layer with the same force that they apply to the robotic layer.(26)

The accuracy evidence of the current period is summarised in the table, and the trajectory across the four periods is summarised in the chronology, with the milestones stated by year (Table 1).

Table 1. Chronology of robotic dentistry milestones by period.

Period	Milestone	Year
Origins	First surgical robot for stereotactic biopsy	1988
Origins	Computer-assisted implant surgery pipeline	2000s
Origins	Levels-of-autonomy framework for medical robots	2017
First autonomous systems	First autonomous/semi-autonomous implant robots	2018-2020
Expansion	Accuracy studies versus static guides and navigation	2021-2023
Current state	Systematic reviews and umbrella reviews of accuracy	2024-2026
Current state	Task-autonomous systems and AI integration	2024-2026

Note: The periods are defined by the review; years are the publication or authorisation years of the milestones.

The safety evidence, although thinner than the accuracy evidence, is consistent with what the accuracy would predict. The studies that reported adverse events or complications alongside their accuracy figures reported few serious events, and the safety record of the supervised-autonomy systems, in which the surgeon can halt the procedure at any point, is a direct consequence of the control architecture rather than a separate finding.(27,28)

The absence of a large safety literature is itself a gap, because the accuracy studies were not designed to detect rare adverse events, and the safety of the systems at the scale at which they would be adopted is therefore an open question that the accuracy evidence cannot settle. This is the same limitation that affects the clinical outcome question, and it is the reason the review treats safety and outcome together as the unproven part of the field.

The remaining accuracy studies of the current period fill in the detail of this consolidated picture. The studies of specific clinical scenarios reported accuracy across the maxillary sinus floor elevation, the edentulous jaw, the tilted implant and the immediate placement, and the autonomous systems performed consistently across them.(27-32)

The comparisons of robotic placement against freehand placement, against static guides and against dynamic navigation each reached the same conclusion, that the robotic approach was among the most accurate.(13,33) The trephination-based and the task-autonomous systems extended the approach to new workflows, and the in-vitro and in-vivo comparisons of autonomous against fully guided placement reported the deviations that define the current performance envelope.(18,34,35)

The accuracy of the robotic approach is therefore not a property of a single system or a single study but a consistent finding across scenarios, comparators and study designs, and it is the most settled conclusion that this review can report. The direct comparisons of robotic against freehand placement, of dynamic navigation against robotic placement, and of robotic against static-guided placement in the same sample all reported the robotic approach at the accurate end of the range,

and the positional-accuracy comparison confirmed the same ordering.(36-38)

DISCUSSION

The objective of this review was to trace the evolution of robotic dentistry and to synthesize the current evidence, and the trajectory answers it in a clear sequence. Each period contributed a distinct capability: the origins contributed the scan-plan-guide pipeline, the first autonomous systems contributed proof of feasibility, the expansion period contributed the accuracy evidence, and the current period contributed the consolidation of that evidence and the turn toward autonomy and artificial intelligence.

The through-line is a consistent movement from a machine that advises to a machine that assists to a machine that, increasingly, acts, and the evidence supports the accuracy of each step while leaving the clinical and economic justification of the final step open.

The accuracy evidence is the most settled part of the field, and its interpretation, unlike the autonomy question, is relatively straightforward. Robotic placement achieves deviations that are small in absolute terms and comparable to or smaller than the guided alternative, and the systematic reviews that pooled the studies reached this conclusion without any substantial dissent among them.(9-11)

What the accuracy evidence does not yet show is whether those small differences translate into a difference that ultimately matters, because the deviation thresholds that define clinical success are not uniform across the studies and the literature has not linked the smaller deviations to differences in implant survival or complication rates. The accuracy claim is therefore established on the evidence reviewed here, and the clinical outcome claim is the specific gap that the next phase of evidence must fill before the adoption question can be settled.

The turn toward autonomy is the part of the trajectory that the literature has not yet resolved, and it is the part that carries the most weight, because it is where the technical question becomes an ethical and legal one. The levels-of-autonomy framework provides the vocabulary, and the task-autonomous systems of the current period occupy the supervised-autonomy level, but the question of whether and when full autonomy is justified remains open, and the barriers named in the literature, cost, workflow and the clinical justification of autonomy, are the real limits that the trajectory has now reached.(4,26)

The artificial intelligence integration is the newest layer, and the embodied-intelligence and vision-free proposals are a direction rather than an evidence base.(23,24) The trajectory of the field, from its origins to the present, is therefore one in which the technical capability has consistently outpaced the clinical and regulatory justification for its use, and this persistent gap between what the machines can do and what the evidence supports is the defining feature of the current state of robotic dentistry.

The trajectory of robotic dentistry mirrors the wider trajectory of surgical robotics, and the comparison is instructive. The non-dental surgical robotics field followed the same sequence, from telemanipulation to increasing autonomy, and it reached the same point of technical maturity with the same unresolved questions of cost and clinical justification.(39-41)

The augmentation of human operators with artificial intelligence, and the evolution of telesurgery documented in the bibliometric studies, are the same forces that are now reaching dentistry, and the trajectory they describe is the one that the dental field is entering.(42-44)

The willingness studies in other specialties suggest that acceptance of autonomous surgery lags behind the technology, which is a caution for the dental field as it moves in the same direction.(45)The dental field is therefore not an outlier but a late entrant to a well-established and already-documented trajectory, and it inherits both the trajectory's accumulated achievements and its still-unresolved questions.

The economic dimension is the barrier that the accuracy literature does not address but that the trajectory makes unavoidable. A robotic implant system is an expensive capital acquisition, and its justification must therefore rest on either a better clinical outcome, a faster or safer workflow, or a capability that the cheaper guided and navigated alternatives cannot provide, and the evidence reviewed here has not established any of these in a form that would compel adoption.

The accuracy is comparable to the guided alternative, not clearly superior in clinical terms, and the workflow cost of the registration and the robotic setup is an added burden rather than a saving. Until the economic case is made, the robotic systems are likely to remain the tool of a subset of practices, and the question of cost, rather than the question of accuracy, may prove to be the one that determines how far the trajectory proceeds.

The regulatory dimension follows the same line. The movement toward greater autonomy raises the question of who is responsible when an autonomous system errs, and the levels-of-autonomy framework is, in part, a regulatory framework that assigns that responsibility.(4)

The dental systems of the current period occupy the supervised-autonomy level, where the surgeon retains responsibility, and the regulatory pathway for a move beyond that level is not yet defined for dental robotics. This is not a technical obstacle but a governance one, and it is the reason that the trajectory toward full autonomy is likely to be slower than the trajectory toward supervised autonomy has been.

The strengths of the chronological method should be stated alongside its limitations, because they determine what the review can and cannot claim. The chronological organisation makes the trajectory itself the object of study, and it is that trajectory, rather than a single cross-sectional summary, that a reader most needs in order to judge the field. The separation of the periods by explicit criteria makes the organisation transparent and falsifiable, and the distinction between the robotic and the artificial intelligence layers prevents the two from being conflated. These are the properties that distinguish the present review from a catalogue of accuracy figures, and they are the reason the conclusions are stated as a trajectory rather than as a point estimate.

The agenda that follows from the trajectory is specific and can be stated in three parts. The evidence now needs studies that link the smaller placement deviations to clinical outcomes, because that is the step that would justify the cost and workflow of the robotic systems.

It needs a settled and consistently applied vocabulary of autonomy levels for the dental systems, because the current descriptions of the same systems are not yet uniform. And it needs evidence on the economic and workflow costs of the robotic approach, because those costs, rather than the accuracy, are the barriers that the literature names and that will ultimately determine whether adoption proceeds.(26) These three questions together are the ones that the next period of the trajectory will have to answer.

The comparison with the orthopaedic trajectory is the most instructive of the non-dental parallels, because orthopaedics reached the same point a few years earlier and its experience is a preview of dentistry's.

The orthopaedic robotic systems for joint replacement were adopted on the strength of accuracy and precision claims that preceded the clinical outcome evidence, and the outcome evidence that later accumulated showed the same pattern that dentistry is now seeing, of a technical advantage that is real but whose clinical translation is slower and less certain than the early enthusiasm suggested.(40,41) The dental field, entering the same trajectory later, has the advantage of that prior example, and the lesson it should draw is that the accuracy advantage, once established, is not the end of the question but the beginning of the outcome and economic questions that follow. This is the reason the review's conclusions are stated as a trajectory with open questions rather than as an endorsement.

CONCLUSIONS

Robotic dentistry has evolved over four full decades from computer-assisted surgery through proof-of-feasibility and accuracy consolidation to the current turn toward autonomy and artificial intelligence, and the accuracy of robotic implant placement is now established as comparable to or better than the guided alternative. The trajectory is a consistent and clearly directed movement toward a machine that acts, from a pipeline that advises the surgeon, to a robot that assists the surgeon, to a system that executes the plan under supervision, and the evidence supports the accuracy of each successive step along that movement.

The questions that remain are not about accuracy but about outcome, autonomy and integration: whether the smaller placement deviations translate into better clinical results, how much autonomy is clinically and regulatorily justified, and whether the cost and workflow of the robotic systems can be borne in routine practice. These questions, rather than the already-settled technical capability, will determine the next stage of the field, and the trajectory reviewed here is therefore best read as a record of a field that has mastered its technique and is now facing the harder question of its proper place.

The questions that remain are not about accuracy but about outcome, autonomy and integration: whether the smaller placement deviations translate into better clinical results, how much autonomy is clinically justified, and whether the cost and workflow of the robotic systems can be borne. These questions, rather than the technical capability, will determine the next stage of the field.

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