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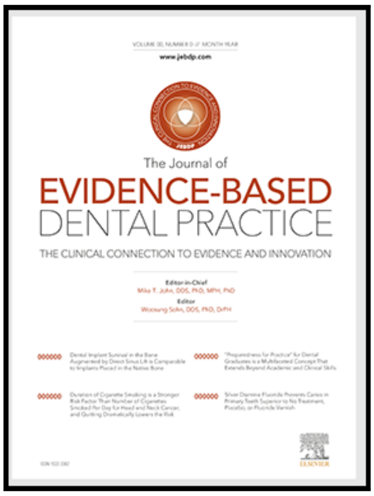


# Digital Dentistry and its Impact on Oral Health-Related Quality of Life

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Anmerkungen

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Abstract:

Over the past 50 years, digitization has gradually taken root in dentistry, starting with computer tomography in the 1970s. The most disruptive events in digital dentistry were the introduction of digital workflow and computer-aided manufacturing, which made new procedures and materials available for dental use. While the conventional lab-based workflow requires light or chemical curing under inconsistent and suboptimal conditions, computer-aided manufacturing allows for industrial-grade material, ensuring consistently high material quality. In addition, many other innovative, less disruptive, but relevant approaches have been developed in digital dentistry. These will have or already impact prevention, diagnosis, and therapy, thus impacting patients' oral health and, consequently, their oral health-related quality of life (OHRQoL). Both software and hardware approaches attempt to maintain, restore, or optimize a patient's perceived oral health. This article outlines innovations in dentistry and their potential impact on patients' OHRQoL in prevention and therapy. Furthermore, possible future developments and their potential implications are characterized.

# Introduction

Conventional dentistry undoubtedly provides effective preventive and treatment options to maintain, improve, or restore patients' Oral Health-Related Quality of Life (OHRQoL).[1] However, digital dentistry offers additional tools to achieve this goal.[2] Dentists can be more precise in diagnosis, prevention, and therapeutic intervention using digital technologies.[3] In addition, digital workflows can make the treatment process more convenient for patients. Describing digitalization's potential and actual effects in dentistry would fill at least one book. Therefore, this paper will focus on the expected benefits of digitization as perceived by the patients on their OHRQoL, excluding artificial intelligence (AI), and will provide an overview of current imaging tools, software, and manufacturing equipment with clinical examples in an interdisciplinary setting, without claiming to be complete.

We will evaluate which effects on OHRQoL are already proven, where there may be potentially unproven effects, and speculate which outcomes may be coming soon. This paper will assess the impact of digitization processes in dentistry according to the four dimensions of OHRQoL, covering the different dental disciplines. However, many changes will affect more than one dimension or multiple disciplines. Since prevention is better than cure, we will start by avoiding disruption and thus maintaining OHRQoL unimpaired. Finally, we will review new developments in digital dentistry that may affect patients´ OHRQoL.



**Oral Health-Related Quality of Life**

Oral Health-Related Quality of Life (OHRQoL) is a multidimensional construct that includes a subjective assessment of an individual's oral health, functional well-being, emotional well-being, expectations and satisfaction with care, and sense of self. It has broad applications in survey and clinical research.[4] OHRQoL is an integral part of overall health-related quality of life.[5, 6] Due to its subjective nature, OHRQoL dimensions are assessed using empirically derived questions. Several questionnaires have been developed to collect this information.[7-9] The most commonly used questionnaires are the Oral Health Impact Profile (OHIP), the General Oral Health Assessment Index (GOHAI) in adults and seniors, and the Child Perceptions Questionnaire (CPQ) in children and adolescents.[10-13] To reduce the burden on patients, there has been a tendency in scientific practice to develop subversions that specialize in specific disorders or diseases, such as temporomandibular disorders or edentulous people.[14] However, this specialization trend has proven unfavorable due to the need for comparability between disease impacts and therapeutic effects. The OHIP is the most internationally translated, scientifically validated, and widely used OHRQoL questionnaire. Fortunately, for this patient-reported outcome measure, the trend to reduce patient burden could be achieved much more efficiently by reducing the number of items through short and ultra-short versions.

The ultra-short version with five items (OHIP-5) still contains 90 percent of the information of the original version with 49 items.[15] Therefore, the OHIP-5 has recently been recommended for general routine use and scientific application, covering all the relevant dimensions.[16] While the original, empirically derived dimension of the OHRQoL proved to be clinically less meaningful, a long process has been reforming it based on the available data.[17, 18] Four major dimensions, clinically relevant aspects of the OHRQoL, have been derived: oral function, orofacial pain, orofacial aesthetics, and psychosocial impact.[18-21]

**Digital dentistry**

Digital dentistry has already had a significant impact on everyday dentistry since its first concepts in the 1970s.[22] Initially born as an idea to make chairside dental restorations out of ceramics instead of metal[23], a whole new industry has developed over the last few decades. There were disruptive changes, such as the introduction of computer-aided design/computer-aided manufacturing (CAD/CAM), causing tremendous changes in available materials and, therefore, dentists' preferences.[24] This makes new materials available for dental purposes and others obsolete. However, there are also many more or less subtle changes in dentistry, ranging from introducing software and other medical imaging tools to manufacturing devices.[25] Many will affect workflows, communication between practitioners and patients, the choice of materials, and clinical outcomes. Most digital technologies start as stand-alone solutions but will be implemented in more extensive digital networks soon after. While digitalization will increase investment costs, there must be gains in other areas to offset them. These can be the speed and quality of communication, reduced time for technical or clinical procedures, improved quality and predictability of outcomes, and patient comfort. However, we must distinguish between digitalization's effects and AI. AI is a logical subset of digitization that uses algorithms and machine learning to automate tasks that traditionally require human intelligence.

## Prevention and Diagnosis

The World Health Organization (WHO) defines prevention as “approaches and activities to reduce the likelihood that a disease or disorder will affect an individual, interrupting or slowing the disorder's progression or reducing disability”.[26] But how does digitization in dentistry help prevent disease or disorder? The first and most obvious point is the intraoral digitization of the dental arches with an **intraoral scanner (IOS),** now opening up a wide range of diagnostic options.[27] But how does it help maintain the patients’ OHRQoL? The idea is to take a full-arch scan at the annual dental check-up, which can be superimposed on the previous situation. Calculation algorithms could detect surface changes (e.g., gingival recession, swelling, tooth migration, tooth wear) before they are visible to the dentist. Some IOS manufacturers already offer internal 3D analysis software for the superimposition of different scan datasets (e.g., OraCheck (Dentsply Sirona, Bensheim, Germany), Trios Patient Monitoring (3Shape, Copenhagen, Denmark)). This allows early prediction of increased tooth wear rates due to extrinsic or intrinsic erosion, attrition, and/or abrasion. Initial clinical study results have shown that IOS can already be used to monitor tooth structure loss on a micrometer level for individual teeth, much earlier than is possible with the naked eye.[28] Also, tooth movement due to periodontal inflammation, lack of antagonists or adjacent teeth, or relapse after orthodontic treatment can be detected early. Therefore, monitoring with IOS allows patient-specific dentistry with individual prognosis for tooth wear and movement, thus avoiding repetitive or invasive treatments that may cause temporary or permanent impairment of the patients´ OHRQoL.[29]

A novel feature of IOS with color display is that it is also possible to display intraorally stained areas with plaque accumulation.[30] This can be helpful in visualization, documenting, and teaching oral hygiene to help patients and parents improve daily oral hygiene and, therefore, maintain their oral health. Digital technologies have been used in pediatric dentistry for about ten years.[31] The focus has been on digital impression-taking, a popular alternative to conventional impression-taking that can be uncomfortable for children. The studies published are mostly case reports regarding feasibility studies for space maintainers, orthodontic retainers, various splints, and devices for cleft patients.[32] The improvement in the quality of life of children with these more gentle technologies has been hypothesized, but it has yet to be measured with appropriate instruments. However, it is known that adolescents prefer IOS to conventional impression-taking.[33] While traditional impression-taking in very young patients can be potentially life-threatening due to the risk of airway obstruction and aspiration of impression material, IOS is a fast, safe, and feasible procedure that can be routinely used even in neonates and infants.[34, 35]

A well-known stand-alone digital device for radiation-free caries diagnostic function is the DIAGNOcam (KaVo, Biberach, Germany). However, some IOS have already implemented this technology, e.g., Emerald S (Planmeca Oy, Helsinki, Finland) iTero Element 5D (Align Technology, Or Yehuda, Israel). These devices use light waves to detect caries. **Near-infrared light reflection** technology enables early detection of interproximal caries. Reflected near-infrared light images generated simultaneously with 3D intra-oral scanning can be reliably used to detect, screen, and monitor proximal caries, thus potentially minimizing the traditional use of ionizing radiation and its subsequent consequences.[36] A similar but promising different approach is **Quantitative Light-induced Fluorescence (QLF)** [37, 38] An IOS-integrated version is already commercially available (Trios 4/5, 3Shape).[39] However, there are still some limitations in differentiating pathological changes from structural anomalies, so their routine use is still a work in progress with the potential to support reliable monitoring of early caries lesions.

A home-based approach uses mobile applications to promote oral health. Standard program features include tools for tracking or reminding one to brush teeth and assisting in scheduling dental appointments.[40, 41] Others are paired with a device such as “smart” **electric toothbrushes** with sensors for tracking things like timing, pressure, and position. Coupled with apps on the phone, this information can motivate and guide patients to clean their teeth more adequately.[42]

Other apps are available to digitally assess **chewing function** in a home setting (e.g., ViewGum®software, dHAL Software, Kifissia, Greece)[43]. In contrast, others are currently available as apps for research purposes only  (e.g., Mini Dental Assessment, Giessen, Germany).[44] These chewing function tests were not developed to replace routine dental examinations but could help to identify the need for dental treatment even for (dental) laypersons.[45]

One step further is **telemedicine**, offering health services at a distance. While some disciplines, such as maxillofacial surgery, have begun to routinely consult patients by telephone after minor dentoalveolar surgery[46], dentistry needs digital equipment and software offering more than a video conferencing tool. In children, telemedicine saves money by reducing unnecessary travel, improving patient and provider satisfaction, and enabling better patient self-management. However, clinical outcomes have not been affected by telemedicine services.[47] Especially in the care of the very old, this could help to narrow a dental healthcare gap.[48] However, digital literacy is a significant barrier for seniors and the very old.

In orthodontics, mobile/tablet-based applications are available (e.g., ClearCorrect Sync®, Straumann, Basel, Switzerland). These can capture, edit, and quickly upload patient case photos. In brief, they fit into the practice workflow by simplifying the process of patient photo capture. However, data on patients' Oral Health-Related Quality of Life comparing conventional and digital methods is unavailable. The combination of the 3D-intra oral scan, CBCT, advanced software, use of mobile phones, and individual CAD/CAM-tailored appliances significantly impacts our patients' treatment experience.[49, 50] The first step is individual software-based information and education before treatment. With these utilities, the patient and, if applicable, the parents are involved and prepared for shared decision-making. Linking intra-oral scan with the consultation, a simulated 3D outcome of the desired tooth position is vivid. Individualized patient education can be compiled in a further step, including texts, videos, and pictures (informadent, HeideSoft GmbH & Co. KG, Soltau, Germany). This data can be shared and accessible via mobile devices for the patient or parents. So, there is always a source of individualized information available at your fingertips.[51] The involvement of the patient and the parents in the therapeutic process continues when 3D treatment plans and the goal of the therapy are discussed together, and special requests can be accommodated.[52]

For oral and maxillofacial surgery, digital planning in connection with an additive manufacturing process such as 3D printing also enables the production of models for patient information, intraoperative haptic control, and the visualization of complex anatomical conditions or the reconstruction result.[25, 53]

Digital technologies could support the early detection of caries and periodontitis as well as the health behaviour of patients and thus improve their oral well-being.[54-58] This would prevent unnecessary treatment, reduce the number of visits patients have to make to the doctor's office or clinic, and preserve patients' OHRQoL. This probably includes all dimensions. Therefore, preventive approaches are the most valuable for the patient.

But there are risks as well as benefits. Known for ”beauty filters” in online communication tools, video platforms, and advertising, the urge to conform to the digital alter ego can become pathological.[59] This can lead to harm from medically unnecessary aesthetically driven treatments such as highly white "perfect" teeth, permanent damage from veneers or even fixed dentures, or extraction of healthy teeth. While this may improve perceived oral health in the aesthetic dimension in the short term, it may cause impairment in the other dimensions. For example, impairment in the pain dimension due to increased tooth sensitivity caused by tooth whitening procedures is a known but reversible side effect.[60]

## Therapeutic intervention

Digitization is occurring not only in new devices but also in **software**. While studies can demonstrate the general benefit of various therapeutic approaches, we know that the therapeutic success of specific procedures depends on the skill of the individual clinician.[61] With the OHRQoL routine patient quality assessment, it is possible to automate small surveys – online or combined with an update of the patient's medical history at check-up visits before and after treatments. Monitoring one's treatment success from the patients' perspective enables the clinician to recognize their success from their perspective. It also provides the basis for value-based oral health care as an additional incentive to provide the best possible care.[62] In addition, new telemedicine infrastructure is accelerating the exchange and availability of medical data, reducing information loss and unnecessary duplication of testing, potentially leading to faster and better treatment decisions. The latest advancement is continuous monitoring of treatment progress through the patient's own activity.[63] He regularly scans his teeth with the smartphone and a special adapter, and monitors with support of artificial neural networks the progress of the orthodontic treatment (www.dentalmonitoring.com, Paris, France). The orthodontist is alerted in case of deviations and can thus remain in direct contact with the patient and communicate at any time about the progress of the treatment. With the same quality of treatment, this system requires fewer visits to the orthodontist.[64] Positive effects on oral hygiene have also been reported.[65] Other software applications have a direct therapeutic approach. A habit control software (BruxAPP, BruxApp Team, Pontedera, Italy) is dedicated to studying and managing bruxism and its health consequences, reducing OHRQoL impairment by offering help to change unfavorable habits.[66] Optionally, ambulatory electromyography, and contingent electrical stimulation devices are available to detect and interfere with bruxism events (Grindcare, Sunstar Suisse SA, Etoy, Switzerland).[67] Both are viable approaches for reducing bruxism-associated pain and subsequent functional and ästhetic impairment due to tooth damage or muscle hypertrophy.

The use of **IOS** is not only good for preventive purposes. It also saves time in many situations requiring precise impressions (immediate chairside quality control of the preparation and local impression correction). In addition, patients are more comfortable, and sometimes entire sessions can be saved, resulting in less disruption to the patient's quality of life.[68, 69] In addition, overlay with previous scan data allows for more similar tooth shapes, making functional adaptation to the new prosthesis easier. However, there is scarce evidence that the digital manufacturing process is superior to the conventional one regarding patients` OHRQoL.[70] A digital impression has shown to be a viable alternative to traditional protocols for implant-supported crowns and implant-retained full-arch immediate loading prostheses.[71, 72] Computer-aided manufacturing made millable, printable, and laser sinterable materials available for dental purposes, such as various ceramics, composites, and polymers or complicated designs.[73, 74] This allows for more tooth-colored restorations, improves fit and esthetics and provides options for patients with dental material allergies.[70, 75] While the traditional lab-based workflow requires light or chemical curing under varying and suboptimal conditions, CAM allows for industrial-grade material, ensuring consistently high material quality. Improving movement flexibility and milling strategies and increasing resolution in printing and sintering processes have already enhanced the trueness and precision of dental medical products.[76] This hopefully results in improved OHRQoL due to better fit, enhanced surface properties, and duration of these products.[77] However, this is not always the case. Milled dentures offer many equal or better properties in mechanical and surface parameters and fit compared to conventional dentures.[78] While patients perceive milled dentures to be at least similar to traditional dentures when given a choice, most patients still prefer conventional dentures to 3D-printed dentures.[79]

Nonetheless, digital data storage allows identical copies to be made if a splint, temporary crown, or full denture is broken or lost. Finally, digital data can be done without physical transportation. Therefore, one-way delivery is possible in long-distance transport, i.e., rural areas, saving time in restoring impaired OHRQoL. The digitization of patient data continues beyond the IOS. In the design process, the use of **virtual facebow** and jaw movement recording data (e.g., Zebris, Zebris Medical, Isny, Germany; Tech in motion, Modjaw, Villeurbanne, France) assists in a dental laboratory setting simulating vertical changes in the jaw relationship.[80] Merging hinge axis, jaw movement data, and data from IOS of the upper and lower jaw in virtual articulators may improve simulation and identify colliding teeth in dynamic occlusion during the virtual design process. However, the clinical relevance of such data is under discussion. **3D facial scan** data is already enabling better esthetic simulation of maxillofacial surgery[81], surgical prosthetic and epithetic outcomes, and orthodontic procedures[82], helping to find the best approach for the individual, both functionally and esthetically.[83] **Cone beam computed tomography** is used for various clinical indications, including resorption, preoperative assessment of surgical and non-surgical endodontic retreatment, location of missing canals, and differential diagnosis.[84] Preventing tooth loss through proper treatment planning in complex situations avoids loss of function and pain. However, reconciling all available data (intraoral, extraoral, and radiographic) is still time-consuming, with limited support, and is not routine. However, computer-aided simulation is helpful for collaborative interdisciplinary planning of complex surgeries with subsequent prosthetic restoration, orthodontic treatment, or fabrication of surgical appliances and customized plates, splints, and implants in oral and maxillofacial surgery.[85] This improves positioning accuracy and saves surgical time, which subsequently reduces postoperative pain and helps to optimize functional, esthetic, and psychosocial aspects by achieving the desired position.[86]

Currently, matching extraoral and intraoral data is routinely available for daily dental practice only in two dimensions to assist orthodontic patients in their aesthetic decision-making (Smile Design, 3Shape). This is done by importing the patients' photos into the software and virtually determining the tooth shape and color. Soon, matching 3D X-rays, 3D face scans, IOS data, and 3D printed splints will become increasingly popular for virtual planning, especially in orthognathic surgery.[87-90] Some IOS, particularly in aligner technology, offer a simulation of the treatment result in a three-dimensional representation of tooth movement. This virtual simulation should be used with caution when communicating with the patient. It is important to emphasize that this simulation does not always reflect the treatment outcome due to the limitations of tooth preparation, tooth movement, and surgical procedures. This may be because the teeth do not move as predicted or because the simulation overcorrects tooth movement, assuming that only part of the planned movement will be achieved.

Nevertheless, 3D simulation of orthodontic treatment can significantly improve communication with the patient, especially when correcting anterior teeth. Some practitioners perform an instant simulation during the initial consultation to explain the need for orthodontic treatment. With digital workflow, technology has provided the modern clinician with the ability for visual collaboration of surgical, orthodontic, facial aesthetic, and prosthetic principles. This visual and accurate simulation allows the patient to interact and connect with the treatment plan. It empowers the patient to try the treatment virtually before committing and connect emotionally to their desires.



## Future developments

Many additional benefits are possible in future scenarios (Table 1). Other technologies can be used to evaluate teeth and surrounding tissues. There is optical coherence tomography, which allows near-surface evaluation of composite and ceramic restorations.[91, 92] Potential software targets may be facilitating diagnosis, e.g., of temporomandibular disorders, or supporting current treatment decisions with the best available evidence.[93] There may be a future where **IOS** replaces a daily routine's manual tooth, plaque, and pocket evaluation. Therefore, in contrast to today, the focus of the discussion about IOS will not be on whether it can completely replace the conventional impression but rather on what additional benefits an IOS offers. Today, the most common IOS offers at least similar precision and accuracy to traditional impression techniques with less discomfort for the individual patient.[94] In the future, IOS will open up a whole new field of dentistry in simulation, predictability, monitoring, and prevention. This will enhance the preventive aspect and is the key to a lifelong best possible unimpaired OHRQoL. Combined with new materials offered by digitized processes, therapeutic options will include longer-lasting restorations with less damage to the patient's oral structures. Better simulation of treatment outcomes will improve shared decision-making and reduce the risk of decision conflicts.[95] In 2023, a unique dental-dedicated Magnetic Resonance Imaging has been presented, offering new diagnostic options in x-ray-free 3D-diagnostic.[96] While today, hard tissues can be replaced routinely, in the future, 3D printing of soft tissues may become an option. Same with digital impression taking with IOS. Today, only attached hard and soft tissue can be scanned. However, correct display of movable oral mucosa is crucial and not feasible today for impression taking in removable prosthodontics. All this will impact patients' OHRQoL in different ways, not comprehensively imaginable today. An important consideration seems to be the potential increase in cost and patient burden. Therefore, traditional approaches should not be abandoned as long as the benefits associated with digital dentistry can be proven to outweigh the relevant risks and costs. However, the immense potential impacts on oral health make it imminent to use a standard metric to measure these impacts.[19]

## Conclusion and Research Perspectives

Most potential advantages of digitization could be more proven regarding OHRQoL benefits, but plausible theoretical thoughts. Therefore, many research questions open up which can deal with the potential of the described manifold digital applications in the light of OHRQoL. Much is estimated, but far less proven by data. Patient-reported outcome measures with a low patient burden could help lower the boundaries for more frequent applications and, therefore, more data. Furthermore, a standard metric would help make research results comparable. Ideally, these data could feed a database usable for AI technologies, offering the best evidence for individualized dental medicine.

Declaration of interest

There are no competing interests by all authors.

Author contributions

O. Schierz and M. Schlenz contributed to the manuscript's conception, design, drafting, and finalizing. Ch. Hirsch proofread and added pediatric dentistry topics. K.F. Krey proofread and contributed to orthodontic issues. C. Ganss proofread and added cariology topics. P. W. Kämmerer proofread and contributed to oral and maxillofacial surgery issues.

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Table 1 Benefits of digital dentistry in terms of OHRQoL. This table has been developed with help of ChatGPT.

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| Precision and Accuracy: Digital tools like intraoral scanners and 3D imaging provide more precise measurements and impressions, leading to better-fitting restorations and reduced discomfort for patients.<br><br>Faster Treatment: Digital workflows streamline the treatment process, reducing the time patients spend in the dental chair. This can improve OHRQoL by minimizing the inconvenience of multiple appointments.<br><br>Improved Communication: Digital technologies enable better communication between dental professionals and patients through visual aids and 3D models, helping patients understand their treatment options and outcomes.<br><br>Customization: Digital dentistry allows for highly customized treatments, ensuring that restorations and prosthetics fit comfortably and function effectively, enhancing overall quality of life.<br><br>Reduced Anxiety: For patients with dental anxiety, digital dentistry can offer a more comfortable and less intimidating experience, potentially improving their OHRQoL.<br><br>Remote Consultations: Tele-dentistry, facilitated by digital tools, allows patients to consult with their dentists remotely, reducing the need for travel and time off work, thus positively affecting their quality of life.<br><br>Digital Records: Digital patient records and treatment histories ensure continuity of care, making it easier for patients to access their dental information and track their oral health progress.<br><br>Proactive Care: Digital technologies enable dentists to detect issues earlier, potentially preventing more significant problems and the associated impact on OHRQoL.<br><br>Patient Engagement: Interactive digital tools can engage patients in their oral health management, |

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| motivating them to maintain good oral hygiene practices and habits. |

Table 2 Current, main research gaps in terms of digital dentistry and OHRQoL. This table has been developed with help of ChatGPT.

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| Long-term Impact: Many studies focus on short-term outcomes. There's a need for more research to assess the long-term effects of digital dentistry interventions on patients' OHRQoL, especially for prosthetic restorations and orthodontic treatments.<br><br>Patient Perspectives: More research is needed to understand the patient's perspective and experiences with digital dentistry. Qualitative studies can help uncover patient's preferences by patient-reported outcomes measures in an comparable manner.<br><br>Cost-effectiveness: The cost-effectiveness of various digital dental technologies and their impact on OHRQoL should be studied comprehensively. This can guide decision-makers and insurers in allocating resources.<br><br>Standardization: There is a lack of standardized protocols and guidelines for incorporating digital dentistry into OHRQoL assessments. Using current standards would improve the consistency and comparability of research findings.<br><br>Comparative Studies: Comparative studies that directly compare traditional dental techniques with their digital counterparts in terms of OHRQoL outcomes are limited. Such studies could provide valuable insights.<br><br>Diverse Populations: Research often focuses on specific patient groups or demographics. More studies should include diverse populations to better understand how digital dentistry affects OHRQoL across different groups.<br><br>Psychosocial Impact: While the physical aspects of OHRQoL are often studied, there's a need for more research on the psychosocial impact of digital dentistry. This could include factors like body image, self-esteem, and social well-being.<br><br>Access and Equity: Research should examine how the adoption of digital dentistry may affect access |

to care and equity in oral healthcare delivery, ensuring that advancements benefit all segments of the population.

Education and Training: As digital dentistry continues to evolve, research on the educational and training needs of dental professionals to effectively utilize these technologies is essential.

Graphical Abstract