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Disruptive Innovation in Dentistry: What It Is and What Could Be Next

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Abstract

Dentistry is a technically oriented profession, and the health care sector is significantly influenced by the ubiquitous trend of digitalization. Some of these digital developments have the potential to result in disruptive changes for dental practice, while others may turn out to be just a pipedream. This *Discovery!* essay focuses on innovations built on artificial intelligence (AI) as the center-technology influencing 1) dental eHealth data management, 2) clinical and technical health care applications, and 3) services and operations. AI systems enable personalized dental medicine workflows by analyzing all eHealth data gathered from an individual patient. Besides dental-specific data, this also includes genomic, proteomic, and metabolomic information and therefore facilitates optimized and personalized treatment strategies and risk management. Based on the power of AI, the triangular frame of "data"/"health care"/"service" is supplemented by technological advancements in the field of social media, Internet of things, augmented and virtual reality, rapid prototyping, and intraoral optical scanning as well as teledentistry. Innovation continues to be critical to tackle dental problems until its routine implementation based on sound scientific evidence. Novel technologies must be viewed critically in relation to the cost-benefit ratio and the ethical implications of a misleading diagnosis or treatment produced by AI algorithms. Highly sensitive eHealth data must be handled responsibly to enable the immense benefits of these technologies to be realized for society. The focus on patient-centered research and the development of personalized dental medicine have the potential to improve individual and public health, as well as clarify the interconnectivity of disease in a more cost-effective way.

Keywords: digital transformation, artificial intelligence, rapid prototyping, augmented reality, personalized dental medicine, teledentistry

Introduction

The theory of disruptive technology was initially introduced by Joseph L. Bower and Clayton M. Christensen in the *Harvard Business Review* in 1995 and has proven to be a powerful way of thinking about innovation-driven development in any business sector (Bower and Christensen 1995). The difference between "incremental" and "disruptive" innovation is in the type of change and its consequences. Whereas modernization is a renewal that does not fundamentally alter the market and usually proceeds gradually or with incremental steps, disruption is the complete reorganization of existing models following an ongoing dynamic process. What are characteristics of a successful disruptive innovation? Typically, 3 mechanisms are key: 1) enabling technology to reach a wider population; 2) coherent value networks, in which the stakeholders involved are better off when disruptive technology flourishes; and 3) business models that target nonconsumers in a particular market (Christensen Institute 2020).

Computer-aided design/computer-aided manufacturing (CAD/CAM), for example, can be considered a disruptive technology (Joda et al. 2017). Today, monolithic full-contour reconstructions can be produced in large quantities with reproducible quality and at reduced costs using standardized processes by CAD/CAM technicians in a digital workflow (Joda, Ferrari, et al. 2018).

Improved information technology (IT) facilities, such as computing capacity, data storage options, cloud technology, and mass market application at affordable prices, have promoted promising technologies in all disciplines of dentistry. In the age of digital transformation, the turnover rate of (dental)

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technologies is estimated to be every 1 to 2 y (Wismeijer et al. 2018). Existing workflows are continuously replaced by novelties at increasingly shorter intervals. What will prevail and what will be replaced?

Probably the most promising IT innovation is artificial intelligence (AI), and data are the necessary ingredient to a successful recipe of any AI model. Companies across all economic sectors are adopting AI to improve and scale up operations and services. Advances in machine learning (ML) and deep learning (DL) are also helping to level up dental research and oral health care. The digital possibilities are not yet fully understood, and their added value will be assessed in the future (Joda et al. 2020).

Therefore, the aim of this *Discovery!* article is to look into the crystal ball and to explore selected technological trends and innovations, which may have the potential to revolutionize and disrupt the direction of dental research and practice of oral health care. At the same time, this article also critically examines the possible risks and dangers associated with these technologies.

Significance of AI

AI is generally defined as intelligent computer systems capable of iteratively learning knowledge and simulating human intelligence processes to accomplish complex tasks (Leite et al. 2020). The development of AI systems to address specific issues has been an exciting topic in various fields, including dental medicine. An intelligent system could automatically perform an individualized analysis of a patient based on the medical history, demographic information, clinical findings, and diagnostic images, to subsequently make evidence-based decisions relying on a real-time, up-to-date large database.

Diagnostic imaging (such as panoramic radiography and cone beam computed tomography [CBCT]) and surface scanning techniques (such as intraoral and facial scanning) have been the first bridge connecting AI and dental medicine because their digitally coded image data were directly translated into computer language (Hung, Montalvo, et al. 2020). Among various AI techniques, ML and its subfield DL are the main approaches to develop image-based intelligent systems for diagnostic purposes and treatment planning (Leite et al. 2020). Image-based ML algorithms developed for purposes in dental medicine cover a wide range of potential clinical applications, including automated diagnosis of diseases (such as root fractures or periodontal defects), classification of lesions (such as maxillofacial cystic lesions), and localization of anatomical structures (such as orthodontic landmarks) (Hung, Montalvao, et al. 2020; Hung, Yeung, et al. 2020).

AI is more than "just" automatic image analysis. AI can be seen as the central technology of a triad formed by patient data management, health care application, and services (Fig.). Through training with multiple data sets with a labeled ground truth, ML/DL algorithms can explore associations between the combinations of specific features and assorted outputs (Joda, Waltimo, et al. 2019). Accessing worldwide data sets facilitates recognizing and diagnosing rare diseases, which otherwise would have possibly never been identified.

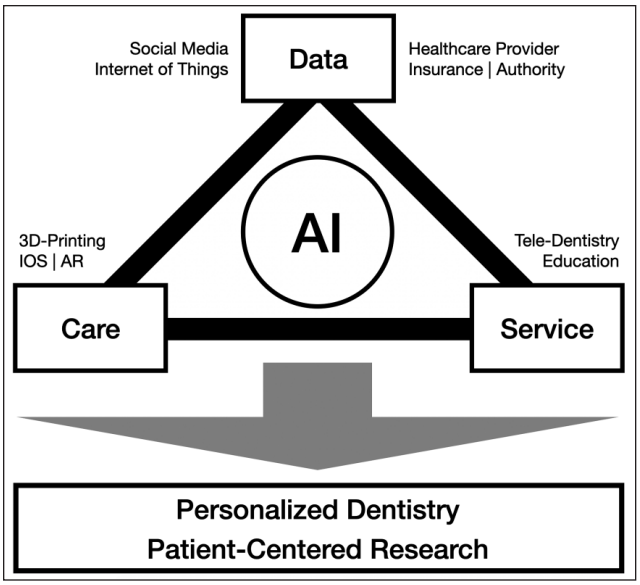

Figure. Artificial intelligence (AI) technologies as the center for disruptive innovation in dental and oral medicine: data generation and its use to optimize health care and services to enable personalized dentistry and patient-centered research. AR, augmented reality; IOS, intraoral optical scanning.

The Power of eHealth Data

Everything starts with data management: defining what should be collected and how data are stored. Generally, it must be distinguished between 2 types of eHealth data: 1) professional data generated by health care providers, insurance companies, and authorities and 2) undifferentiated data generated on social media and from Internet of things (IoT) directly by the patients (Joda, Waltimo, et al. 2018).

Successful health data management depends on the ubiquitously accepted definitions of standards that will guide the implementation within electronic health records and health information technology ecosystems. Such an ecosystem of the future should integrate front-end utilization of health data in clinical decision making by caregivers for patient-centered treatment planning and, secondarily, back-end AI algorithms analyzing the standardized collected data to update population-based policy decisions, such as resource management and research actions (Joda, Waltimo, et al. 2019).

Whenever and wherever clinicians and patients interact with the virtual community, they leave their digital fingerprints, and the collected data are automatically and invisibly analyzed in the background using AI technology (i.e., by social media companies or dental technology companies). The role of social media for dentistry is defined by the timely sharing of information that reaches a broad audience. Various social media platforms can also be helpful for dental education of both students and patients, such as demonstrating different dental treatments

with YouTube videos and discussions through Twitter (Arnett et al. 2013). As social media platforms allow anyone to upload content, the quality of online information can be questionable. This may not be readily recognized by laypersons, such as misinformation about oral health care during the outbreak of COVID-19 (Tao et al. 2020). Social media platforms are also used for sharing views and disseminating research outputs, with the Altmetric Attention Score (AAS) measuring the online attention received by published articles (Warren et al. 2020). In addition, social media are used to connect dentists and patients, although e-professionalism has to be observed closely to ensure both parties are respected and mutual confidence is maintained (Neville and Waylen 2015). For dentists, social media can be beneficial to their practices in terms of saving patient contact time by explaining procedures and providing correct information to their patients prior to the appointment (Walker 2015) and for marketing if local regulations allow (Snyman and Visser 2014). For patients, social media allow them to share treatment experiences, outcomes, and decision making, thereby facilitating information exchange and peer support (Barber et al. 2018).

Health Care Applications

AI is also the promotor for clinical and technical workflows in dental medicine. Currently, the most prominent areas are rapid prototyping (RP) in combination with intraoral optical scanning (IOS) and augmented reality/virtual reality (AR/VR).

RP is a relatively young technique for speedy mass production of 3-dimensional (3D) models. The additive manufacturing with 3D printers allows automated processing and low-cost fabrication of any geometry from diverse materials (Quan et al. 2020). In dentistry, RP offers huge potential through the use of digital workflows with IOS and subsequent fabrication of dental models for further processing of complex prosthetic reconstructions. Initial results were reported for treatment with 3D-printed fixed dental prostheses made of zirconium dioxide (Galante et al. 2019). The development of new printable materials is a hot topic in dental research. In contrast to subtractive manufacturing by means of CAD/CAM milling, RP allows the design and production of innovative 3D designs, such as hollow implant and prosthetic components used for a time-controlled release of anti-inflammatory mediators to promote and to maintain oral health (Zocca et al. 2015). The disruptive potential of RP is 3D bioprinting to synthesize one-of-a-kind parts on demand (i.e., by using diverse cells, growth factors, and other biomaterials to create and imitate natural tissue characteristics customized on patient-specific needs, such as connective tissue, cartilage, and bone). A completely revolutionary feature will be the complex synthesis of dental biomaterials to re-create lost tooth structures using RP technology (Bose et al. 2018). On the one hand, a virtual tooth databank could deliver a variety of morphologies, scalable and modifiable according to the patient's needs. On the other hand, a personalized digital dental data set could be obtained at the age of adolescence, stored in an open data format, and used for any future dental reconstruction or even for the replication of an entire tooth by means of a customized dental implant. Thus, biological rehabilitations of lost hard and soft tissue with unlimited availability would replace all kinds of artificial prosthetic reconstructions. Overall, RP has the potential to disrupt the oral health care sector to facilitate personalized dental treatment solutions (Joda et al. 2020).

AR is an interactive technology that enriches a real-world situation with computer animation to enhance reality with virtual content. In contrast, VR only uses simulated computerized environments without involvement of reality (Sutherland et al. 2019). Here, visual, auditory, and haptic qualities of sensation can be integrated—depending on the technique used (Pensieri and Pennacchini 2014). AR/VR technologies are becoming increasingly important in all disciplines of dental medicine, with interesting opportunities for both the benefit of the patient and the support of health care providers in their treatment strategies (Kwon et al. 2018; Farronato et al. 2019; Joda, Gallucci, et al. 2019). A key feature of AR/VR is the opportunity to match virtual visualizations with recordings of the patient in physical motion, especially for the treatment in complex oral and maxillofacial rehabilitations with interdisciplinary involvement (Joda and Gallucci 2015). The ideal treatment outcome can be augmented into the individual patient scenario in advance. For example, various prosthetic virtual setups can be tested and evaluated in real time in a completely noninvasive manner (Li et al. 2020). AR/VR can help to explain the impact of different therapeutic options to the patient and to demystify complex treatments. At the same time, the exchange between dental professionals is simplified and made more efficient, leading to more predictable treatment outcomes (Joda et al. 2015). In this context, guided implant surgery could be revolutionized using AR glasses to display CBCT-based virtual implant planning while highlighting vulnerable adjacent structures directly in the patient's oral cavity. The dental clinician could use all the information from 3D radiographic diagnostics paired with the real-time action of 3D implant positioning. This would enable prosthetic-driven implant surgery without cumbersome drilling templates. AR glasses can also improve IOS workflows during digital impression taking to project and to immediately display the optically detected areas.

Dental Services in the Digital Age

AI enables completely new possibilities in the field of services and operations. Key areas here are teledentistry and the entire education sector.

Teledentistry is the remote provision of dental care without a physical personal contact (Khan and Omar 2013). In the past, transmission of digital images and clinical records for distance diagnosis was conducted by email (Torres-Pereira et al. 2008). Nowadays, a smartphone with applications such as WhatsApp allows patients and members of the dental team to ask questions, send clinical images and videos to facilitate initial consultations, and arrange subsequent examinations more efficiently (Petruzzi and de Benedittis 2016). Telecommunication with smartphone applications is helpful in communities with few oral health care specialists (i.e., oral and maxillofacial radiologists)

Table. Innovative Technologies in Dental Medicine: Status Quo and Their Disruptive Potential Based on the Structure Presented in the Figure; Artificial Intelligence (AI) as the Center-Technology within the Triad of Data Management, Health Care, and Service to Foster Personalized Dental Medicine.

Technology	Status Quo	Disruptive Potential
Artificial intelligence	• Initial tests of automated diagnostics in dental imaging and maxillofacial radiology	• Center-technology for disruptive innovation in computerized dentistry • Optimization of repetitive workflows with increased efficiency • Evidence-based decision making for treatment options
Data management		
Social media	• Dental forums for self-diagnostics • Health care apps	• Platform for research dissemination • Tool for patient education and monitoring • Connector for patient-dentist communication
Health care		
Rapid prototyping	• Three-dimensional printing of temporaries, dental casts, and templates for guided implant surgery • Laser melting of metal frameworks	• Synthesis of dental biomaterials (i.e., teeth, soft and hard oral tissues) • Replacement of artificial dental prostheses
Augmented reality/virtual reality	• Motor skill training in dental undergraduate education	• Virtual dental classroom teaching with 24/7 access • Pretreatment planning and noninvasive outcome simulation • Clinical application in guided (implant) surgery and intraoral scanning
Service		
Teledentistry	• Country-dependent implementation of privatized video-mediated health care	• Virtual consultation and monitoring of patients without physical contact • Change of health care provider infrastructure with centralized dental supervisors
Personalized dental medicine	• Limited use due to data privacy regulations	• Analysis of genomic, proteomic, and metabolomic patient health data to facilitate individual risk management and therapy

and is particularly applicable to diagnosis, treatment planning, and monitoring/following up of patients' oral health (Giudice et al. 2020). It also improves access to dental care for the underserved patients by removing some of the geographic and economic barriers (Fricton and Chen 2009). Consultations can be conducted through real-time videoconferencing, and patients or their caregivers can be instructed to adjust lighting and retract lips and cheeks for the dentist to remotely examine their oral conditions (Villa et al. 2020). Teledentistry has the disruptive potential to remotely diagnose and monitor patients who have limited access to dental care providers or emergency units. Besides patient care, teledentistry can also be used to educate dental and health care students and professionals on dental medicine (McFarland et al. 2018; Zitzmann et al. 2020).

Dental education, both under- and postgraduate, will benefit significantly from AI systems, especially in combination with AR/VR technology. AR/VR has the power to change the entire field of dental education within the next few years, transmitting theory and practice with interactive 24/7 access (Zitzmann et al. 2020). In under- and postgraduate education, challenging and complex clinical protocols can be trained in a completely virtual environment without risk or harm for real patients (Ayoub and Pulijala 2019; Durham et al. 2019).

The Other Side of the Coin

In fact, AR/VR, RP, & Co. are ubiquitous buzzwords, and almost everyone thinks they are used in some way. Are all these technologies just like big balloons that burst and disappear? To what extent are these supposed innovations really disruptive in character, and will they displace established workflows?

The Table summarizes the discussed innovative technologies in dental medicine, including their status quo and disruptive potential. Nevertheless, all novel technologies must be viewed critically:

- The relationship between cost and benefit of these (dental) technologies for the clinicians and the patients
- The ethical implications of a faulty diagnosis produced by computerized AI algorithms
- The role of the spread of misinformation in social media regarding self-treatment and auto-medication for oral diseases

Fraudsters who take advantage of the system will always exist. It is necessary to define and establish transparent rules for dealing with the new media, novel tools, and digital applications. This task is a collective responsibility of society as a whole, not just for politicians, universities, or representatives of (dental) associations or the influential MedTech industry. Responsible handling of highly sensitive eHealth data must be guaranteed to realize the immense benefits of these technologies for the patients. Not everything that seems technically possible at the time makes sense to implement (Table).

Conclusions and Future Outlook

The main objective of innovative dental medicine is to promote personalized dentistry based on patient-centered research.

Personalized dental medicine involves the use of a person's individual clinical, genetic, behavioral, and environmental features to tailor personalized prevention and monitoring strategies for various oral diseases, improve early diagnosis, and provide more effective treatment on an individual basis (Reddy et al. 2019). By combining several AI systems with a deeper understanding of the molecular basis of oral diseases, health care resources could be more efficiently allocated to higher-risk individuals using an interdisciplinary approach. Diagnoses and subsequent preventive measures could be established early, and treatment planning and therapy could become transparent and available at early stages for routine implementation.

AI systems build the basis for data management, oral health care, and services and operations focusing on patient-centered research to develop personalized dentistry. AI has the disruptive potential to facilitate and foster organized eHealth data generation and management. This may help improve diagnostic accuracy and work efficiency following fully automated AI systems and to contribute to the further development of personalized dental workflows by analyzing data gathered from the molecular to the clinical level to improve treatment decision making on an individual patient basis (Joda et al. 2020).

Author Contributions

T. Joda, A.W.K. Yeung, K. Hung, N.U. Zitzmann, M.M. Bornstein, contributed to conception, design, and data analysis, drafted and critically revised the manuscript. All authors gave final approval and agree to be accountable for all aspects of the work.

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