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The Fourth Industrial Revolution's impact on dentistry

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SUMMARY

Introduction Even the greatest visionaries could not have guessed at what speed the profession and science of dentistry would accept the concept of the Fourth Industrial Revolution. In terms of its scale and complexity, this transformation has been greater than any known before and it has been described in the literature as Dentistry 4.0. The digital revolution in dentistry has allowed for nearly all clinical and laboratory procedures to be supported by digital technologies. The aim of this paper is to understand the role of Industry 4.0 in the profession of dentistry and identify its research status today and in the future.

Methods An electronic search of Medline literature was performed via PubMed and Google Scholar databases with the terms "fourth industrial revolution," "digital dentistry," "dentistry 4.0," "CAD-CAM." The option "related articles" was also utilized as well as an additional manual search of review articles and the most relevant papers.

Results The paper describes the most frequently used diagnostic and therapeutic procedures supported by digital technologies.

Conclusion The sophisticated technologies of the Fourth Industrial Revolution have led to more rapid and precise diagnoses of oral diseases. Clinical procedures have become easier, more precise and predictable to the dentist, and more comfortable to the patient. The long-term benefits also include financial savings and environmental protection.

Keywords: digitalization; Fourth Industrial Revolution; digital dentistry; Dentistry 4.0

INTRODUCTION

Dentistry is a highly dynamic scientific field and the changes that occur in this field reflect the development of basic sciences technology [1]. Throughout history, there have been many examples of technological innovations that created new diagnostic and therapeutic procedures in clinical dentistry.

The profession of dentistry has experienced continuous growth, taking advantage of all the opportunities that resulted from the industrial revolutions. The Third Industrial Revolution that marked the transition from analogue electronic technology into a digital era (1980s) propelled a huge leap forward in clinical dentistry. This is when the term digital dentistry was coined, defined as "any digital or computer-aided technology or device in dentistry, as opposed to mechanically or electronically controlled tools" [2]. Digital dentistry opens completely new perspectives where communication, documentation, manufacturing and many other clinical procedures are brought under the umbrella of computer-based algorithms.

Quicker than was expected, another crucial advancement followed that led to automation and the use of robotics both in the industry and in the medical sciences. This shift was so profound that it became known as the Fourth Industrial Revolution – the term first used by Klaus Schwab, head of the World Economic Forum, in 2015. Unlike the three preceding revolutions, this one was not based on groundbreaking new technology but implied a transition to new systems developed using the infrastructure of the previous, digital revolution. Automation is facilitated by the cyber-physical systems enabled by the Internet of things and cloud computing [3].

Even the greatest visionaries could not have anticipated the speed at which both the profession and the science of dentistry, as well as the accompanying industry, would accept the new concept of digital transformation. In terms of volume and complexity, this transformation was greater than any known before. In dentistry, the digital revolution allowed for the possibility for almost all clinical and laboratory procedures to be supported by digital technologies (Figure 1). This new concept soon found its place and received the name Dentistry 4.0 [4, 5].

This paper aims to understand the role of Industry 4.0 in the profession of dentistry and to identify its research status both today and in the future. In dentistry, a truly wide array of diagnostic and therapeutic procedures exist that are based on the technological discoveries within Industry 4.0. Thus, here, only the most important ones will be briefly described.

An electronic search of Medline literature was performed via PubMed and Google

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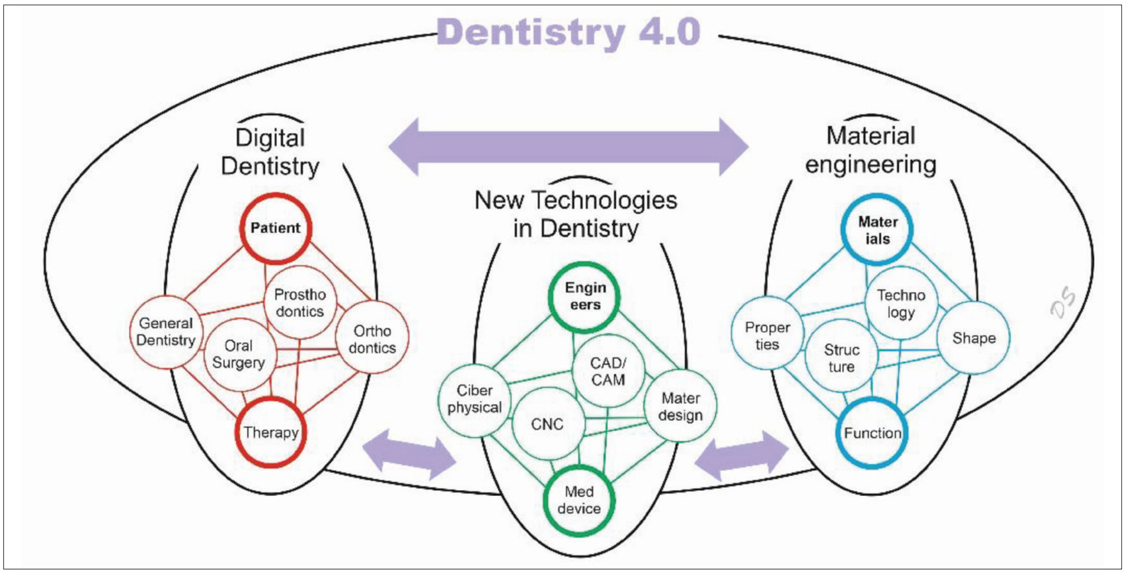

Figure 1. Dentistry 4.0 – synergy of dentists and engineers

Scholar databases with the terms "fourth industrial revolution," "digital dentistry," "dentistry 4.0," "CAD-CAM." The option "related articles" was also utilized, as well as an additional manual search of review articles and the most relevant papers.

MEDICAL IMAGING

Medical imaging is the visualization of anatomical structures using computerized recording techniques. The result of medical imaging is a digital image, which is the first step in digital dentistry. Many diagnostic and therapeutic procedures have been created by generating digital images [1]. Let us mention only those that are used today in routine practice.

Digital teeth impressions

These are virtual, computer-generated copies of the hard and soft tissues in the mouth. Engineers have developed a medical device for digital impressions that is comprised of an intraoral scanner (IOS – hardware), a computer and software. The IOS records a three-dimensional image of an object (a tooth or the surrounding structures) by using concentrated light beams to precisely "capture" the tooth and the surrounding tissue and generates an image in the Standard Tessellation Language (STL) format (Figure 2). More recent intraoral scanners also register the color and texture of the tissue in a Polygon File Format (PLY) file. Laboratory scanners work on a similar principle (Figure 3).

Figure 2. Image of the teeth of the upper and lower jaw obtained with an intraoral scanner

The digital tooth impression operates on a similar principle and, in comparison to the conventional impression, is more precise and easier for the dentist and less unpleasant for the patient. The digital impression is also the first step in prosthodontics, orthodontics, and dental implant treatment.

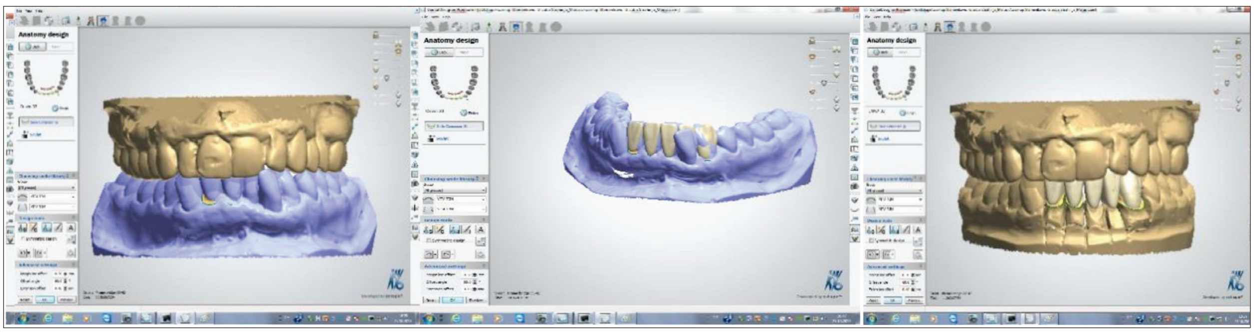

Figure 3. A – image of a cast model of the upper and lower jaw; B and C – computer animation in the Smile Design program in planning treatment for tooth anguish in the lower jaw

Cone-beam computed tomography

Three-dimensional diagnostics (computerized tomography, CT) has long been a superior diagnostic tool in nearly all branches of medicine. The conventional medical CT provides a good three-dimensional representation of the hard tissues and enables their easy visualization. Yet, with regard to our field of interest, this implies both a high dose of radiation and a costly price to pay. These were the basic reasons behind the development of cone-beam computed tomography (CBCT). CBCT uses cone-shaped X-radiation focused on the region of interest, which significantly reduces the effective dose of radiation in comparison to the conventional CT. Some 10 years after the first application of CBCT in angiography and mammography (1982, Mayo Clinic), CBCT-based devices were developed that were specifically intended for dentistry (Figure 4).

By representing the anatomical structure of the orofacial region in three planes, the CBCT technology brought significant advancement in the diagnostics and treatment used in oral and maxillofacial surgery, periodontics, endodontics and orthodontics. The three-dimensional representation of bone structures has enabled computer-aided surgical procedures that employ specially designed software.

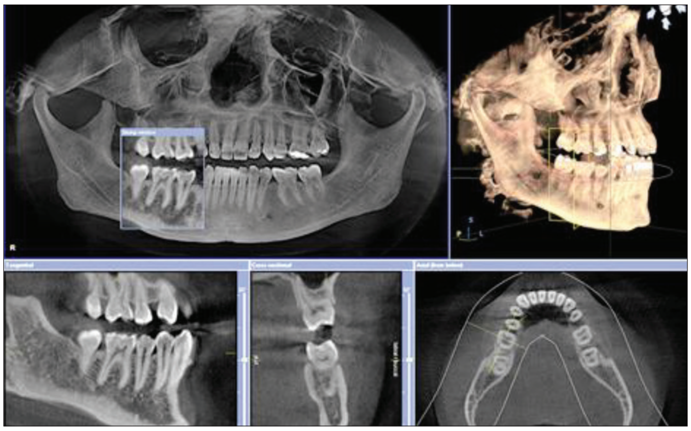

Figure 4. Cone-beam computed tomography screenshot with a small field of view – 6 × 6 cm

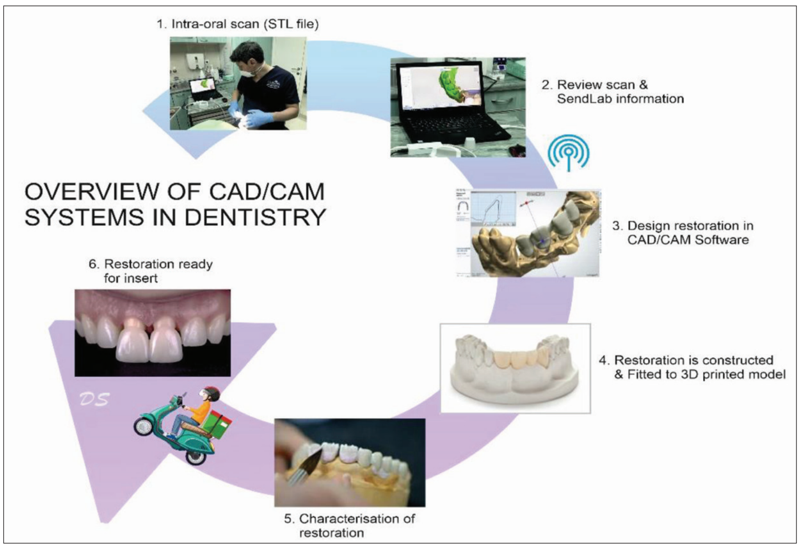

Figure 5. Overview of CAD/CAM systems in dentistry

Digital photography

In combination with the appropriate commercial software for image processing, digital photography allows virtual facial reconstruction, virtual occlusion (Real-Time 3D Reconstruction for Occlusion), smile designing (Digital Smile Design, Smile Creator), etc.

DATA PROCESSING

There is a large number of commercial software products for data processing available today that are designed to support the diagnostic procedures and therapeutic treatments in dentistry.

Computer-aided design and computer-aided manufacturing software

Commercial 3D computer-aided design (CAD) software has been developed that uses several standard data formats. The data files created when taking a digital impression (STL file) are transferred into CAD software to design a dental appliance. After the virtual dental appliance is formed, the files are transferred into the computer support software (computer-aided manufacturing/modeling/machining, CAM software). Based on the CAD model (virtual model), the CAM software then determines a tool path for the computer numerically controlled (CNC) machine (Figure 5). Data processing will depend on the type of machine that will be used for the final shaping of the appliance [6].

Digital facebows and virtual articulators

These are computer software tools that reproduce jaw relationships and simulate the movements of the lower jaw. In digital dentistry, digital facebows have replaced conventional facebows and facilitated their transfer to the space of an articulator. Digital images of three reference points (projections of centers of temporomandibular condyles and the infraorbital point) and an intraoral scan of the upper jaw are sufficient elements for fixating a virtual model of the upper jaw to the upper member of the articulator [7, 8].

Shade matching

Shade matching has resolved many doubts and issues that surface with regard to the visual determination of tooth shade. Machines used for the quantitative analysis of tooth color can determine the characteristics of the light reflected from the examined tooth surface. Today, several well-rounded concepts are employed for instrumental tooth shade matching [red-green-blue (RGB) machines, spectrophotometers, colorimeters]. What all these concepts have in common is the integrated digital camera and image processing software [9].

Digital Smile Design

This is another computer tool that found an application in digital dentistry. Several digital images and a specially designed software package are enough to achieve the visualization of the existing state and the virtual simulation of different therapeutic plans in designing a smile (Figure 2). Besides visualization, the predictability of future treatment is the main advantage of this computer tool. Before the dental intervention, the patient can "see" or even create together with the physician the end-result of treatment [10].

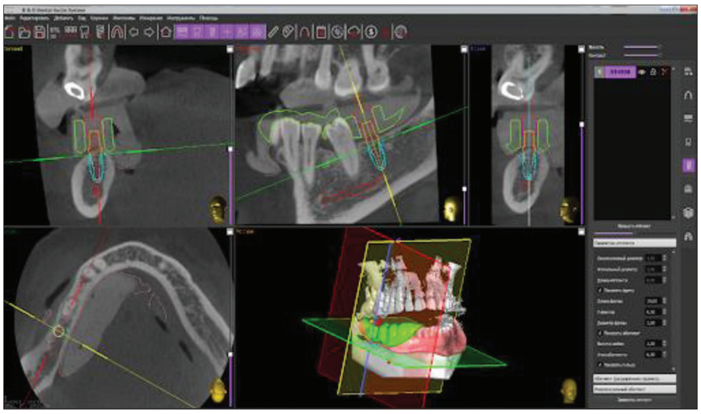

Figure 6. Cone-beam computed tomography screenshot in the preoperative treatment of implant insertion

Computer-guided implant surgery

This is a good example of the Fourth Industrial Revolution in dentistry. This concept involves a series of sophisticated procedures, from diagnosis to implant insertion, and indeed deserves to be called a generator of computerized dentistry. Advanced imaging methods such as CBCT and digital volume tomography supported by 3D software for the examination and analysis of radiograms allow three-dimensional reconstruction of the tissue into which an implant is to be inserted. In this way, the preoperative planning of the optimal implant position is achieved (Figure 6).

Today, the widely accepted technique for inserting implants involves using surgical splints that determine the direction and depth of implant insertion. This method is also known in the literature as "static navigation for implant placement" [11]. Computer-guided implant placement in its full capacity is the technique known as "dynamic navigation for dental implant surgery" or the navigation technique. As its name says, this technique "navigates" the handpiece in real-time during implant placement based on the dental global positioning system without the use of surgical splints or temporary appliances [11–14]. Further development of computer-guided implantology will likely derive from this navigation method. Even now, several commercial programs are present on the market (X-Guide Dynamic 3D Navigation System, Nobel Biocare Co, Kloten, Switzerland; Navident – dynamic navigation system, The Dental Imaging Company Ltd., Shoreham-by-Sea, UK, etc.).

Virtual diagnostics and treatment planning in orthodontics

The digitalization in orthodontics has a long tradition and includes three basic groups of programs: those for office management and patient files' management, those for designing and analyzing digital models, and those for cephalometric analysis (digital cephalometry). There are numerous software packages that support cephalometric analysis (Dolphin Imaging, Dolphin Imaging Systems LLC; OnyxCeph, Image Instruments GmbH, Chemnitz, Germany; AxCeph, Audax, Ljubljana, Slovenia, etc.). Invivo5 (Anatomage Co., Santa Clara, CA, usa) is certainly the most well-known software offering visualization of anatomical structures and other innovations of importance to orthodontics [15, 16].

COMPUTER-AIDED MANUFACTURING

CAM implies the application of software to control tool machines in the manufacturing of various 3D objects. A virtual model designed using CAD and if necessary verified by computer-aided engineering is introduced into the CAM software that controls the CNC machine during the manufacturing process. Essentially, this software allows for the automatization of the process, faster and more precise work and material savings. Machines used in dentistry include milling, sintering, rapid prototyping, and 3D printing machines.

Subtractive manufacturing

The first CAD/CAM systems appeared in dentistry in the 1980s, namely, CEREC (Sirona Dental Systems Inc., New York, NY, USA) and Procera (Nobel Biocare). CNC machines, guided by CAM software, utilize firm blocks of material (ceramic or metal alloys) for milling to form the required shapes [4, 17]. These systems have developed in two directions, which resulted in in-office and laboratory systems.

In-office systems (chairside CAD/CAM technique)

These systems are intended for manufacturing smaller fixed dental appliances in one patient visit. The prepared tooth is scanned and the 3D image is sent to the computer that creates a fixed dental appliance using the CAD/CAM software. The in-office CAD machine quickly mills the dental appliance that is also cemented during the same

Figure 7. Left – the action of milling a ceramic crown in an in-office CAD/CAM machine; right – a ceramic block from which the ceramic crown is milled

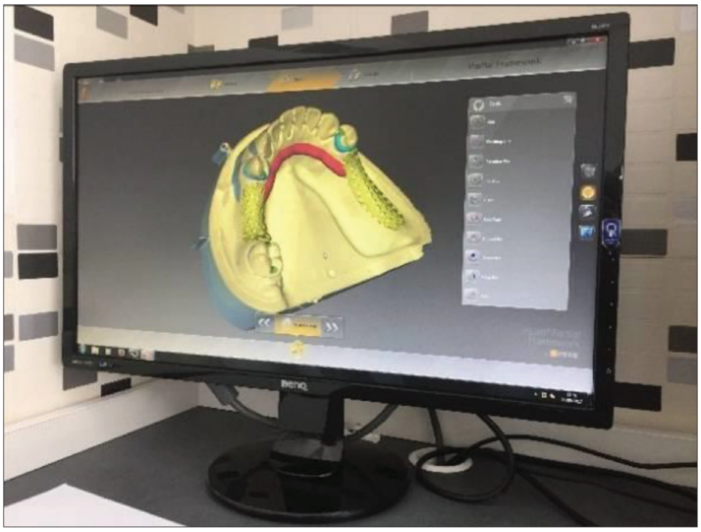

Figure 8. Screen of a monitor showing a virtual model and a model of the dental appliance designed in the 3Shape Partial Denture System (3Shape, Copenhagen, Denmark) program [20]

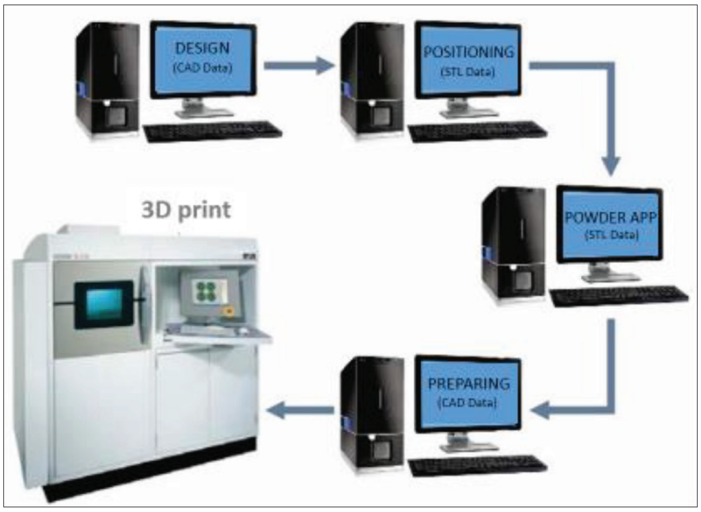

Figure 9. Schematic representation of the manufacturing of a frame using the selective laser melting technology [20]

patient visit. The advantages of this technique are the digital impression, no temporary crowns, and no laboratory costs. Insufficient precision of the gingival sulcus (soft tissue management) and the impossibility of individualizing the appliance are the basic shortcomings of this procedure (Figure 7).

In-lab systems (non-chairside CAD/CAM device)

An impression or model is sent to a laboratory that, after scanning the impression or model, designs and mills the frame (using a ceramic or a metal alloy) in the CNC machine and returns it to the dental laboratory for the application of veneering material and individualization of the appliance. These systems require two patient visits. Due to the fact that they connect the physical with the virtual world, the described systems share many common elements with the cyber-physical systems. The typical examples are Procera AllCeram all-ceramic system (Nobel Biocare), Lava CNC 500 Milling Machine (3M ESPE AG, St. Paul, MN, USA), KaVo Everest CAD/CAM System (KaVo Dental GMBH, Biberach, Germany), InLab (Sirona), etc.

Additive manufacturing technologies

These technologies are broadly applied in the dental industry. In the literature, they are described as additive technologies and rapid prototyping, 3D printing and the manufacturing of free forms. What all formative technologies have in common is that the 3D form is obtained by adding new layers of material. Additive technologies enable direct production of physical shapes (dental appliances, dental implants, obturators, teaching aids, etc.) by using a 3D digital geometric model as input. The geometric model is either designed in a CAD program or obtained by 3D scanning an existing object.

There are numerous examples of the manufacturing of 3D objects in oral and maxillofacial surgery, oral implantology, prosthodontics, and orthodontics. In prosthodontics, there is basically no appliance that cannot be manufactured using additive technology, either in ceramic or composite material, or a metal alloy. The framework of a removable denture is an example of the superiority of this technology over traditional methods. A digital impression of a partially edentulous patient is sent to the laboratory via the Internet and serves as a basis for the virtual model from which the framework is manufactured, in five steps, using the selective laser melting technology (Figures 8 and 9) [17–20]. In order to transfer the physical framework of the denture to a real model and send it to the dental office, a real working polymer model is made on a 3D printer (dental model resin).

BIOMATERIALS

Teeth can be restored, moved or upgraded using materials that in addition to good physical and mechanical

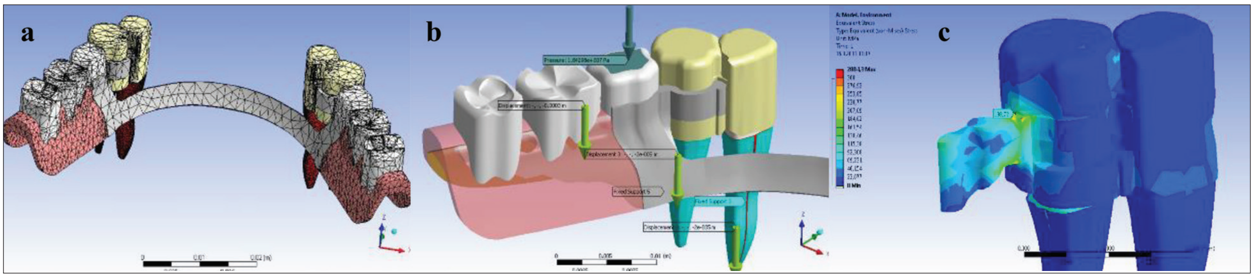

Figure 10. a – the mesh of finite elements of a partial complex denture: 110,970 elements and 213,931 nodes [21]; b – a virtual model of the free-end saddle of a complex partial denture with a point load of 700 N on the first molar [21]; c – stresses and deformations of a complex denture's fixed appliance with a point load of 700 N on the first molar [21]

characteristics also have to possess good biological properties, i.e., they have to be compatible with the oral tissues and the human organism as a whole. When inserted into the stomatognathic system, these materials most often exhibit predictive behavior. From time to time, however, inexplicable observations can be made that are the result of interaction between a material and the living organism. Hence, their name is justified – biomaterials. In the science of materials, in general, dental materials are classified as belonging to the group of advanced materials or materials of the future (nanomaterials and smart materials) [21]. With the accelerated development of the synthesis, shaping, and manufacturing of biomaterials with strictly controlled characteristics in terms of composition, structure, and physicochemical properties, new possibilities are being opened in bioengineering [21, 22, 23].

Dentistry uses a wide spectrum of materials. Most are the products of sophisticated technology. In nanodentistry, expectations are the same as in nanomedicine, except the field of action of the nanoparticles is limited to the stomatognathic system. In the field of dental materials, there are two strategic tasks: synthesis of new polymer and ceramic materials with specific characteristics and synthesis of new nanomaterials (scaffolds) as biological carriers [22].

Smart materials are already used in modern dentistry and they are often described as advanced materials. Some typical representatives include bio-shape-memory alloy and smart composites (these contain amorphous phosphates that act as calcium and phosphate depots) [22, 23, 24]. The widely applied glass-ionomer cements are known as smart materials because of their programmed release of fluoride in caries prevention.

VIRTUAL EDUCATION AND SCIENCE

This technological revolution in the form of virtual reality has fundamentally changed our way of living, working, and connecting. At all stages of education, from the elementary to the highest levels, there is an ongoing gradual transition from the analogue to the digital way of functioning.

In the education of students and residents, digital technologies have reached various degrees of application depending on the resources of particular schools. One of the greatest challenges in the digital education of future dentists is the need for continuous adjustment to technological advances [1, 25]. In dental schools, new courses have been introduced: Computerized Dentistry, Visualization Techniques, and the like. Most clinical courses (Oral Implantology, Prosthodontics, Orthodontics) utilize 3D images, video clips and simulation programs as teaching aids [26, 27, 28].

Continuing professional development (lifelong learning) is the product of this era and can be seen in all professional and scientific fields. In the medical sciences, it is known as continuing medical education (CME). Especially, the traditional CME has grown into eCME and this is one of the fastest rising trends in dental education both here and around the globe [1, 25]. The eCME allows for designing courses and webinars in an interactive form. Also, the comfort provided to users by the eCME is indeed substantial: every student can set his or her own tempo and time for education (the education is not bound by precise hours and locations). A mere glance at the work schedules of scientific and professional organizations will reveal numerous virtual events (webinars) that are conducted live online and enable the lecturers and attendees to connect in an interactive manner. In addition to a screen device and internet access, a software tool for webinars (Zoom, Skype, GoToWebinar, Google meet, Google Plus Hangouts) is needed that provides interactive participation via a chat box or the Q&A function. Webinars as a format of the eCME have given access to education to anyone interested, at any place and any time. During the pandemic (COVID-19) and social distancing, this format of eCME has gained even more significance.

The saying "without technology, medicine is powerless; without medicine, technology is blind" may best illustrate both the association and the inter-dependence between medicine and technology, or between physicians and engineers. Nearly all scientific and research projects in dentistry have engaged engineers to participate as researchers. In the study of dental sciences, the most frequently applied method of numerical analysis is the finite element method (FEM). In short, the FEM considers the physical domain (tooth, dental implant, denture or bridge, temporomandibular joint, etc.) as a real continuum where the points have infinitely many degrees of freedom of movement and reduces it to a discrete (virtual) model with a specific number of points (called nodes) with a finite number of degrees of freedom that can be described mathematically [21, 29].

The appearance of intraoral digital scanners and CBCT scanners allowed for the definition of a real physical model with complex geometry (teeth and the supporting structures of teeth, etc.). Specialized software translates the 3D images into a digital 3D model [20, 25, 29]. The following procedure is nowadays routine in the engineering world: a numerical model is produced by generating a mesh of nodes that comprise the so-called finite elements (Figure 10a). Doctors are expected to define the project assignment – in the case shown in the figures, this would be the loading and elastic deformations of the dental appliance, teeth and supporting structures of the teeth (Figures 10b and c). The physical characteristics of materials and tissues that should be considered to complete the calculation are Young's modulus, Poisson's ratio, and shear modulus [21, 29]. By using program packages for the finite element method analysis (such as the innovative platform ANSYS Workbench, ANSYS, Inc, Canonsburg, PA, USA), beside obtaining the values of stresses and elastic deformations, it is also possible to create animations of the movement of the free-end saddle of the denture and the carrier tooth in a three-axis Cartesian coordinate system (x-y-z) (in dentistry, the terms sagittal, frontal, and horizontal plane are traditionally used instead of the x-y-z system). A visual representation of the virtual movement of the free-end saddle of a complex denture and teeth in operation is a good example of digitalization in teaching dentistry students (Figure 10).

All research projects require the consent of the ethical committee, whose work is based on the principles of good clinical practice as the ethical and scientific standard of quality in designing, managing, monitoring, and reporting about studies done in humans. Sometimes, however, when it comes to investigating the behavior of tissues and organs of the orofacial region, dental appliances or implants under conditions of loading, it is impossible to obtain the ethical committee's consent. In such instances, the application of FEM is the method of choice. FEM should also be given advantage in cases when the proposed experiment is economically unsustainable. The results of FEM should not be taken as final but rather as preliminary findings that signal towards more valid methods, such as clinical studies.

PATIENT RECORD MANAGEMENT

Today, the complete healthcare system has been digitalized, which has made all the management activities simpler and quicker. Due to commercially available software, the management of patient records has become easier and permanently accessible. All patient documentation (dental chart, medical and dental patient history, treatment protocols, radiographies, photographs, digital models before and after the intervention, etc.) can be easily stored and made available in digital form. One of the software tools most often utilized for this purpose is the patient records management dental software [30]. The future holds a transition to web-based patient files, in which data are stored in centralized web servers instead of computers located in individual dental offices [30].

CONCLUSION

The increasingly sophisticated and integrated digital technologies in everyday dental practice (medical imaging, CBCT, digital photography) have led to a more rapid and precise diagnosis of oral diseases. Clinical procedures have become simpler, more precise and predictable for the doctor, and more comfortable to the patient (digital teeth impressions). A large number of commercial software products as CAD/CAM software for milling crowns and bridges, digital facebows and virtual articulators, shade matching, Digital Smile Design, computer-guided implant surgery and digital cephalometry have contributed the most to the progress of dentistry.

The benefits of new technologies in dentistry are enormous. Also, financial savings and environmental protection (less medical and communal waste) are no less important in the long run. At the same time, these technologies can be frustrating because they require great investments and a certain knowledge of informatics from all the members of a dental team. These would also be one of the main reasons behind the unequal level of application of digitalization in dental offices and dental laboratories.

Conflict of interest: None declared.

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Утицај четврте индустријске револуције на стоматологију

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САЖЕТАК

Увод И највећи визионари нису могли да претпоставе којом брзином ће стоматолошка струка и наука прихватити концепт четврте индустријске револуције. По обиму и сложености ова трансформација је већа од свих до сада познатих и у литератури је описана као *Dentistry* 4.0. Дигитална револуција је стоматологији омогућила да готово све клиничке и лабораторијске процедуре могу бити подржане дигиталним технологијама. Циљ овог рада је разумевање улоге четврте индустријске револуције у стоматологији.

Методе Претраживање базе *Medline* извршено је путем база података *PubMed* и *Google Scholar* за термине „четврта индустријска револуција“, „дигитална стоматологија“, „стоматологија 4.0“, „*CAD-CAM*“. Такође су коришћене опције „сродних чланака“ уз додатно ручно претраживање прегледних чланака и релевантних текстова.

Резултати У раду су описане најчешће дијагностичке и терапијске процедуре које су подржане дигиталним технологијама.

Закључак Софистициране технологије четврте индустријске револуције довеле су до брже и прецизније дијагнозе оралних обољења. Клиничке процедуре постају једноставније, прецизније и предвидљивије за лекара, а комфорније за пацијента. Дугорочно, ту су и економске уштеде и очување животне средине.

Кључне речи: дигитализација; четврта индустријска револуција; дигитална стоматологија; стоматологија 4.0