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Review Article

Dentistry 4.0: A Whole New Paradigm

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ABSTRACT

Industry 4.0 and, more recently, Healthcare 4.0, are completely changing the way of working in the service and production sector. Similar to Industry 4.0, Healthcare 4.0 is based on Internet of Things, Cloud and Fog Computing, and Big Data technologies, and has revolutionized the health care. However, this evolution has not had any profound impact on dental care. In this manuscript, we are focusing on the concept of Dentistry 4.0, which is based on Industry 4.0 technologies and will change the way traditional dental care is rendered. It will lead to an enormous saving in the dental sector, as it will move from reactionary to pre-emptive treatment and will transform the conventional hospital centric approach. This shift from curative to preventive approach will happen due to predictive diagnosis through virtual monitoring and use of latest technologies based on concepts of Industry 4.0. This manuscript envisions the use of sensors or nanoparticles embedded intraorally or in dental appliances, such as toothbrush, floss, mouth cleansers, orthodontic brackets, tooth varnishes, etc. which will share intelligent information (like brushing frequency, pattern, movement of teeth, change in pH etc.) with clinicians. Dentistry 4.0 will lead to the concept of "talking teeth" which through various signals (such as pH changes, biomarkers, etc.) and intelligent analysis will drastically improve oral health-related quality of life. In serious and co-morbid cases, these innovations will reduce the chances of complications.

Keywords

Dentistry 4.0, Internet of Things, IoT, cloud computing, big data analytics, smart devices, preventive dentistry, predictive dentistry, intelligent dentistry, Industry 4.0.

Abbreviations

Internet of Things (IoT), Big Data Analytics (BDA), Information and Communications Technology (ICT), Cyber-Physical Systems (CPS), Artificial Intelligence (AI), World Health Organization (WHO), International Telecommunication Union (ITU), Internet of Personal Health (IoPH), Internet of m-health Things (m-IoT), Computer-aided design ad computer-aided manufacturing (CAD-CAM).

SUMMARY

1. Introduction

The increase in population, scarcity of healthcare ecosystem coupled with the need for a better quality of life has led to tremendous focus and advancement in healthcare. The advances in core science and technology have been supported by tremendous growth in Information and Communications Technology (ICT) usage in healthcare. Healthcare has evolved from paper-based patient systems to predictive care, and different degrees of digitization characterizes Healthcare 1.0 to Healthcare 4.0. Healthcare 4.0 is somewhat a recent phenomenon and signifies predictive care through the use of real-time tracking and response solutions. Similar to Industry 4.0 (for manufacturing sector), Healthcare 4.0 is realized through the adoption of 3 technologies - the Internet of Things, Big Data Analytics, and Cloud Computing[1,2]. However, contrary to well documented and researched Industry revolutions (also Industry 4.0) there is very limited research which has happened in evolution of healthcare as well as Healthcare 4.0.

Industry, which refers to manufacturing of material goods that are highly mechanized and automatized, has been in forefront of innovation and is characterized by 4 industrial revolutions[3]. Industry 1.0 (first industrial revolution) improved efficiency through the usage of steam power and development of machine tools; Industry 2.0 bought electricity and mass production while Industry 3.0 is defined by accelerated automation using electronics and information technology. Industry 4.0 is based on the concept of Cyber-Physical Systems (CPS) and is driven by adoption of 3 technologies: Internet of Things (IoT), Cloud Computing and Big Data Analytics.

While evaluating the literature, one thing which was noticeable was that dentistry has very little literature with respect to usage of ICT. Dentistry, which refers to diagnosis and treatment of problems pertaining to teeth and surrounding tissues, is a very different field as compared to generic healthcare and should be treated separately.

Considering the need for special focus for advancement of ICT in dentistry, we would like to propose the concept of Dentistry 4.0 which would not only bring about intelligent dental care but also define the way to revolutionize the whole ecosystem. Though Dentistry has not gone through 4 revolutions like Industry, we have proposed the name Dentistry 4.0 as it will be an application of Industry 4.0. Dentistry 4.0 can be defined as "Artificial Intelligence (AI) based decision making for personalized and predictive dental care through real time data collection from networked smart devices supported by cloud."

Dentistry 4.0 will not only change the way of working and bring about better quality of health care but will also lead to business model innovation.

2. The need for advancement in dental care

Despite advancements in science and technology, the global burden of dental problems remains high. Some communities of the society like the rural and underprivileged socioeconomic group are far deprived from dental health facilities. When we talk in terms of prevalence, dental caries, which is the most common reason to visit a dental clinic, followed by periodontal diseases are the most prevalent dental diseases. The prevalence varies from different geographical distributions, not only globally but also within the country[4]. According to the World Health Organization (WHO) dental caries affects 60-90% of schoolchildren and the majority of adults, i.e. 2.40 billion adults and 621 million children are affected by dental caries[5-7]. But when we talk in terms of the burden of diseases in the more economically developed countries, which is more appropriately calculated by disability- adjusted life years, edentulism tops the chart whereas, the lowest burden is of untreated dental caries and severe periodontitis[8].

Oral and dental problems can lead to difficulty in mastication, speech, pain, swelling, loss of sensation, bleeding from gums, poor self-confidence, psychological implications, and affects the quality of life depending upon the severity of the problem. Poor oral health also has a major effect on systemic health and the mouth is considered a window to general health. Compromised oral health can lead to an increased risk of infective endocarditis, problems in the digestion of food, cardiovascular disease, stroke, bacterial pneumonia, complications in patients of rheumatic fever and organ transplant, and even preterm delivery[9]. Oral pain has devastating effects on children likesleep loss, poor growth,

behavioral problems, and poor learning.

In addition, oral problem adds directly or indirectly to the economic burden of the world. Indirectly, dental problems lead to absenteeism from work. Worldwide, oral diseases lead to a treatment cost of US$298 billion yearly and an indirect loss of US$144 billion yearly[10]. Hence, the focus needs to shift to timely preventive and personalized dental care.

3. Major tenets of Dentistry 4.0

The advancement in technology in the area of acquisition of real-time data from devices, ability to communicate the same with any other device or thing, bring intelligence to a large amount of captured data, and do all this without committing to a planned infrastructure, will be the cornerstone for the adoption of Dentistry 4.0. We not only foresee a high degree of adoption of all the above-mentioned things, but we also envisage a dramatic change in the business models being currently adopted by the practitioners of dentistry.

Similar to Industry 4.0 the major technology drivers of Dentistry 4.0 will be Internet of Things, Cloud or Fog Computing, and Big Data Analytics.

3.1 Internet of Things in Dentistry 4.0

International Telecommunication Union (ITU) defines IoT as "a global infrastructure for the Information Society, enabling advanced services by interconnecting (physical and virtual) things based on, existing and evolving, interoperable information and communication technologies", understanding it as a far-reaching vision with technological and societal implications[11]. In simplistic terms, IoT can be referred to as anytime, anyplace connectivity of anything.

Due to the emergence and spread of low-cost connectivity in under-developed and developing countries, IoT based dental services can be easily leveraged. This will lead to better dental health in remote corners of the world and a decrease in overall demand for dental care.

One of the first adoptions of IoT was in Industry (manufacturing) sector and was the industrial Internet of Things (IoT) or just the Industrial Internet. The devices or things in the manufacturing plants communicate with each other. Looking at the successful adoptions in the Industrial sector, several of the other areas where there is adoption are in vehicles, healthcare, agriculture, etc. and are termed as the Internet of Vehicles, Health Internet of Things, Internet of Personal Health (IoPH), Internet of m-health Things (m-IoT), Internet of Agriculture, and Agriculture Internet of Things[12-18].

Dentistry is one of the most neglected but one of the most attractive areas for the adoption of IoT. There is quite a lot of research happening towards smart tools (smart brushes, smart brackets) in dentistry. IoT will enable the gathering of data from smart toothbrushes, floss, mouth cleansers, brackets, etc. The information from these devices along with the pathological parameters obtained through the wearable devices can enable one to predict the oral health of the person and hence make a decision regarding the future treatment pattern.

3.2 Cloud computing in Dentistry 4.0

Cloud computing is the on-demand availability of computer system resources, especially data storage and computing power, without direct active management by the user. Considering the unpredictable amount of data generated in IoT devices/sensors, it is very difficult to predict the amount of data and compute required. Cloud simplifies operations as there is no need to forecast the resources required. They can be defined on the fly as well as scaled as per the need.

As the intelligence in the embedded devices is increasing, there is a tendency for a lot of applications to be moved to the cloud. Cloud is not a solution to all problems. Cloud has a lot of shortcomings concerning latency, bandwidth, and availability of connection between cloud datacenter and devices at all times. This has been solved by moving some of the processing to edge devices or fog nodes. Fog computing proposes to transfer some cloud computing services to the edge network, close to user devices and possibly partially relying also on users' device resources, thus distributing the load between end devices and traditional cloud datacenters and bringing, among others, local-term security, low-latency rates, and faster responsiveness, while helping to improve performance scalability to the whole system[19].

3.3 Big data analytics in Dentistry 4.0

Traditionally, analytics is defined as an approach to get a retrospective view of the output based on deductive reasoning. BDA on the other hand uses

inductive reasoning for the prospective analysis of data. BDA has been defined as "advanced analytic techniques operating on big data sets to help discover what has changed and how we should react" [20].

BDA is typically characterized by 5V's: volume, variety, velocity, veracity, and value. They are defined as follows:

- Volume: magnitude of data due to the huge number of data sources.
- Variety: assortment of data due to heterogeneous data sources like sensors (in toothbrushes, etc.), social media (like Twitter), mobile devices, etc. which will generate structured, unstructured and semi-structured data.
- Velocity: speed of generation of data. Can vary based on the requirement and range from real-time to batch processing.
- Veracity: authenticity, and quality of data. Disparate data sources like social media etc. will impact the efficacy of data.
- Value: worth of data that will support decision-making.

BDA techniques find a lot of usage in Industry 4.0 and will have a far-lasting impact in Dentistry 4.0. As various devices of dentistry become smarter, they will generate real-time data to enable the clinicians to get a lot of data from the patients related to their oral health practices. This coupled with lifestyle information of the patients will enable clinicians to make predictive analysis and preventive treatment. Also, a lot of medical discussions are now part of social media. This could range from opinions about the doctors to discussion on new ways of treatment. Social Media analytics will impact the way research will progress.

4. Applications of Dentistry 4.0

Dentistry 4.0 will transform dental care by remote monitoring of patients, administration of drug delivery, activation of an appliance, etc. thereby drastically reducing the number of visits to the clinic (Figure 1). It will majorly improve the quality of life of differentially abled patients, syndromic patients requiring prolonged treatment, senior citizens, and children with special needs. It will also lead to a manifold increase in the reach of dental services to far-flung villages and unhospitable terrains for soldiers, etc. We have covered some of the applications of Dentistry 4.0 in this section.

4.1 Monitoring oral health and post-op conditions

The progress towards wearable monitoring and sensing devices will usher in the concept of "talking teeth." These devices would be placed in the mouth and will generate and communicate signals to the clinician based on a change in pH, mineral content of the tooth, or level of biomarkers. Along with knowledge of family history, these devices will continuously monitor diet content and coupled with the signals regarding a change in pH value and increased bacterial colonization will pre-warn the patients about the possible advent of caries. High-risk caries patients or those who have recently undergone surgery or patients with devices like prosthetic implants, micro-implants, dentures, or retainers are highly prone to bacterial colonization and early warning signals would lead to prompt corrective action.

It has been noticed that in long-drawn treatments like orthodontics, there are major compliance problems that do not lead to expected results. These smart devices can monitor the compliance of the patient in terms of the duration of wear of an appliance like a functional or orthopedic appliance or wear of intraoral elastics. They could also be used to monitor the markers of inflammation or tooth movement post-surgery or during orthodontic treatment. In regard to post-surgery, this type of monitoring will be extremely useful for checking on bleeding, increase in blood sugar, temperature, or oxygen saturation. This post-surgery monitoring will be all the more useful in co-morbid patients and timely intervention can lead to the saving of many lives or complications.

These devices could also be used to monitor syndromic patients, patients with obstructive sleep apnea, and oral cancer patients and thereby reduce the number of check-up visits. These smart devices could be in the form of nano-patches or microneedles or in-body devices and would require a strong network connection[21].

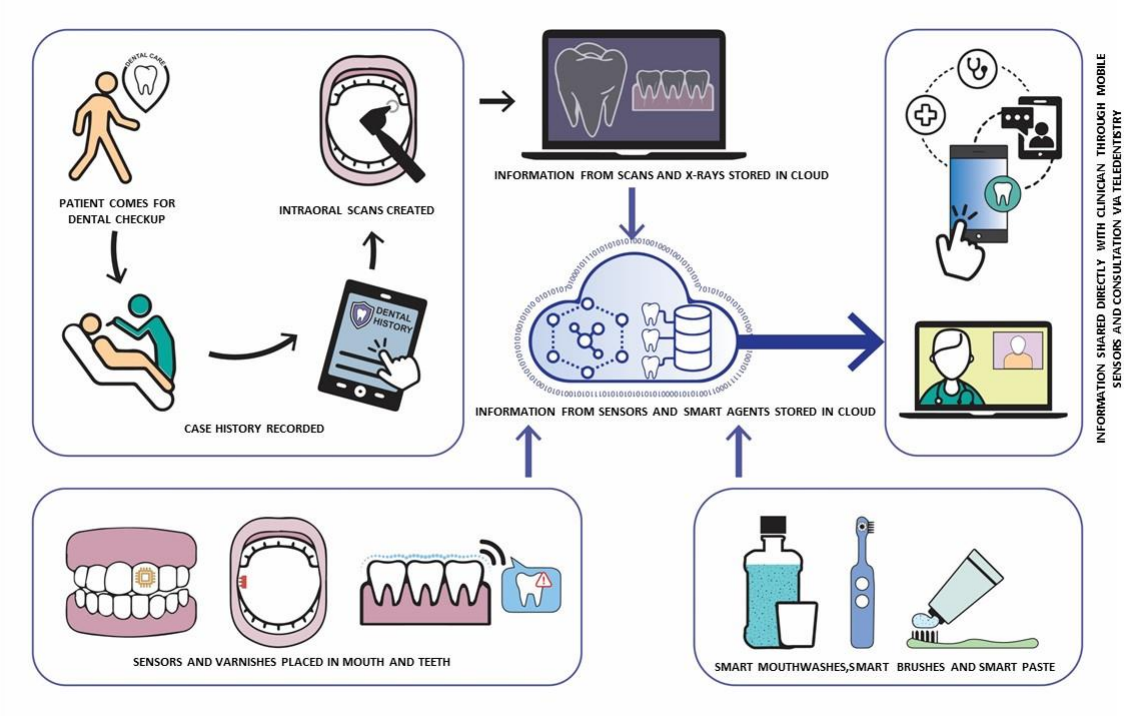

Figure 1: Model of Dentistry 4.0

4.2 Preventive dentistry

Prevention is better than cure and prophylactic measures taken timely would reduce the sufferings and economic burden of oral diseases. It is well known now that an increase in sugar intake and poor oral hygiene makes a patient prone to caries. It is also well documented that prophylactic agents like fluorides when delivered or applied locally can help in the prevention and cessation of dental caries. Through these wearable devices which will be monitored timely, the development of new carious lesions or white spot lesions can be monitored as cavitation leads to change in mineral density and pH. Timely signaling to the patient will help in preventing the development of white spot lesions into a full carious lesion or extraction in the worst circumstances.

Plaque accumulation leads to periodontal diseases and nanosensors that could detect plaque accumulation or poor oral hygiene can be incorporated in intraoral sensors. They could also release anti-plaque agents as a prophylactic agent in high-risk patients like diabetic or immune-compromised patients. Certain malocclusions like protruding incisors can lead to an increased risk of trauma to teeth. These prophylactic gadgets could calculate the overjets, quantify certain malocclusions and refer them for timely orthodontic intervention. Certain oral habits like increased smoking, alcohol consumption can make one prone to oral pre-cancerous and cancerous lesions. These devices can monitor and alarm the patients in such case scenarios.

4.3 Monitoring medication compliance

In certain oral lesions and post-surgery, timely delivery of medication is important which is highly dependent on patient compliance. Through these devices, medications can be delivered to targeted tissues. The effectiveness of treatment is highly dependent on patient compliance in such cases. Since they will be network operated devices, they can be coordinated at various centers and will follow strict prerecorded protocols thus reducing the bias in the study. The other way could be delivering medications with nanoparticles. These nanoparticles can be traced and the time and dose of medications can be calculated and recorded.

4.4 Personalized health care

With Dentistry 4.0 we will be able to customize the treatment and provide personalized treatment. The amount and time for drug release can be

customized for example a diabetic or hypertensive patient would need monitoring post-surgery or post extractions. These gadgets would have the history pre-recorded and would release the medicine if the sugar levels increased or would release coagulants at the site of surgery if bleeding starts in a hypertensive patient. They would also be able to sense the bone density and periodontal conditions which could already be saved in the personalized history in the sensors and could control the force applications and subsequent activation based on them. Patients in the high caries risk group could be monitored for sugar intake and fluoride applications. Patients with cleft lip and palate could be guided at every stage for their next consultation based on their genetic information.

4.5 Data sharing through cloud

Cloud-based systems can be developed for mass collaborations within and amongst institutes. This would simplify the history recording which is sometimes repeated for interdisciplinary care cases and would be highly timesaving for the patient as well the clinician. These systems would collect, process, and share clinical records which would add to the huge repository of big data. They could also be used in hospital administration and development. The systems developed should be designed so that they fulfill the security, privacy, and ethical norms.

4.6 Tele dentistry

With pandemics knocking at the doors every ten years, we need to develop systems that don't come to stand still in such times. The concept of teledentistry which involved telephonic booking of the appointments, triaging, consultation, prescribing medicines and emergency consultation has already picked up after COVID-19[22]. With many infectious diseases spreading through the respiratory and oral systems, dentistry would be affected if such robust systems are not developed. With the advent of intraoral scanners and treatment options that are CAD-CAM governed, the dentist's work may get complimented by e-supervision. This would lead to fewer visits to the clinics, less commuting time, less absentia from school and offices, and would save money, time and energy.

5. Business model innovation

In the current scenario, a patient has a tooth problem and he/she goes to the dentist to get it resolved.

Typically, the clinicians and dental care facilities charge the patients for the current problem at hand. The concept of the preventive check-up is not prevalent in dentistry. Hence, the treatment takes place after the disease has spread rather than at the starting stage of the disease, causing an extended time and discomfort for the patient.

In a factory setting, the yardstick of the machine is defined by the cost required for the treatment of the machine as well as the downtime of the machine. The more the machine is under maintenance, the more is the overall impact on the business. We liken the human body to a machine in the factory. We measure the time taken to treat the disease (dental problem) as well as the duration of the time the person is incapacitated due to the pain caused by the dental problem.

Drawing parallel to Industry 4.0, we foresee that the advent of Dentistry 4.0 will revolutionize the business models for the treatment of dentistry. This innovative business model will be based on the current condition of the teeth as well as the pain-free experience given to the person. One such instance of the business model would be that a dentist will decide a yearly charge based on the condition of the teeth. This charge will be based on the cost perceived by the dentist based on the probable treatments required by the patient in the next year. Depending on the dentist and maturity of the model, the business model can consider having a penalty charge whenever the patient experiences pain. The business models can be decided based on the maturity of the digitization of the dental clinic.

6. Conclusion

This work is intended as a reference aimed at helping researchers, clinicians (or dental hospitals) and industries in visualizing the next generation of dentistry, so as to adapt, further develop and implement smart dental appliances and focus largely on preventive treatment and improving efficiency in curative treatment. It briefly covers the technology foundations required to realize this concept, as well

as details the different application scenarios of Dentistry 4.0. We touch base upon the emergence of a new business model due to the realization of such a concept. The research in the current avatar has been limited to the definition and need of Dentistry 4.0. Further work needs to be performed to detail the various use cases.

Conflict of interest

The authors declare no conflicts of interest.

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