J. Electrochem. Sci. Eng. **13(1)** (2023) 83-97; http://dx.doi.org/10.5599/jese.1498

Open Access : : ISSN 1847-9286
www.jESE-online.orghttp://www.jese-online.org/

Review paper

Artificial intelligence in use of ZrO_2 material in biomedical science

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Received: May 30, 2022; Accepted: October 13, 2022; Published: October 21, 2022

Abstract

The rapidly growing discipline of artificial intelligence (AI) seeks to develop software and computers that can do tasks that have historically required the intelligence of people. Machine learning (ML) is a subfield of AI that makes use of algorithms to "learn" from data's innate statistical patterns and structures to extrapolate information that is otherwise hidden. A growing emphasis on cosmetic dentistry has coincided with rise of ZrO_2 *to prominence as a result of its improved biocompatibility, visually pleasant look, strong oxidation resistance, better mechanical properties, and lack of documented allergic responses. Advances in the field of AI and ML have led to novel applications of* ZrO_2 *in dental devices for biological objectives. Artificial intelligence (AI) technologies have attracted a lot of attention in* ZrO_2*-related research and therapeutic applications due to their ability to analyze data and discover connections between seemingly unrelated events. Specifically, their incorporation into zirconia is largely responsible for this. Versatility of zirconia in the scientific community means that how AI is used in the area varies with the specific directions in which zirconia is utilized. Therefore, this article primarily focuses on the use of AI in the biomedical use of* ZrO_2 *in dentistry.*

Keywords

Biomedical engineering; artificial intelligence; machine learning; zirconia

Introduction

The field of dentistry makes extensive use of digital technology, which plays an important part in a variety of processes and activities, including clinical treatment, laboratory operations, student teaching, administration, and dentistry research [1]. Clinical therapy including the use of digitally performing CAD/CAM, shade analysis, smile design, impressions, and virtual communication are all examples of how digitization has played a part in clinical treatment [1,2]. The term "artificial intelligence" (AI) was invented in the 1950s to describe a technology that is currently undergoing fast development based on computer technology [3]. Artificial intelligence (AI) *i.e.* a subfield of computer science enables computers or intelligent software to carry out activities that would normally need human intellect. The development of artificial intelligence has allowed for the creation of contemporary robots that are capable of learning from their past mistakes, adapting to new needs, and performing duties that are analogous to those performed by people [4].

The use of AI technology may be seen in many facets of human civilization, such as dentistry and medicine, and it is becoming increasingly widespread in both of these fields (Figure 1). Implants should be corrosion-resistant. Most of the materials degrade due to corrosion and wear processes [5-18]. Zirconia is a type of high-tech ceramic that has been utilized in many biomedical applications ever since the 1960s [19]. Zirconia has received a lot of interest in the field of dentistry since it has great biocompatibility, is visually beautiful, has high corrosion resistance, has strong mechanical qualities, and there have been no recorded adverse responses to it [20-22]. In ZrO_2-based research and biomedical applications over the past few decades, AI techniques have garnered a great response because they are associated with data analysis and provide regression/correlation between complicated phenomena. This is large since these techniques can be applied in clinical applications. Therefore, to study the uses of ZrO_2, dentists require a complete grasp of AI in ZrO_2-based research. In this study, we provide a summary of current advancements and issues about AI approaches used in ZrO_2-based dental applications.

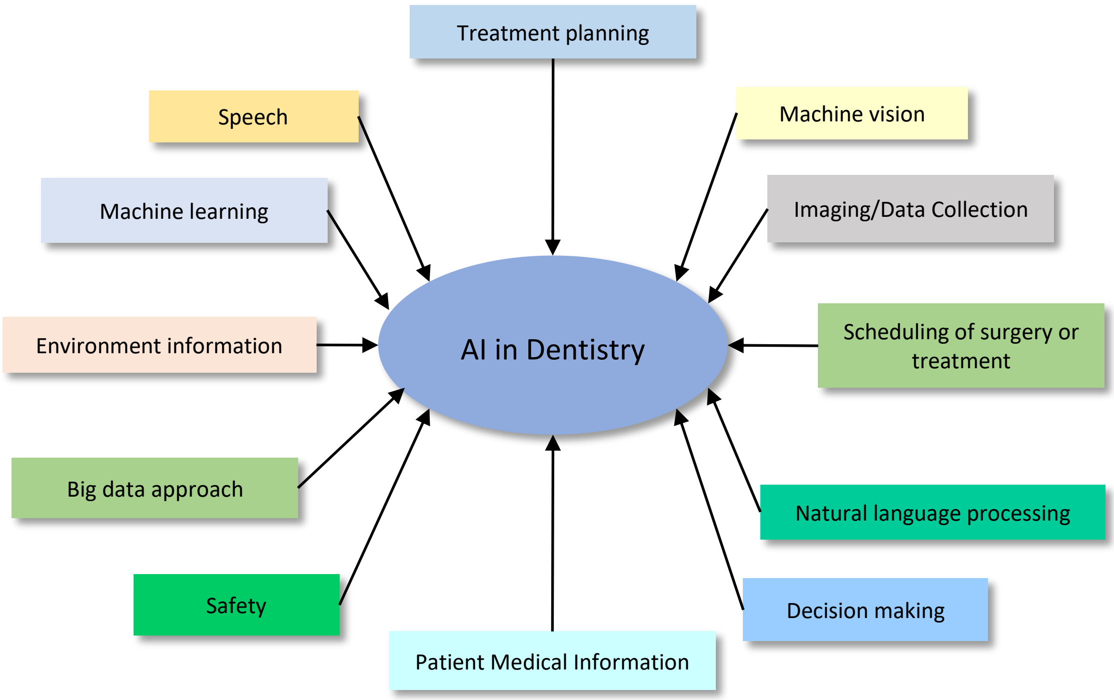

Figure 1. *AI applications in the field of dentistry science*

Use of AI in dentistry applications and industry

Machine learning (ML) is now expanding at a very quick rate. ML may teach itself and progress on its own by analyzing various data sets, followed by compiling previous knowledge and techniques [23,24]. The advent of AI-ML has not only opened up new potential but also presented new obstacles in the field of dentistry, medicine, and other medical specialties. A precise diagnosis serves as the foundation for an effective treatment plan in several subspecialties of dentistry, including maxillofacial surgery, orthodontics, and prosthodontics, amongst others [25]. Because it can identify links between operational records as well as patterns in large data, machine learning makes it easier to diagnose and anticipate illnesses as well as assess the efficacy of different treatments [26-28].

The dentistry industry is seeing significant advancements in AI application technology as a result of the rise of data computation as well as the acquisition and analysis of a large number of clinical patient data sets [2,19]. The investigators offered a comprehensive review of the most current data available. The investigators provided a complete and up-to-date summary of the most recent facts about the diagnostic and diagnostic imaging of AI dentistry. It is vital for dentists and dental surgeons to comprehend artificial intelligence (AI), learn it, and become an expert in it to stay updated with the latest technology of medicine and implement it clinically. For example, Hung *et al.* conducted an in-depth review of the research that has been done on the clinical applications of AI in the fields of dentistry and maxillofacial radiology [29]. An artificial neural network (ANN) was built by Kositbowornchai *et al.* [29] to fix a vertical fracture in a tooth. To assist orthodontists in determining the treatment plan, Jung *et al.* developed neural network ML models through the use of a back-propagation algorithm. These models were used to diagnose extractions [29]. Li *et al.* [30] used a neural network prediction technique to obtain the medical records of a new patient and characterized the 24 different inputs which included demographic data, cephalometric data, dental data, and soft tissue data which were retrieved, as illustrated in Figure 2. Because the extraction probability (0.955) was greater than 0.692, they concluded that this was an extraction instance, and the information was then sent to the other two networks. The results that are produced by the other networks include the probabilities of a variety of extraction patterns and anchoring patterns. The physician investigated each of these potential courses of therapy, considered a number of other factors, and in the end came up with an efficient treatment strategy.

At this moment in time, AI is implemented in many dentistry applications like oral disease diagnosis and oral monitoring. However, in dental clinics and hospitals, AI-implemented applications like appointments and medical advice are more advanced technologies. In the future, AI-based dentistry applications possible can be oral surgery, cosmetic dentistry, radiography analysis, oral healthcare, *etc.* [31]. For example, Li *et al.* employed AI algorithms on pixel semantic segmentation of patient images to identify gum inflammation [32]. This was accomplished with the assistance of a deep neural network. The findings point to the possibility that this method, which utilizes mobile applications, might be appropriate for dental self-examination.

In addition, AI and ML play an increasingly significant role in the classroom, in scientific research, in the management of oral health, and the treatment of oral diseases. There is no question that ML can be of assistance to the dentist and offer a great deal of ease. It is not safe to believe that ML can perform at the same level as humans. However, the goal of using AI-ML in dental science is not to obsolete dentists, but rather to help them make more accurate clinical diagnoses and treatment recommendations. This is the case even though the goal of the implementation of AI-ML in dentistry is to replace dentists. A brand new era of AI is going to dawn as a direct result of the rapid advancement of technology. The progression of artificial intelligence and machine learning has resulted in the development of unique ways the use ZrO_2 in dental devices for biomedical purposes. The implementation of AI in the field of ZrO_2 science shifts depending on the direction in which ZrO_2 is applied. In the current day, AI-ML technologies have transitioned from being a concept of the future to practical use in everyday life. Researchers from a wide variety of professions had in-depth conversations about the effect that it had on society, the economy, the healthcare system, and politics. Additionally falls under this category in the field of dentistry. It is widely held that AI will play a crucial role in advancing dentistry and contributing to its future growth.

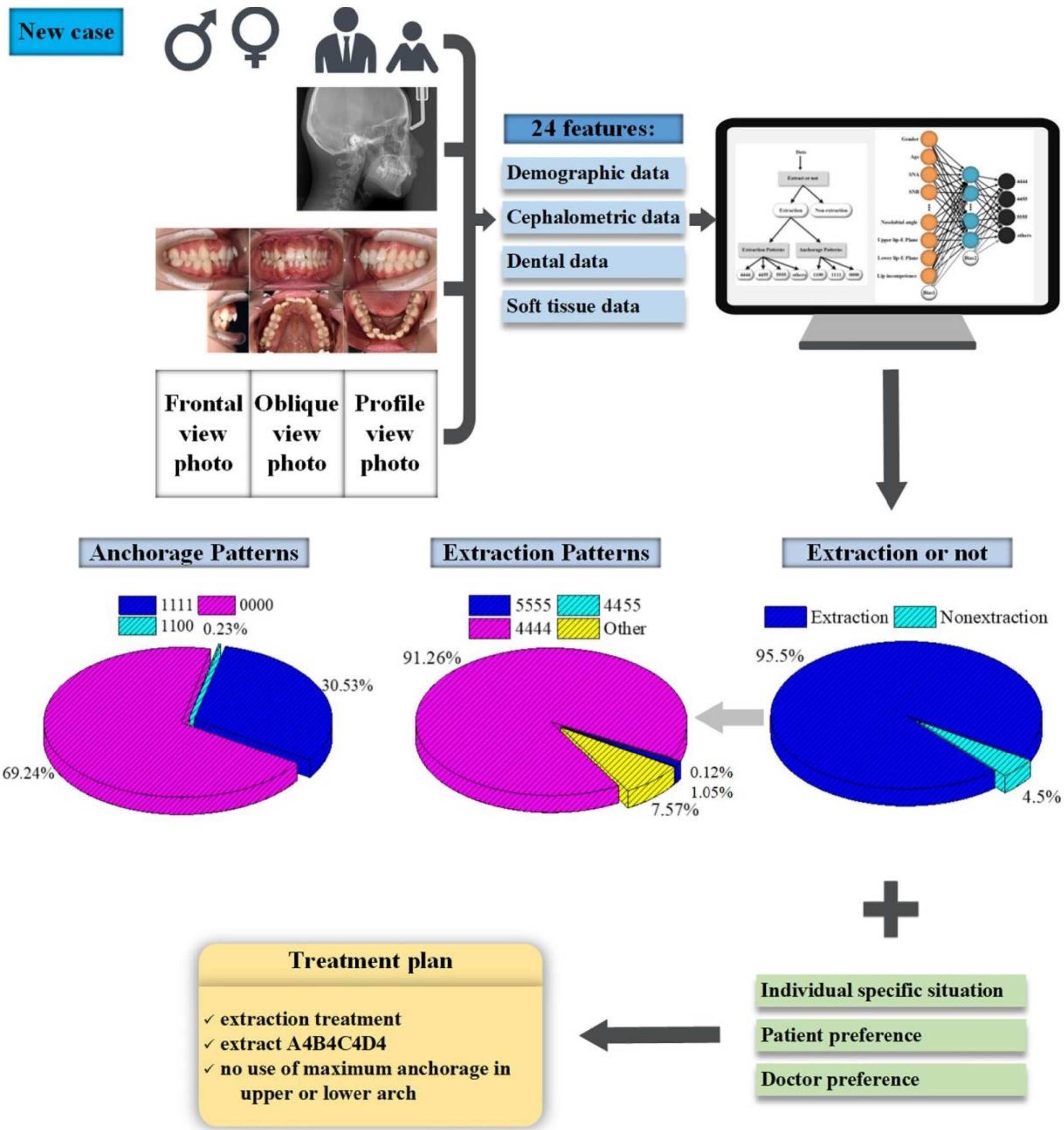

Figure 2. *An example of the clinical applications of the ANN [30]*
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Preparation of artificial tooth AI technology

A complex process is followed during the preparation of ZrO_2 restorations. The job that a dentist does daily includes preparing teeth for crowns and bridges. Even though the dentist has years of expertise, the job is nevertheless difficult. The most difficult part of the process is figuring out how to preserve as much of the natural tooth as possible while yet leaving enough room for restoration. Tooth preparation normally utilizes mechatronics engineering. The use of a robotic arm as a tool to aid dentists in the process of tooth preparation is an intriguing and astute suggestion. A dental drill was the first invention by Simon *et al.* [33] which was the first electromechanical system. During the process of tooth preparation, the robotic arm may assist the dentist in operating the instrument more accurately and smoothly. The mechatronic technology lessens the likelihood of iatrogenic oral injuries and may decrease the number of handshakes that are necessary due to weariness. Using this mechatronic system resulted in a 53 % increase in positional accuracy. The mechatronic system improved the accuracy by giving support and stability while the dentist was working with dental drills. The general agreement and goal of the global medical community are to go in the direction of precision medicine. As a result, the great precision, dexterity, and speed of the robot may eventually surpass the limitations of manual operation, therefore improving the effectiveness and precision of clinical operation [34]. Yuan *et al.* [35] developed a robotic tooth preparation system to increase the quality, accuracy, and clinical effectiveness of the procedure. This was done to avoid the drawbacks of the constraints that conventional manual procedures provide. LaserBot is a micro-robotic system that was developed by Wang *et al.* [36] which was effective in tooth finishing by utilizing the laser beam. Li *et al.* [37] developed a robotic manipulator system with a smaller and softer bracer for dentistry applications. This system was fitted with a tendon sheath transmission mechanism. This particular robot's electric-motor actuators don't have to be in close proximity to the manipulator. This system provides tool interchangeability and can be completely modified to meet the requirements of any dental operation. As a result, it has the potential to be used in a variety of contexts, such as the treatment of crowns and the elimination of caries. Many other systems were developed to improve the precision of dentistry treatments as compared to conventional treatment [38,39].

AI in digital impression

AI is also helpful in obtaining colorimetry and 3D impressions of the teeth and tissues [40]. This further helps in designing the restorations through readable 3D data. The dental prosthesis was produced using a process known as computer-aided manufacturing. At the moment, more recent research makes use of tooth preparation robots with a respectable level of intelligence and precision. These robots have become the direction that the development of digital dental prostheses is heading. In the realm of dentistry, high-precision restorations may be crafted with the use of CAD/CAM-based technology (Figure 3). In addition, inlays, crowns, bridges, and inlays are designed and manufactured with the help of AI-based technologies [41].

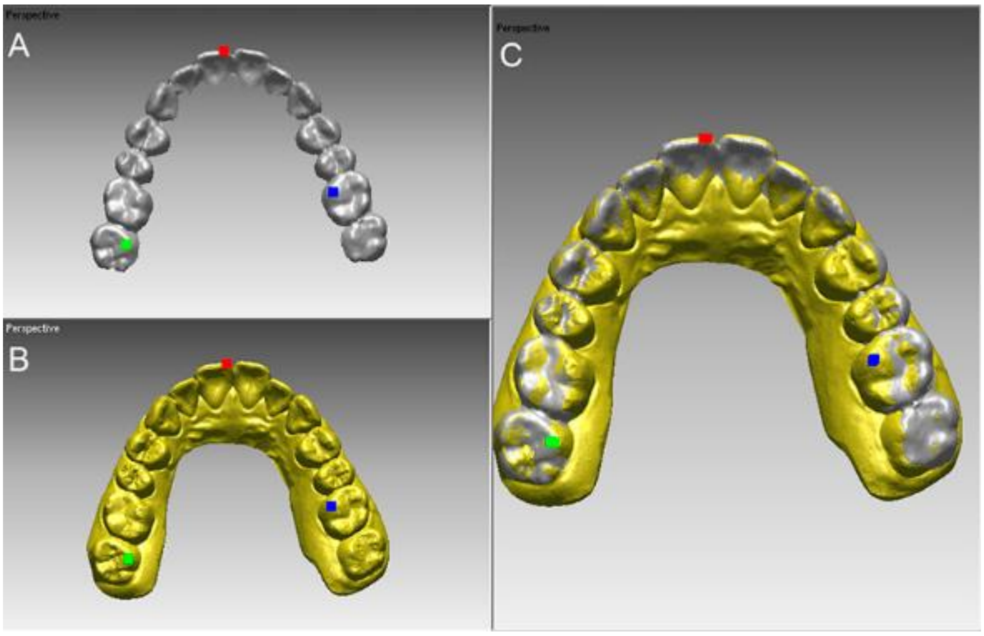

Figure 3. *Digital impression of teeth using iTero scan* [42]

These systems take the place of the conventional approach to the creation of restorations, which has the potential to minimize the amount of time spent on production and the number of mistakes that may occur. Dentists have greater standards than ever before for the ease with which their practices may be carried out. Patients are becoming more particular about the aesthetics of their dental care, and they are hoping that their visits to the dental clinic would take less time. The CAD/CAM technology that is used in contemporary dentistry has become an essential component in the production of zirconia restorations. Additionally, the digital intraoral impressions technology that is used in dentistry is regarded as an effective impression procedure [43,44]. A study was conducted by Gao *et al.* [45] to examine the precision of digital scanning. They identified that digital impression scanning was far better than conventional intraoral and cast scanning. Oh *et al.* [46] also suggested that scanning an impression is the most effective method for developing a digital dental model.

AI in digital media

Digital technologies particularly digital Information and communication, are finding more and more use in the dentistry industry [41]. Computers play a vital role in dental practices [47,48]. A large-scale online survey was carried out by Parmar *et al.* [49] to investigate the perspectives of patients and dentists regarding the utilization of social media platforms (specifically Facebook) and their activities conducted online in the present day. They researched to investigate the prospects and possible hurdles associated with the adoption of social media techniques by dentists. They investigated the beliefs, ideas, and activities associated with using social media from the points of view of both patients and dentists. According to the findings, the level of contact and involvement of patients may be raised with a greater level of social media activity on the part of the dentist. They can contact their dentists more conveniently and efficiently via the use of social media platforms for their dental treatment. In the same vein, dentists may use digital media to connect with patients as well as CAD/CAM tools to fabricate restorations [49]. This made the clinical job of the dentist easier and more efficient. In the future, AI-ML will digitalize the numerous phases throughout the process of aesthetic treatment by assessing through digital smile design [50].

AI in dentistry labs

Additionally, AI-adapting dentistry labs can learn from the experiences of millions of patients in order to create more effective designs for prostheses inside design software used for restoration [51]. An AI system may be provided with a data set for picture training. Within this system, one network can concentrate on creating a newer image. However, at the same time, another network attempts to determine which photos are false and which are genuine. With the use of this technology, restorations may be crafted to look exactly like the patient's native anatomy. Library-based systems tend to create more intricate anatomical structures comparable to surrounding dentitions that wear down with usage. This is especially true for elderly individuals. The design that was produced by the GAN program successfully matches the patterns and detail that occur as a result of wearing dentures.

Use of AI in ZrO_2 biomedical applications in dentistry

ZrO_2 in dentistry

Researchers and dentists are currently focusing on producing an aesthetically pleasing restorative material that does not include any metals because of rising concerns about cytotoxicity and allergic reactions associated with certain metals [52,53]. In restorative dentistry, ZrO_2 may be used in a variety of applications, including implants, abutments, posts, cores, crowns (both complete and partial), bridges, inlays and onlays, and veneers [54,55]. Zirconia has been shown in previous clinical investigations to have an abrasive impact on dentition, which results in excessive wearing in the structure of the tooth [56-58]. In 2018, Pjetursson *et al.* [59] conducted a comprehensive study to explore the survival rates of ZrO_2 and metallic-ceramic crowns as well as the rates of technical, biological, and cosmetic complications associated with these crowns. Single crown implants made of zirconia showed a 97.6 % survival rate after 5 years (95 % confidence interval: 94.3-99.0), and it exhibited a similar frequency of biological difficulties while having fewer cosmetic issues.

In addition, by studying the evolution of modern dental ZrO_2 ceramics, Zhang *et al.* aimed to make zirconia materials more transparent without compromising their strength [60]. ZrO_2 might also be employed as an option for titanium implants even though it is a non-metallic biomaterial. Additionally, ZrO_2 exhibits high fracture toughness and flexural strength as compared to many other ceramics materials [61,62]. According to the findings of Hashim and colleagues, the survival rates of 1- and 2-piece ZrO_2 implants after one year of function were found as 0.92 (0.95 confidence interval: 87-95) [63].

It has been found that monolithic zirconia with no veneer possesses greater fracture resistance than traditional ZrO_2, and it is anticipated that this will lead to a decrease in the frequency of porcelain fracture in the region of the posterior teeth [64]. Shen *et al.* performed a retrospective clinical analysis on the monolithic ZrO_2 single crowns and tried to learn more about the performance of monolithic ZrO_2 prostheses that are held in place by implants [65]. They took panoramic radiographs at various times throughout the therapy and the follow-up visit to research the marginal bone level (MBL). During the healing phase, patients whose implants were covered by monolithic ZrO_2 saw MBL changes of 0.25 mm, whereas those whose implants were covered by conventional ceramics saw MBL changes of 0.43 mm. There are no statistically significant differences between the monolithic zirconia and metal-ceramic groups ($P > 0.5$), suggesting that both groups have similar rates of peri-implant bone resorption.

ZrO_2 crown

Implant material namely monolithic ZrO_2 crowns (MZCs) mounted on the back of patients' mouths was included in a recent retrospective study by Lerner *et al.* [66]. They checked the MZCs' chromatic integration, survival, and success rates. Their research created the customized ZrO_2 abutment in CAD software, after which they obtained the initial visual imprint of the patient's mouth with the help of the CS 3600XR intraoral scanner. Notably, the scientist employed a fully digital procedure to create the zirconia crown, automating the process of creating margin lines with AI. Notably, the scientist employed a fully digital procedure to create the zirconia crown, automating the process of creating margin lines with AI. As a result, they were able to effectively produce MZCs that were subsequently cemented on bespoke hybrid abutments. According to the findings of the study, the success rate and survival rate of MZCs produced by an all-digital process were, respectively, 99.0 and 91.3 % after three years.

*Prediction of the longevity of ZrO_2 **r**estorations*

Dental restorations have a limited lifespan, and this lifespan is heavily influenced by the material that was used to create them [67]. Zhang *et al.* [60] presented an overview of the several generations of commercial dental zirconia and a synopsis of each generation's mechanical and compositional characteristics. The first-generation 3Y-TZPs had to bend strengths more than 1 GPa in flexure. The sintered Al_2O_3 content of these first-generation 3Y-TZPs was 0.25 weight percent. The next step is monolithic ZrO_2, which was created to take into complete consideration the aesthetics and mechanical properties of zirconia. Developing a partially stabilized ZrO_2 with higher Yttria contents, such as 4Y-PSZ (4 mol.%) or 5Y-PSZ (5 mol.%), which produces a more non-birefringent c-phase, achieves this goal. This decreases the opacity of the material. The development of transparent ZrO_2 resulted in several benefits, including improved mechanical qualities, increased decreased wear, less tooth preparation, and increased strength on antagonistic surfaces [68,69]. Because of this, there are a wide variety of zirconia materials on the market, each with its distinct brand name and set of technical parameters, from which patients and dentists may pick. However, therapies for patients might change depending on the characteristics of the restorative material that is used. They have a hard time deciding which material will serve them the best and endure the longest.

Fortunately, AI is playing an important part in resolving this issue. For instance, Aliaga *et al.* [67] gathered data from Dr. Vera's restorative therapy notes, graphs, and radiological data. They next used artificial intelligence (AI) to analyze the data gathered to find the best material and subsequently advance the creation of teeth restoration. In addition, AI might be utilized to estimate how long CAD/CAM crowns will last in the patient's mouth. Case-based reasoning (CBR), a method developed by Aliaga *et al.* [67], can model and predict how long dental restorations will survive. In a separate investigation that was carried out by Yamaguchi *et al.* [68], an AI-based convolution neural network (CNN) was utilized to develop the CAD/CAM crowns. Data was procured from 24 instances in total, of which half had debonding problems with their crowns. Additionally, they acquired 8,640 2D images of the 3D models created from virtual teeth. According to the findings, artificial intelligence technology, namely the CNN approach, demonstrates improved performance in forecasting the likelihood of debonding in CAD/CAM crowns.

Matching of ZrO_2 colors

Patients place more importance on the cosmetic qualities of their restorations, in addition to the zirconia material's reputation for durability and capacity for functional recovery. Aesthetic dentistry places a significant emphasis on the processes of color matching and shade reproduction [69]. Recently, a variety of zirconia ceramics, each with its distinct optical characteristics, have been available for purchase in the marketplace. When trying to match the color of the restoration to the patient's natural teeth, it can be challenging for both the patient and the dentist to select the proper configuration, appropriate material, and precise shade. A back-propagation neural network, also known as a BPNN, has previously been put to use in the dental clinic for computer color matching [70]. However, BPNN has some drawbacks, including low accuracy and instability. To improve the accuracy of the matching, the initial weight and thresholds in the BPNN, Li *et al.* [70] used a genetic algorithm (GA). The findings of the experiment show that the suggested strategy plays a significant part in enhancing the consistency and accuracy of color matching when choosing repair materials. Additionally, AI was utilized to forecast the shade of the teeth that would result from the bleaching treatment. The clinical decision support system that was created by Thanathornwong *et al.* [71] used an AI-based regression model. Results demonstrated that this approach was capable of accurately predicting the color shift by making use of colorimetric variables.

ZrO_2 abutment

ZrO_2 abutments are advised alternatively to metal abutments since they produce superior outcomes in terms of aesthetics. After five years, fixed implant single crowns with zirconia abutments had a 99.3 % success rate in the posterior locations, which did not show a statistically significant difference when compared to titanium abutments, which had a success rate of 99.57 % ($P = 0.26$). The research was conducted by Vechiato-Filho *et al.* [72] and was based on a systematic evaluation and analysis. In most cases, the bespoke abutment begins with the use of computer-aided design (CAD), which is followed by milling and zirconia sintered production [73]. During the extraoral cementation procedure, there is tolerance between the ZrO_2 abutment and the boding foundation. This can lead to cementing mistakes [74]. Even though they are extremely minor, these inaccuracies can lead to positioning issues for monolithic ZrO_2 restorations when they are delivered to patients in the form of bespoke abutments and temporary restorations [75]. Fortunately, the aforementioned challenges may be conquered with the help of AI, which has decreased the number of mistakes and the prosthetic therapy cost [76,77].

Biomedical applications of ZrO_2

Additionally to its use in therapeutic applications, artificial intelligence has found widespread usage in zirconia-related research, being the subject of several studies [78]. Hydroxyapatite (HAP)/ZrO_2-based composites were also used in biomedical applications. HAP is a bioactive material used in metallic implants [12,13]. HAP coated by plasma spraying is used in many dental and orthopedic prostheses [13]. Arif *et al.* [79] developed an ANN model to wear the performance of Al (element) hybrid composites that were reinforced with nano ZrO_2 (0-9 %). The use of AI was successful in studying the impact of several control parameters on hybrid composite wear behavior. The advancement of robotics, automated systems, and AI-integrated devices will be greatly aided by the creation of artificial muscle shortly. Because of its substantial free surface area and fewer grain boundaries, zirconia shape-memory ceramics have the potential to dramatically improve shape-memory characteristics by an additional 8 %. Du *et al.* [80] created highly aligned shape-memory ZrO_2-based yarns and springs using AI as a consequence. These materials have the potential to be employed as artificial muscles at very high temperatures. In addition, ZrO_2 is an essential transition metal-oxide that plays a significant role in the development of high-performance computer systems. The authors The Behler-Parrinello Neural Network (BPNN) may be employed in the molecular dynamics simulation of the O_2 vacancy diffusion since its accuracy is similar to simulations [81] based on density functional theory (DFT) [82].

Conclusion and future perspective

In conclusion, ZrO_2 has received a great deal of attention in the field of dentistry since it is highly biocompatible, has appealing aesthetics, is very resistant to corrosion, and does not cause allergic responses. The use of technology that utilizes artificial intelligence is hastening the transition from one period to the next in the field of dentistry. The progression of artificial intelligence and machine learning has resulted in the development of unique ways the use zirconia in dental devices for biomedical purposes. As a result, having a solid comprehension of the principles behind AI technology and applications will be advantageous in the years to come. We have high hopes that all aspects of dentistry will soon be able to make full use of AI in their respective disciplines.

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