Neural Networks – Explanation and Application in Prosthetic Dental Medicine and Dental Implantology. Review

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Невронни мрежи – описание и приложение в протетичната дентална медицина и денталната имплантология. Литературен обзор.

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Abstract

Artificial intelligence or as it is known in the English-language literature "AI" is broad term and is used in several fields of science. Artificial intelligence explores the possibility of computers performing tasks that would normally require human intelligence. This literature review describes the applications of different neural networks in dental medicine specifying the fields of dental implantology and prosthetic dental medicine. Neural networks are specific type of artificial intelligence and are used now a days in prosthodontic and dental implantology for enhancing the diagnostic process, creating treatment plans, generating 3D images and executing treatment plans. Creating 3D images is crucial for both branches of dentistry so one of the most sophisticated neural networks for generating such kind of images is well presented, the generative adversarial networks (GANs). Few limitations of this technology are also discussed. The purpose of this literature review is to investigate the different types of artificial intelligence and the purposes for their use in the domain of prosthetic dental medicine and dental implantology. Moreover, to establish the type of artificial intelligence with the highest performance for designing a 3D constructions.

Keywords: *Artificial Intelligence, Neural Networks, Generative Adversarial Networks, Design*

Резюме

Този литературен обзор описва приложенията на различните невронни мрежи в денталната медицина, по-специално в областите на денталната имплантология и протетичната дентална медицина. Невронните мрежи са специфичен вид изкуствен интелект и в днешно време се използват в протетиката и денталната имплантология за подобряване на диагностичния процес, създаване на

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планове за лечение, генериране на 3D изображения и изпълнение на планове за лечение. Създаването на 3D изображения е от съществено значение и за двете области на денталната медицина, поради което една от най-усъвършенстваните невронни мрежи за генериране на такъв вид изображения – генеративните състезателни мрежи (GANs), е подробно представена в този преглед. Разгледани са и някои ограничения на тази технология.

Introduction

In recent years, artificial intelligence (AI) has emerged as a transformative technology in various fields, including healthcare. Within dentistry, AI applications are gaining momentum, promising to revolutionize diagnosis, treatment planning, patient management, and research. This literature review explores the current state of AI in dental medicine, focusing on its applications, challenges, and prospects specifically in the field of prosthetic dental medicine and dental implantology.

Definition of Artificial Intelligence

The term "artificial intelligence" (AI) or as it is known in the English-language literature "AI" is broad term and is used in several fields of science. AI explores the possibility of computers performing tasks that would normally require human intelligence. There are many definitions characterizing AI (Rivera et all). Here are some examples: "Artificial intelligence is a computer system that exhibits behavior that is generally thought to require intelligence," (1). "Artificial intelligence is the science of making machines do things that would require intelligence if done by a human." (2), "Artificial intelligence is the science and engineering of creating intelligent machines, particularly intelligent computer programs."(3).

From these definitions, the term "intelligence" can be summarized as referring to the ability to plan, reason, learn, sense and perceive knowledge, and to communicate in natural language (4). There are different approaches that can be used to program AI. Different types of AI perform different activities, and separate classifications exist for them.

Classification

Currently, 3 types of generations of artificial intelligence are known in terms of capabilities. The first generation is the so-called weak/narrow artificial intelligence, the second is artificial intelligence, and the third, most revolutionary, is artificial superintelligence (5).

According to the functionalities, artificial intelligence is divided into: AI type Reactive Machines, AI type Limited Memory, AI type Theory of Mind, AI type Self-Awareness (6).

Weak/narrow AI is so called because it is designed to solve limited, single tasks. Most of the artificial intelligence systems currently in operation are of the "weak/narrow" type with a clearly defined function. It is a technology that allows high-functioning systems to replicate, and even surpass, human abilities in terms of assigned tasks (7). Existing AIs today are mostly limited (narrow) (8).

Strong AI describes systems with understanding knowledge and cognitive abilities that make it indistinguishable from natural intelligence, although the speed and ability to process data is much faster and of unparalleled volume and capacity. Such artificial intelligence will be able to make systematic generalizations, reason and learn from its experiences. He will have an experiential understanding of his surroundings, just like humans, but with much faster reaction capabilities. In this way, a specific type of new (non-biological) entities could emerge (7). Research on strong AI should be very cautious, as it may raise ethical issues and may be dangerous. So far, there is no evidence of a strong artificial intelligence being invented.

A superintelligence is a type of intelligence that will surpass human intelligence in all parameters,

from creativity to wisdom and problem solving. It is widely believed that the emergence of superintelligence will follow immediately after general, general artificial intelligence (7).

A. AI Type Jet Engine

Such AI systems are memoryless and designed to perform a very specific task. Since they cannot remember previous results or decisions, they only work with currently available data. Reactive AI is derived from statistical mathematics and can analyze vast amounts of data to produce a seemingly intelligent result.

An example of a Reactive Machine AI is "IBM Deep Blue": IBM's chess-playing supercomputer. Watching AI beat chess grandmaster Garry Kasparov in the late 1990s by analyzing the pieces on the board and predicting the likely outcomes of each move

B. AI Type Limited Memory

This form of AI can extract information from past events and outcomes and observe specific objects or situations over time. An AI with limited memory can use data from the past and the present to decide on a course of action that is most likely to help achieve the desired outcome. However, while an AI with limited memory can use past data for a period, it cannot store that data in a library of past experiences for long-term use. As more data is trained over time, memory-limited AI can improve performance.

Example of Memory-Limited AI – Generative AI: Tools like ChatGPT, Bard, and DeepAI rely on memory-limited AI capabilities to predict the next word, phrase, or visual element in the content it generates.

Virtual assistants and chatbots: Siri, Alexa, Google Assistant, Cortana, and IBM Watson Assistant combine natural language processing (NLP) and memory-limited AI to understand questions and requests, take appropriate actions, and compose responses.

Self-Driving Cars: Autonomous vehicles use limited-memory AI to understand the world around them in real-time and make informed decisions about when to accelerate, brake, turn, etc.

C. Theory of Mind type AI

Is a functional class of AI that falls under the class of general AI. Although an unrealized form of AI with theory of mind functionality today, it would understand the thoughts and emotions of other subjects. This understanding can affect how AI interacts with the people around them. In theory, this would allow AI to simulate human relationships. Because it will be able to infer human motivations and reasoning, it will be able to personalize its interactions with individuals based on their unique emotional needs and intentions. Such type of AI is currently being developed.

D. AI Type Self-Awareness

It's a kind of functional AI for applications that would have super abilities. It doesn't exist yet, but if ever invented, it is supposed to have the ability to understand its own internal conditions and traits, along with human emotions and thoughts. It will also have its own set of emotions, needs and beliefs.

2.3 Types of Weak Artificial Intelligence

The subclasses of weak artificial intelligence are: machine learning, deep learning, and neural networks. Neural networks, in turn, are a subclass of machine learning, and deep learning is the most sophisticated subclass of neural networks (Fig. 1).

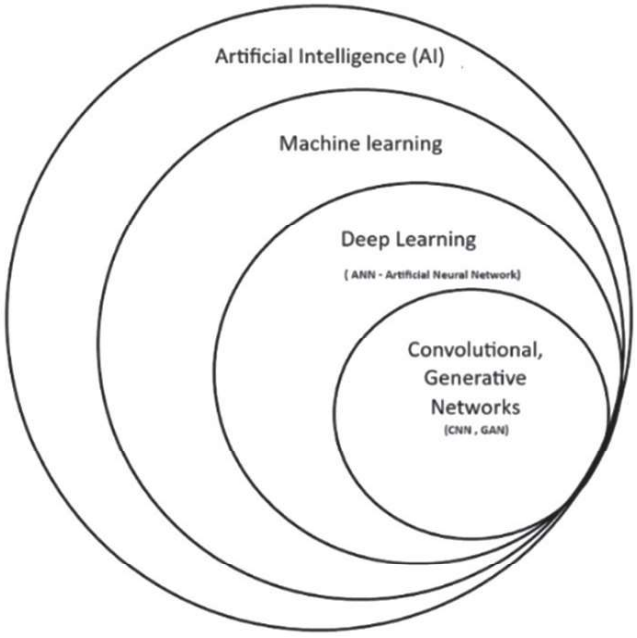

Figure 1. *(Artificial Neural Network (ANN) and Deep Neural Network (DNN)) (10)*

Machine learning can be further classified as supervised, semi-supervised and unsupervised learning. Deep learning is currently a very important research area and a subset of machine learning. It may consist of both supervised and unsupervised learning (9). A deep neural network is capable of extracting features from imported large datasets without requiring human intervention.

Neural networks are biologically inspired networks that can be seen as the basis of deep learning algorithms. There are different variations of neural networks, the most important of which are artificial neural networks (ANN), convolutional neural networks (CNN), and generative adversarial networks (GAN). An artificial "neural network" consists of a minimum of three node layers – input, multiple "hidden" and output layers, so that each layer consists of a different number of interconnections (Fig. 2). The process of transmitting data from one layer to the next determines the neural network as a feed-forward network, similar to a decision tree model (9).

An ANN consists of a group of neurons and layers and is a basic deep learning model consisting of a minimum of three layers.

The entered data is processed only in the forward direction (11). CNN is a type of deep learning model mainly used for image recognition and generation. A CNN consists of an input layer, an output layer, and many hidden layers in between. Three of the most common layers are: convolution, activation or ReLU, and pooling. Convolution puts the input images through a set of convolutional filters, each of which activates certain features from the images and reduces their complexity due to weight sharing through convolution.

The rectified linear unit (ReLU) enables faster and more efficient learning by mapping negative values to zero and holding positive values. This is sometimes called activation because only activated features are carried forward to the next layer. Pooling simplifies the output by performing non-linear down sampling, reducing the number of parameters the network needs to learn.

A fully connected layer is used after the convolution layer and pooling layer. As the name suggests, the fully connected layer connects all the activated neurons in the previous layer and transforms the 2D features into 1D. The 1D features are then associated with certain classification categories of nodes. CNN has shown higher performance and accuracy in image recognition compared to ANN (12, 13).

GAN is a type of deep learning algorithm developed by Goodfellow et al. in 2014 (14, 15). This type of algorithm consists of two neural networks, called a generator and a discriminator, which are trained simultaneously. The generator tries to create data that is indistinguishable from the real one, while the discriminator tries to distinguish the real data from the fraudulent ones generated by the generator. Over time, the generator gets better at creating data that looks real, while the discriminator gets better at spotting fakes. This process continues until the generator produces data that is so convincing that the discriminator cannot distinguish it from the real thing. The two networks compete and improve in the process of competition (Fig. 3).

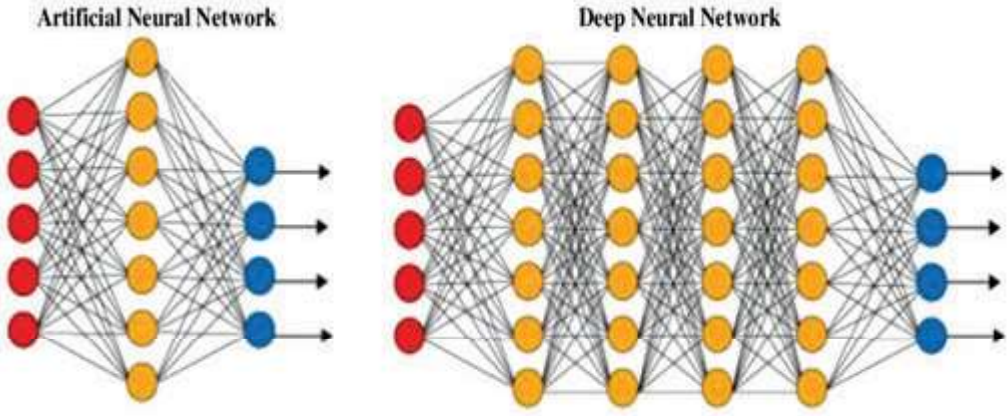

Figure 2. *Competitive Generative Neural Network (10)*

Since GANs have been around, they

Figure 3. *Model of Generative Adversarial Network*

have quickly found applications in AI. They are mainly applied to the translation of image to image and the generation of believable photographs of objects, scenes and people (16, 17).

Wu et al. (18) proposed a new 3D-GAN in 2016 based on a traditional GAN network. 3D-GAN generates 3D objects from a given 3D space by combining recent advances in GANs and volumetric convolutional networks. Unlike traditional GAN, it can generate objects in 3D directly and/or from 2D images. This new GAN network gives a wider range of possible applications in 3D data processing than the previous 2D form.

AI can be used in almost every aspect of dentistry: for diagnosis, for the formulation and execution of a treatment plan from both a clinical and laboratory perspective (9).

3. Artificial Intelligence in Dental Medicine

3.1 Prosthetic Dental Medicine

In prosthetic dentistry, AI is used for: generation of three-dimensional design of prosthetic structures and abutments, treatment planing, recognition and classification of the prosthetic field, smile design, virtual articulation and occlusion analysis, color determination, analysis and improvement of digital impressions and intraoral scans, prediction of changes in appearance after complete tooth extraction, prediction of the possibility of disbonding of CAD/CAM structures, to increase the efficiency of printing.

In most cases, the delegated task of dental technicians to create the three-dimensional design of CAD/CAM constructions is now partially being taken over by AI, thus completely automating the work regarding their modeling. Commercialized products such as CEREC, 3Shape, ExoCad, etc. offer the possibility of manual digital CAD/CAM modeling. Although this greatly increases the efficiency of the modeling process, by using pre-built libraries of tooth designs, a customized design for individual patients cannot yet be achieved (19). Currently, several programs offer AI solutions for modeling artificial crowns on filed natural teeth, which allows the fabrication of this type of construction to take place in the office in a short period of time (chair side procedures). Such programs are: the online based software www.dentbird.com and the specialized dental CAD software – 3Shape, it should be noted that the AI design capabilities are severely limited in both programs to single restorations on natural teeth, offering no design capability of crowns on dental implants.

With the development of AI, Hwang et al. (20) it takes a technician years of training to design synthetic crowns that restore the function and integrity of missing teeth. Each crown must be customized to individual patients, and it requires human expertise in a time-consuming and labor-intensive process, even with computer-assisted design software. We develop a fully automatic approach

that learns not only from human designs of dental crowns, but also from natural spatial profiles between opposing teeth. The latter is hard to account for by technicians but important for proper biting and chewing functions. Built upon a Generative Adversar-ial Network architecture (GAN and Tian et al. (21) proposed new approaches based on 2D-GAN models for artificial crown generation by training AI from a design made by dental technicians. The training data used were 2D converted from 3D dental models.

Ding (22) described a 3D-DCGAN network that directly uses 3D data in the process of generating the design of artificial crowns, describing the morphology of the generated crowns as similar to natural teeth and predicting the possibility of debonding of the CAD/CAM constructs.

Reinhard Chun Wang Chau et al. (23) describe a 3D GAN network that successfully models a molar wrap-around crown prosthetic construct mimicking the morphology of a natural healthy tooth by using tooth features from the rest of the dentition for training. The results showed mean Hausdorff values ranging from 0.441 to 0.752 mm and Intersection Over Union (IoU) values of 60%, demonstrating that the AI system could potentially automate the design of biomimetic prosthetic constructs of the species with high accuracy. The study concludes that with further algorithm optimization and training, AI could significantly increase the accuracy and efficiency in modeling this type of prosthetic constructs, which is a promising direction for future research and application in prosthetics and dentistry in general.

Hao Ding et al. (22) described a new approach using artificial intelligence for modeling dental crowns based on a real 3D deep learning algorithm (3D-DCGAN), which showed less discrepancy to natural teeth compared to modeling done by dental technicians. Regarding occlusal contacts, 3D-DCGAN and dental technicians have similar results. Regarding the dynamic morphology, no zones of concentrated stress are observed in the modeling created by 3D-DCCAN, and the survival of this type of structures is high enough.

Jun-Ho Cho and colleagues investigated crowns designed using two networks based on a deep learning model, which showed similar results regarding morphological features occlusally and axially. Their overall evaluation is clinically comparable to the dental technician design in terms of internal fit and number of occlusal contact points. Deep learning model-based networks made for crown design can optimize the digital workflow and minimize the need for additional design optimization by the dental technician (24).

Sukun Tian and team design a novel two-stage generative adversarial network (GAN) for tooth crown surface reconstruction in integrity- and functionally compromised tooth roots. In the first stage, the conditional GAN (CGAN) is designed to learn the intrinsic relationship between the defective tooth and the target crown, which solves the case of restoring occlusal relationships. In the second stage, an improved CGAN is further developed to analyze the occlusal fissures, thus the generator enriches the functional features of the occlusal surface. Experimental results show that the proposed model significantly outperforms state-of-the-art deep learning methods in functional occlusal surface reconstruction (21).

Zhaodan Gu and team created a cGAN to reconstruct occlusal morphology, the results of which show that the images generated using the network are of high quality and detailed features of pits and fissures of the crown and are comparable in quality to the design made by experienced experts (25).

Taseef Hasan Farook et al. (26) reported that a network using 3D deep learning could generate and predict the design of partial crowns in need of treatment with this type of construct.

Integrating AI into CAD/CAM or 3D printing can achieve a more efficient workflow (27). There is evidence that artificial intelligence has also been used to determine the color of future prosthetic

constructs (28) as well as to predict the possibility of debonding of CAD/CAM constructs (29).

In removable prosthodontics, existing machine learning algorithms are oriented to support the design process of removable prostheses, in particular for classification of dental arches (30) and prediction of facial appearance in totally edentulous patients (31, 32). Researchers from the Faculty of Dentistry at the University of Hong and the Department of Computer Science at Chu Hai College of Higher Education are developing a new approach using artificial intelligence to automate the design of removable dentures to improve treatment efficiency and patient satisfaction with treatment (31).

Most modern intraoral scanners are integrated with artificial intelligence to analyze intraoral scans in real time in order to: detect and delineate the boundaries of dental preparations, differentiate and remove unnecessary soft tissues and tongue. Automatic detection of prosthetic field boundaries can improve the precision of prosthetic restorations, as such it facilitates the precise fit of the construction to the respective tissues and reduces the need for manual adjustments. The ability to remove artifacts is also an advantage, allowing the files to be stored in a smaller data size.

Virtual articulation and occlusion analysis is another aspect where AI algorithms are present. They can analyze digital dental models and simulate virtual articulation to assess occlusal contacts, identify malocclusions and assess functional dynamics.

AI systems are also used in the creation of aesthetics as part of prosthetic treatment, as well as color determination. AI can analyze digital images of natural teeth, thus helping to determine and predict the color of the future structure under different types of lighting on it. Yupaporn Wanna et al (33) reported a model in a mobile application with 97.2% color accuracy according to the Vita 3D Master color scheme. Automatic recognition of bioconstants used during smile design is another application of AI models integrated into various digital smile design applications – “Preteeth AI Pro”, “Ivosmile”, “SmileFy” “Smilecloud” are some examples for such applications. Gülsüm Ceylan et al concluded that age, education level, and clinical experience did not significantly influence individuals’ aesthetic preferences for hand- or AI-generated smile designs. They also found that in cases where AI-generated smile designs were found to be preferred or equivalent to manually created ones, their use on symmetrical faces was considered acceptable by both clinicians and patients, potentially saving clinicians time (34, 35, 36).

Smile designing can be performed by an AI powered smile design software. These software’s are highly accurate, generating natural simulated images, patient friendly – involving the patient in the treatment process. Patient satisfaction, connection and efficiency in teamwork are greater. With this software a virtual patient is created using data from intraoral images and CBCT scans entered in the program. This ability to simulate, customize, and test the results gives the ability of both patient and dentist to be engaged understanding the situation before proceeding with the planned dental treatment.

AI can automatically outline the marginal lines with precision so can be used to assist in margin preparation.An example is the convolutional neural network model called Sparse Octree which can extract accurate margins (37). In other studies AI algorithms are used for ceramic shade selection included fuzzy logic, back-propagation neural networks, CNN, ANN, support vector machine algorithms (38).

3.2. Dental Implantology

In dental implantology, AI is used to: recognize the brand of the implant system in use from X-ray images, as an aid in the process of making surgical guides for implantation, to optimize the contact surface of the implant, for treatment success, for real-time navigation in the implantation process, for autonomous implantation, etc.

As an X-ray image implant recognition accuracy score, different models have 93.8% to 98% success rates. Models created to predict the success

of implant osseointegration have a success prediction score of 62.4% to 80.5%. AI models have also been successfully applied to optimize the three-dimensional design of implants. This leads to a minimization of stress at the implant-bone interface by 36.6%, to optimize the porosity of the implant surface, to improve the choice of length and diameter of the implants, as well as to accurately determine the elastic modulus of the implant-bone interface (39). There is a trend in implementing AI to automatically overlay the DICOM images and STL files needed to make surgical guides.

In addition, these CAD softwares automatically recognize certain critical structures that must be considered during virtual and real implant positioning and can automatically remove unnecessary tissue. Such software's at the moment are: coDiagnostiX, Diagnocat, etc. Tae Jun Jang and team generated a model that has the capability of fully automatic registration and correction when integrating two different images (IOS and CBCT images) into one scene. They found that they successfully compensated for the loss of data from the surfaces in the CBCT examination with their reconstruction from the high resolution of the intraoral scanner. They also make a valuable scientific contribution by achieving a high clinical accuracy of the method, even in CBCT with many artifacts from metal structures (40).

Francesco Guido Mangano and colleagues describe a protocol in which AI combined with Augmented Reality technology can be successfully used in guided implant placement surgery that can replace conventional CAD software (41).

Mafawez (42) and colleagues describe machine learning algorithms to predict the need for dental implants from patient diagnosis data. As a result, the proposed model can predict when patients may need dental implants based on their previous and current health data as well as current symptomatology.

Ping Li and colleagues investigated a robotic surgery method with integrated AI – Autonomous Technology (r-CAIS) and reported that it is an accurate and precise surgical approach for placing dental implants in patients with completely edentulous and/or extractable teeth. Although autonomous robotic surgery has various drawbacks, r-CAIS technology indeed opens a new chapter in computer-guided implant surgery (43).

Lee JH and all describes the efficacy of CNN models used to classify implants using X-rays. The bone is assessed by using AI algorithms using CBCT images, the clinicians can measure the amount of bone loss more accurately and detect areas of potential bone loss (44).

In 2021, an autonomous robot-assisted surgical system called "Remebot" was approved for dental implant placement in China. It is classified as a semi-active and autonomous robotic system. Osteotomy and implant placement are performed automatically using images that guide robot-assisted technologies (45).

Some of the limitations using this kind of technology are, but not limited to: integration of AI networks in dentistry rise concerns about privacy of patient data and confidentiality. Ethical concerns about implications of AI-generated diagnoses or treatment plans now presents. Biases may present in AI so that it can provide us with unfair or discriminating results. There is possibility of potential loss of jobs specifically for dental technicians (46). If the diagnostic procedures relay more and more on AI systems, growing risk of responsibility will also be a concern (47).

Conclusions

Neural networks – ANN, CNN and GAN are the most sophisticated types of AI used now a days in dental implantology and prosthetics for automation the diagnostic process, creating treatment plans and generating prosthetic or implantology constructions. The most sophisticate and promising network from these used to create 3D virtual structures is the generative adversarial network – GAN. These AI systems reduce the time of treatment. Still all the available AI systems can only generate just a few types of prosthetic constructions over natural teeth but none over dental implants.

We found artificial intelligence is used now a days in prosthetic dental medicine and dental implantology for: generation of specific three-dimensional designs, treatment planning, recognition and classification of the prosthetic field, smile design, virtual articulation and occlusion analysis, color determination, analysis and improvement of digital impressions and intraoral scans, prediction of changes in appearance after complete tooth extraction, prediction of the possibility of disbonding of CAD/CAM structures and to increase the efficiency of printing, brand recognition of the implant, making surgical guides, to optimize the contact surface of the implant, for real-time navigation, for autonomous implantation.

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