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Expert systems in dentistry

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SUMMARY

Introduction Artificial intelligence (AI) has become an important factor in social, scientific, and economic development today. It has wide possibilities for application, including dentistry. Its history spans eight decades, and a special area of this research and development is expert systems (ES) related to dentistry. The goal is to analyze the state of development and application of ES in dentistry, and to propose the possibility of their application today.

Methods Using elements of systematic analysis, a representative sample of articles from Web of Science and Scopus references was selected (PubMed/MEDLINE databases), which were analyzed from the point of view of the time dimension of the development of AI and ES.

Results The paper is structured so as to provide answers to the following questions: what is AI and how was it developed, how did ES in dentistry come about and how did it develop, including in Serbia, what are the prospects for the application of AI/ES in dentistry, and what are possible future directions in this area?

Conclusion AI and ES in the field of dentistry are moving from an era of experimental research to the verge of becoming good clinical practice. Digitization and the Industry 4.0 model are current directions, already widespread, which represent strong support for the faster application of these models in dental practice.

Keywords: artificial intelligence; expert systems; dentistry

INTRODUCTION

Artificial intelligence (AI) is a branch of the science of intelligence, which can be natural or artificial. AI is the science and engineering of creating intelligent machines and software systems. These two fields of research are connected and have contributed to each other over the past eight decades. Advances in natural intelligence have laid a solid foundation for AI research: artificial neural networks (ANN), genetic algorithms (GA), etc., while advanced AI tools have helped accelerate new discoveries in natural intelligence [1, 2]. Thus, there is an eight-decade-long history of AI that is more promising today than ever, as it applies to dentistry.

This review paper aims to provide readers with basic facts and knowledge about the development and application of expert systems (ES) in dentistry, to date. The beginnings of application refer, first of all, to AI, which itself has a history of development, also analyzed in detail in this paper. Why? Because ES have been a good basis for the application of AI tools and techniques in dentistry, especially deep learning in the last decade of this century. This work is intended for scientists, researchers and students who want to get concise information about the beginning of the development of a new scientific branch in dentistry, smart dentistry.

This system analysis was performed according to the PRISMA methodology [3], and our queries were the following: Q1 – How ES are used in dentistry, and Q2 – How ES improve decision-making: diagnosis, treatment planning, monitoring treatment progress, and evaluation of therapy success. For these questions, the following were defined: time period of analysis, type of study, ES models, search methodology and assessment of study quality. The sample included 268 papers, and 32 papers met the set criteria.

This paper has several parts: (i) how AI was created and developed, (ii) overview of the development of ES for dentistry, up to today, including Serbia, (iii) challenges and future development of ES for dentistry, (iv) conclusions and future research.

A BRIEF HISTORY OF AI

Before detailing ES in dentistry, it is necessary to briefly analyze the history of AI, which is shown in Table 1 [1, 2, 4]. It covers an interval of eight decades (1940–2020) and has four stages of development, as indicated in the table below.

It can be said that the history of AI starts from the early 1940s. It started with the binary ANN model created by W. McCulloch and W. Pitts of the University of Illinois in

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Table 1. Overview of the development of artificial intelligence (AI) (adapted from Toosi et al. [1], Negnevitsky [2], and Silver et al. [4])
Tabela 1. Pregled razvoja veštačke inteligencije (AI) (prilagođeno prema Toosi et al. [1], Negnevitsky [2] i Silver et al. [4])

Year of appearance Godina pojavljivanja	AI development period Period razvoja AI	Event name Naziv događaja	Characteristic Karakteristika
1943	The Dark Ages of AI Mračno doba AI	Binary ANN model (W. McCullouch, W. Pitts) Binarni ANN model (W. McCullouch, W. Pitts)	Two-state neuron Neuron sa dva stanja
1950		Turing test – can machines think? (A. Turing) Tjuringov test – mogu li mašine da misle? (A. Turing)	Communication: examiner – examinee – computer Komunikacija: ispitivač – ispitivani kompjuter
1951		The first neural computer (M. Minsky, D. Edmonds) Prvi neuronski računar (M. Minski, D. Edmonds)	A network of forty neurons Mreža od četrdeset neurona
1956	The rise of AI Uspon AI	First AI Workshop (J. McCarthy) Prva AI radionica (J. McCarthy)	Artificial intelligence defined Definicija termina „veštačka inteligencija (AI)“
1958		LISP – The First AI Language (J. McCarthy) LISP – Prvi AI jezik (J. McCarthy)	Still in use today – functional language Koristi se i danas – funkcionalni jezik
1961		General Problem Solver (GPS) (A. Newell, H. Simon) Opšti rešavač problema (GPS) (A. Newell, H. Simon)	Uses formal logic to find solutions (does not solve complex cases) Koristi formalnu logiku za traženje rešenja (ne rešava složene slučajeve)
1965		Fazzy sets (L. Zadeh) Neizraziti skupovi (L. Zadeh)	A continuous transition from not belonging to complete belonging Kontinualni prelaz od nepripadanja do potpunog pripadanja
1969		Dendral (E. Feigenbaum, B. Buchanan, J. Lederberg, C. Derassi)	The first expert system – spectrogram identification of chemical compounds Prvi ekspertni sistem – spektrogramska identifikacija hemijskih jedinjenja
1970	AI "winter" AI „zima“	ANN Learning (A. Bryson and Y. Ho) ANN učenje (A. Brajson i Y. Ho)	Backpropagation model Model propagacije unazad
1975		GA (J. Holland)	The first genetic algorithm Prvi genetski algoritam
1976		Mysin (E. Shortliffe)	The first expert system for diagnosis Prvi ekspertni sistem za dijagnozu
1982		Hopfield networks (J. Hopfield) Hopfildske mreže (J. Hopfild)	Memory systems with binary boundary nodes, a model for understanding human memory Memorijski sistemi sa binarnim graničnim čvorovima, model za razumevanje ljudskog pamćenja
1986		Backpropagation (BP) (D. Rumelhart, J. McClelland) and DAI (Distributed AI) (A. Bond, L. Gasser) Propagacija unazad (BP) (D. Rumelhart, J. McClelland) i DAI (Distribuirana AI) (A. Bond, L. Gasser)	Neural error (BP) computation and distributed solutions for AI Izračunavanje greške neurona (BP) i distribuirana rešenja za AI
1992	AI becomes a science AI postaje nauka	Genetic programming (GP) (J. Koza) Genetsko programiranje (GP) (J. Koza)	LISP symbolic code LISP simbolički kod
1995		Intelligent agents (M. Wooldridge, R. Jennings) Inteligentni agenti (M. Wooldridge, R. Jennings)	They act on the environment in an intelligent way Deluju na okolinu na inteligentan način
2002		ACO, PSO, AIO, DNA computing ACO, PSO, AIO, DNA računarstvo	AI tools Alati AI
2006		Honda ASIMO robot Robot Honda ASIMO	Moving and climbing stairs Kretanje i penjanje uz stepenice
2016		AlphaGo DeepMind	Man–computer games Igre čovek–kompjuter
2017		IBM Watson	Man–computer games Igre čovek–kompjuter
2022	ChatGPT	Open AI	AI for different fields AI za različite oblasti

1943 [5]. Although their model only considered a binary state (i.e., on/off for each neuron), this model was used as a basis for ANN research in the late 1980s. In 1950, the British mathematician A. Turing proposed the famous Turing test, which is used to determine whether machines can think [6]. The Turing test is performed through computer communication, which includes an examiner, a person (subject), a participant in the experiment, and a computer, which are separated from each other, but communicatively connected. The examiner can ask any question. If the examiner cannot distinguish a machine from a human based on their answers, the computer has passed the test. In 1951, M. Minsky and D. Edmonds, two graduate students from Princeton University, built the first neural computer simulating a network of 40 neurons [7].

An important turning point in the development of AI was the first AI workshop, held in 1956 at Dartmouth College, under the leadership of J. McCarthy [8]. This workshop marked the end of the "Dark Age of AI" and the beginning of the "Rise of AI" in the history of AI. The term "artificial intelligence" was then proposed by J. McCarthy, and it is still in use. He later moved to the Massachusetts Institute of Technology to define the first AI language, LISP, in 1958, which is still in use today. One of the most ambitious projects in this area was the General Problem Solver (GPS), which was created in 1961 by A. Newell and H. Simon from Carnegie Mellon University [9]. GPS is based on formal logic and can generate an infinite number of operators trying to find a solution; however, it is ineffective in solving complicated problems. In 1965, L. Zadeh of UC Berkeley published the famous paper "Fuzzy Sets," which is the basis of the theory of fuzzy sets, or uncertain decision making [10].

The first ES, Dendral [11], was developed at Stanford University in 1969 in a project funded by the National Aeronautics and Space Administration (NASA), led by J. Lederberg, winner of the Nobel Prize for genetics. However, at the time, most AI projects could only solve gaming problems, rather than real-world ones, so many projects in the United States, Great Britain, and several other countries failed, or were useless. That's how AI research entered the so-called "AI Winter."

Despite reduced funding, AI research continued, so in 1970, Bryson and Ho [12] proposed a back-propagation model for neural network learning. Moreover, the first GA was proposed in 1975. Holland [13], from the University of Michigan, used selection, crossover and mutation as genetic operators for optimization and thus developed the GA model. The same team, which was developed by ES Dendral [14], at Stanford University, developed MYCIN in 1976, which is based on IF–THEN rules, as an expert system for the diagnosis of blood diseases using 600 rules, if (IF) – then (THEN). Research has shown that it works better than a junior doctor [15].

After 30 years, the work on ANN has restarted research on them as an important area of AI. A new era has begun in which AI has become a science. It was in 1982 that Hopfield [16] published his Hopfield networks, which are still popular today. In 1986, back propagation became the first implemented learning algorithm in ANN, 16 years after the publication of this model [17]. Also, this year is the beginning of the application of distributed AI (DAI) through parallel distributed knowledge processing. After 22 years, fuzzy set theory or fuzzy logic was successfully incorporated into the operation management of dishwashers and washing machines in 1987 by Japanese companies that produced these household appliances. In 1992, genetic programming was proposed by Koza [18] for manipulation of symbolic code generated in the LISP language. Based on the ideas of DAI and artificial life, intelligent agents gradually took shape in the mid-1990s. In the late 1990s, hybrid systems of fuzzy logic, ANN, and GA became popular tools for solving complex problems. Various new AI approaches have since emerged, including ACO, particle lake optimization (PSO), artificial immunity optimization (AIO), and DNA computing, as well as intelligent agents [19]. The potential of AI in the future – such as dentistry – remains great and currently unpredictable.

The first popular AI tool was AI-based chess software – the computer program Deep Blue, created by International Business Machines Corporation (IBM) [20]. Garry Kasparov, the then world chess champion, played against it in 1997 in an exhibition match, and lost to it by 2.5 to 3.5. Another early example is the Honda ASIMO robot in 2005 that could climb stairs. For a robot to move in an unstructured environment and be commanded by a human, it requires natural language processing capabilities, computer vision, perception, object recognition, machine learning and motion control during operation. Recently, in 2016, AlphaGo DeepMind beat world champion L. Sedol in four out of five games, using cloud computing, supported learning, and a Monte Carlo search algorithm combined with a deep neural network for decision making [21]. Its newer version, AlphaGo Zero, surpassed AlphaGo's ability in just three days through self-learning from scratch [4, 22]. A new breakthrough in this area was IBM Watson, an intelligent platform.

The latest approach is ChatGPT, a general platform for the use of AI in various fields, including dentistry. This is one of the future directions of development of this field in dentistry.

Today, AI techniques and systems can be used in a variety of fields, from chess games to robot control, disease diagnosis, airplane autopilot, smart design, and smart dentistry. In addition to the AI techniques outlined in Table 2, machine learning and deep learning show much promise for smart dentistry. This table classifies typical machine learning models based on whether they are supervised, semi-supervised or unsupervised, discriminative or generative, learning or deep learning. Those used in dentistry are colored red.

Namely, supervised learning finds relations between inputs and outputs over labeled datasets during system training. In unsupervised learning, the model extracts realities, that is, regularities from the data, without mapping inputs to outputs. Semi-supervised learning combines supervised and unsupervised learning by using both labeled and unlabeled data. In addition, a branch of machine learning that particularly stands out in terms of results in recent years is deep machine learning. Generally speaking, it is about the application of ANN with a larger number of layers. Another classification that has been very current in recent years distinguishes between discriminative and generative models. Discriminative models aim to recognize the differences between different types of data, that is, learn what details separate one class of data from another. Generative models try to learn the distribution of data and generate new data [23, 24]

EXPERT SYSTEMS IN DENTISTRY – OVERVIEW OF DEVELOPMENT

ES are intelligent computer programs that solve problems the way experts do, and they represent one of the most important areas of AI research [1, 4]. They have been described as "computerized knowledge," and the British Computer Society has defined ES more fully as "... creating in a computer a component based on knowledge from an expert skill in such a form that the system can

Table 2. Overview of learning models; Toosi et al. [1], Silver et al. [4]
Tabela 2. Pregled modela učenja (primenjenih u stomatologiji); Toosi et al. [1], Silver et al. [4]

<table>
<tr><th>Machine learning model
Model mašinskog učenja</th><th>Supervised/semi-supervised/ unsupervised
Nadgledano / polunadgledano / nenadgledano</th><th>Discriminative/generative
Diskriminativno / generativno</th><th>Learning / deep learning
Učenje / duboko učenje</th></tr>
<tr><td>K-means
K srednjih vrednosti</td><td>Unannounced
Nenadgledano</td><td>Generative
Generativno</td><td>Learning
Učenje</td></tr>
<tr><td>K-nearest neighbor
K najbliži sused</td><td rowspan="11">Supervised
Nadgledano</td><td rowspan="10">Discriminative
Diskriminativno</td><td rowspan="9">Deep learning
Duboko učenje</td></tr>
<tr><td>Support vector method*
Metod podržavajućih vektora</td></tr>
<tr><td>Hidden Markov model*
Skriveni Markovljev model</td></tr>
<tr><td>Random forest model*
Model slučajne šume</td></tr>
<tr><td>Extreme Gradient Boosting (XGBoost)
Ekstremno pojačavanje gradijenta (XGBoost)</td></tr>
<tr><td>Ensemble method
Metod ansambla</td></tr>
<tr><td>Convolutional neural networks*
Konvolucijske neuronske mreže</td></tr>
<tr><td>Recurrent neural network*
Rekurentna neuronska mreža</td></tr>
<tr><td>Long short-term neural network
Duga kratkoročna neuronska mreža</td></tr>
<tr><td>Naive Bayes classifiers*
Naivni Bajesovi klasifikatori</td><td rowspan="2">Learning
Učenje</td></tr>
<tr><td>Gaussian mixture model
Gausov mešani model</td><td>Generative
Generativno</td></tr>
<tr><td>A generative adversarial network
Generativna suparnička mreža</td><td>Semi-supervised
Polunadgledano</td><td>Discriminative
Diskriminativno</td><td>Deep learning
Duboko učenje</td></tr>
</table>

*Applied in dentistry

offer intelligent advice or make an intelligent decision about the subject area" [23]. ES solve real problems from different fields, which would otherwise require human expertise. The goal is that the computer program always gives correct answers, in the given field, no worse than an expert, but this is difficult to achieve. That is why a less ambitious goal is set, the system is requested to provide decision-making support.

ES have played a major role in the development and application of AI models (Table 3). However, as the analysis in the table below shows, new generations of ES, based on deep knowledge, are once again entering the scene.

Earlier it was said that Mysin was the first ES used by doctors [15, 25–29], and in this regard everything started with the development of the first ES – Dendral [14, 11], which was used to solve a specific task in science: to help organic chemists in the identification of unknown organic molecules, by analyzing their mass spectra, using knowledge from chemistry. The Dendral software program is considered the first ES, because it automated the decision-making process and defined the problem-solving behavior of organic chemists. The project consisted of two programs – Heuristic Dendral and Meta-Dendral, as well as several subprograms. It is written in the LISP programming language, which is considered the language of AI because of its flexibility. Many ES are derived from Dendral, including MYCIN, Molgen, Prospector, Xcon, and Steamer.

MYCIN was the first AI program to search backwards, which it used to identify bacteria that cause severe infections, such as bacteremia and meningitis, and to recommend antibiotics, with a dose adjusted to the patient's body weight. The very name of this ES comes from the antibiotics themselves, as many antibiotics have the suffix "-mycin." The MYCIN system has also been used to diagnose blood clotting disorders. His knowledge base was defined by rules, and the method of searching and connecting rules for the purpose of reasoning is still an example of a good model of reasoning [from symptom(s) (consequences) to cause(s)].

A detailed analysis of the literature shows that the first ES in dentistry was developed for oral dentistry in 1983 (Table 4) [30]. It was a set of software modules that were used for the diagnosis of clinical conditions and management hypotheses from the knowledge base. These modules were the following: Problem-Knowledge Coupler, Coupler Editor, Knowledge Network, and Problem-Oriented Computerized Medical Record. It contained a section related to oral dentistry.

The next model was developed in 1986 [31]. It is a knowledge-based system, which also works on the basis of rules. Orthodontists have defined a number of characteristic points, or landmarks, on an X-ray image of the human skull that are used to study growth or as a diagnostic aid. The original image was pre-processed with a pre-filtering operator (median filter) followed by an edge detector (Mero-Vassi operator). A knowledge-based line-tracing algorithm is then applied, involving a system with organized rule sets and a simple interpreter. In the inference algorithm, *a priori* knowledge is applied, which takes into account the facts of biological facial shapes,

Table 3. Context of expert systems and artificial intelligence development (amended according to Toosi et al. [1] and Silver et al. [4])
Tabela 3. Kontekst razvoja ES i AI (dopunjeno prema Toosi et al. [1] i Silver et al. [4])

Time period Vremenski period	Period of development of ES Period razvoja ES	Basic characteristic of the period Osnovno obeležje perioda	Detailed characteristics of the period Detaljna karakteristika perioda
1955–1975	First AI jump Prvi skok AI	Search and reasoning (database) Pretraživanje i rezonovanje (baza podataka	New technologies, neural network and perceptron, were applied to search and reasoning. These paradigms made AI capable of performing some intellectual activities, provided it was given rules and goals (solving puzzles, playing chess, and proving mathematical theorems). However, the AI boom entered its first winter in the 1970s, because search and reasoning could not solve more complex problems. Za navedene ključne reči (pretraživanje i rezonovanje) primenjene su nove tehnologije, neuronska mreža i perceptron. Ove paradigme su AI učinile sposobnom da obavlja neke intelektualne aktivnosti, pod uslovom da su joj data pravila i ciljevi (rešavanje zagonetki, igranje šaha i dokazivanje matematičkih teorema). Međutim, AI je ušao u prvi zastoj tokom 1970-ih, jer pretraživanje i zaključivanje nisu mogli da reše složenije probleme.
1975–2000	Second AI jump Drugi skok AI	ES (specially organized knowledge) Ekspertni sistemi (Posebno organizovano znanje)	To break the first AI winter, the new technology of ES was defined. ES were focused on solving complex problems, by transferring expert knowledge into computers. In the early 1970s, the representative expert system MYCIN was developed at Stanford University [13, 24, 25, 26] for the diagnosis of infectious blood diseases, and its accuracy was approximately 60–70%. Thanks to the growth of ES (in number and in the domains to which they were applied), the second leap of artificial intelligence occurred in the 1980s. However, ES had several problems. In particular, they required large amounts of expert knowledge, which were difficult to collect and accurately input into computers at that time (a process known as knowledge engineering). Furthermore, ES were unable to handle exceptional cases because their knowledge was stored mainly as IF–THEN rules. For these reasons, the AI boom entered its second winter in the late 1990s. Da bi se prekinuo prvi „zimski period" AI, definisana je nova tehnologija – ekspertni sistem (ES). ES su bili fokusirani na rešavanje komplikovanih problema transplantacijom znanja stručnjaka na računar. Početkom 1970-ih na Univerzitetu Stanford razvijen je reprezentativni ekspertni sistem MYCIN [13, 24, 25, 26] za dijagnostiku zaraznih bolesti krvi, čija je tačnost bila 60~70%. Zahvaljujući porastu ES (po broju, a i oblasti na koje su se odnosili), drugi skok veštačke inteligencije je nastao 1980-ih. Međutim, ES su imali nekih problema. Posebno, oni su zahtevali ogromnu količinu znanja stručnjaka, koju je bilo teško prikupiti i tačno uneti u računar u to vreme (inženjerstvo znanja). Štaviše, ES nisu bili u stanju da se izbore sa nekim izuzetnim slučajevima, jer je njihovo znanje bilo uglavnom sačuvano kao pravilo AKO–ONDA. Iz ovih razloga, AI je u[la u svoj drugi „zimski peropd" krajem 1990-ih.
2000–2015	Third AI jump Treći skok AI	Learning Učenje	The third AI boom emerged due to advances in machine learning and the rise of deep learning. Moreover, this leap was enabled by the advent of smartphones, improvements in computer performance, and the advent of big data analytics (BDA) resulting from the expansion of the Internet. Thanks to these technologies, artificial intelligence that surpasses human abilities has emerged in certain fields, such as IBM Watson (which defeated quiz players in 2017) [27] and AlphaGo (which defeated professional Go players in 2015) [28]. Treći bum veštačke inteligencije je stigao zbog napretka mašinskog učenja i pojave dubokog učenja. Štaviše, ovaj skok je izazvan pojavom pametnih telefona, poboljšanjem performansi računara i dolaskom ere velikih podataka (BDA) zbog ekspanzije interneta. Zahvaljujući ovim tehnologijama, veštačka inteligencija koja prevazilazi ljudsku pojavila se u određenim oblastima kao što su IBM Vatson (koji je 2017. pobedio igrače na kvizu) [27] i AlphaGo (koji je pobedio profesionalne igrače igre Go 2015) [28].
2015–present 2015. do danas	Quadruple jump AI Četvrti skok AI	Deep learning Duboko učenje	The fourth and most recent boom of AI arose as a consequence of the development and rapid implementation of Industry 4.0, based on CPS, the IoT, and BDA. These factors have accelerated the development and application of new deep learning models, paving the way for smart manufacturing and smart systems. Today, IBM Watson is a technology platform that uses NLP and ML to extract knowledge from large volumes of unstructured data, which can then be handed over to experts for analysis and decision-making. This method enables support for experts to generate expert knowledge from vast datasets, which forms a new basis for the development and application of a new generation of ES. Poslednji, četvrti bum veštačke inteligencije nastao je kao posledica razvoja i brze primene Industrije 4.0, zasnovane na CPS, IoT i BDA. Ovi činioci su ubrzali razvoj i primenu novih modela dubokog učenja, na putu izgradnje pametne proizvodnje i pametnih sistema. Danas je IBM Vatson tehnološka platforma koja koristi NLP i mašinsko učenje da bi otkrio činjenice iz velikih količina nestrukturiranih podataka, koji se zatim mogu predati ekspertima na analizu i odlučivanje. Ovaj metod omogućava podršku stručnjacima za generisanje ekspertskih znanja iz ogromne količine podataka, što čini novu osnovu za razvoj i primenu nove generacije ES.

ES – expert systems; AI – artificial intelligence; BDA – big data analytics; CPS – cyber-physical systems, IoT – Internet of Things, NLP – natural language processing; ML – machine learning

Table 4. Overview of developed expert system models and artificial intelligence / machine learning models for dentistry
Tabela 4. Pregled razvijenih modela ES i modela AI/ML učenja za stomatologiju

Year of appearance / reference Godina pojavljivanja / referenca	ES name Naziv ES	Basic characteristics Osnovne karakteristike	Application Primena
1983 [33]	KBS M/D	Based on the rules, it suggests a diagnosis. Na bazi pravila, predlaže dijagnozu.	Diagnosis in oral dentistry Dijagnoza u oralnoj stomatologiji
1986 [34]	Orthodont	A knowledge-based system, which is organized through rules (IF–THEN); four types of operators are used to generate the inference form Sistem na bazi znanja, koji je organizovan preko pravila (AKO–ONDA). Koriste se četiri vrste operatora da generišu oblik zaključivanja.	Orthodontic analysis of X-ray images of the human skull, in order to define and monitor the patient's OP; automatic extraction of OP Ortodontska analiza rendgentskih snimaka ljudske lobanje, radi definisanja i praćenja ortodontskih parametara (OP) pacijenta. Automatsko izdvajanje OP
1987 [35]	KBS M/D	Medical ES with dentistry supplement Medicinski ES sa dodatkom za stomatologiju	Diagnosis and treatment plan in oral dentistry Dijagnoza i plan lečenja u oralnoj stomatologiji
1989 [36]	Orad	By means of Bayes' theorem, the radiograph of patients with intraosseous lesions is evaluated. Pomoću Bajesove teoreme se ocenjuje radiografski snimak pacijenata sa intrakoštanim lezijama.	Support to clinical doctors in formulating a differential diagnosis Podrška kliničkim lekarima u formulisanju diferencijalne dijagnoze
1989 [37]	FRIEL	Using fuzzy logic, the state of the dental arch shape in children is evaluated and a decision is made for further treatment. Pomoću fazi logike se ocenjuje stanje oblika zubnog luka kod dece i donosi odluka za dalje lečenje.	Pediatric dentistry Dečja stomatologija
1991 [38]	Decision-making models Modeli odlučivanja	The following models are used for decision-making in the ES knowledge base: Bayes' theorem, decision tree, ROC curve, sensitivity analysis, impact assessment and others. Za odlučivanje u bazi znanja ES koriste se sledeći modeli: Bajesova teorema, Drvo odlučivanja, ROC kriva, analiza osetljivosti, ocena uticaja i druge.	They are used in different branches of dentistry. Primenjuju se u različitim granama stomatologije.
1991 [39]	Decision model analysis Analiza modela odlučivanja	A detailed overview of different decision models for use in dentistry Detaljan pregled različitih modela odlučivanja za primenu u stomatologiji	Different areas of dentistry Različite oblasti stomatologije
1992 [40]	KBS	Orthodontic analysis of class II occlusion and case 1 Ortodontska analiza zagrižaja klase II i slučaja 1	The knowledge base includes cases with proposed solutions. Baza znanja obuhvata slučajeve sa predlogom rešenja.
1992 [41]	Analysis of ES for medicine and dentistry Analiza ES za medicinu i stomatologiju	The first decade (1980–1992) of development and application of ES Prva dekada (1980–1992) razvoja i primene ES	608 articles in the field of medicine and 8 in the field of dentistry were published. Objavljeno je 608 članaka iz oblasti medicine i osam iz oblasti stomatologije.
1993 [42]	Expert Rule	The knowledge base includes thirteen bite models. Baza znanja obuhvata trinaest modela zagrižaja.	Orthodontics – diagnosis with treatment planning Ortodoncija – dijagnoza sa planiranjem lečenja
1996 [43]	KBS	Orthodontic analysis Ortodotska analiza	Expanding the knowledge base for each new case Proširenje baze znanja za svaki novi slučaj
1996 [44]	KBS	Decision analysis study of doctors and ES Studija analize odluka lekara i ES	Sample of 100 cases, accuracy 88% Uzorak od 100 slučaja, tačnost 88%
1998 [45]	KBS	Application of ANN in ES Primena ANN u ES	Third molar treatment planning Planiranje lečenja trećeg molara
1998 [46]	KBS	ES response validation Validacija odgovora ES	Diagnosis and treatment with orthodontic appliances Dijagnoza i lečenje ortodontskim aparatima
1999 [47]	EIS0-1	Supplementing the knowledge base using the RDR model of knowledge engineering Dopuna baze znanja pomoću RDR modela inženjerstva znanja	It is used for planning orthodontic treatment. Koristi se za planiranje ortodotskog tretmana.
2010 [48]	KBS	Orthodontic treatment of patients (children) Ortodontski tretman pacijenata (dece)	Treatment planning Planiranje lečenja
2015 [49]	eD ES	Oral dentistry (ANN and fuzzy logic) Oralna stomatologija (ANN i fazzy logika)	Diagnosis and treatment plan Dijagnoza i plan lečenja
2020 [50, 51, 52]	Web ES	The certainty factor (CF) between symptoms and diagnosis Faktor izvesnosti (CF) između simptoma i dijagnoze	Oral health diagnosis Dijagnoza oralnog zdravlja
2020 [53]	ES	A CNN with four network depth models CNN sa četiri modela dubine mreže	Diagnosis of radiographic images in oral dentistry Dijagnoza radiografskih snimaka u oralnoj stomatologiji

Year of appearance / reference Godina pojavljivanja / referenca	ES name Naziv ES	Basic characteristics Osnovne karakteristike	Application Primena
2021 [54, 55]	AI/ML	Six models of ML algorithms in use are analyzed. Analizira se šest modela algoritama ML u primeni.	Application in dentistry, especially in orthodontics Primena u stomatologiji, a posebno u ortodonciji
2021 [56]	CNN	ES for automatic identification of 13 points on the patient's face ES za automatsku identifikaciju 13 tačaka na licu pacijenta	Diagnosis of malocclusion with treatment plan Dijagnoza nepravilnog zagrižaja sa planom lečenja
2021 [57]	AI in dentistry AI u stomatologiji	Future trends Budući trendovi	CAD/CAM modeling, implantology, robotic oral surgery CAD/CAM modeliranje, implantologija, robotska oralna hirurgija
2021 [58]	ES based on Bayesian rules ES na bazi Bajesovih pravila	Multiple simultaneous symptoms Više istovremenih simptoma	Diagnosis of the patient's oral health condition Dijagnoza stanja oralnog zdravlja pacijenta
2022 [59]	CNN	700 orthodontic cases, accuracy 97% 700 ortodontskih slučajeva, tačnost 97%	Diagnosis and treatment plan Dijagnoza i plan lečenja
2022 [60]	WebCeph ES (CNN)	Determination of linear and angular cephalometric landmarks Određivanje linearnih i ugaonih cefalometrijskih orijentira	Orthodontic diagnosis and treatment plan Ortodontska dijagnoza i plan lečenja
2023 [61]	AI/ML	Analysis of the application of AI/ML in orthodontics Analiza primene AI/ML u ortodonciji	The best results are achieved by applying deep learning models. Najbolji rezultati se postižu primenom modela dubokog učenja.
2024 [62, 63]	ML	Application in orthodontics Primena u ortdonciji	Dentistry 4.0 Stomatologija 4.0
1993 [65] 1994 [66]	ES	Application in prosthetics Primena u protetici	Rule-based model Model zasnovan na pravilima

ES – expert systems; AI – artificial intelligence; KBS – knowledge-based system; CNN – convolutional neural network; ML – machine learning; CAD – computer-aided design; CAM – computer-aided manufacturing; ANN – artificial neural networks; OP – orthodontic parameters; RDR – Ripple-Down Rules; CF – certainty factor

which can vary significantly from one patient to another. Therefore, the algorithm takes into account objective quality criteria through rules. It is especially noted here that the first positive experiences in the application of this ES were later used, including today, for the development of advanced ES in this area.

The ES example in a study by Abbey [32] was developed for medicine, but was also used in dentistry. This ES is a knowledge-based system (KBS), which generates variable data from the patient and links it to a large fixed knowledge base, which is designed to capture the patient's specific problems. The results in the form of advisory diagnoses and treatment plans are available to the dental clinician, and they relate to oral dentistry.

This ES (Orad) uses Bayesian theorems to evaluate the radiographs of patients with intraosseous lesions, in order to establish a diagnosis [33]. Ninety-eight lesions of the jaw are described in the knowledge base, according to their prevalence and distribution, and according to age, sex, race, presence of pain, number, size and localization of lesions, connection with teeth, etc. The user follows a menu of 16 questions to characterize a specific lesion. ES outputs a list of lesions in order of their estimated probability. Studies show that this ES is useful in assisting clinicians in formulating differential diagnoses.

Using fuzzy logic programming language (FRIL), a consulting ES for orthodontics was developed [34]. It helps dentists in general practice to use ES to assess the shape of the dental arch in children and, based on that, refer them to an orthodontist for detailed diagnosis and further treatment. The goal is for the young patient's permanent teeth to grow properly later on.

Decision-making in clinical dentistry is shaped by various and numerous influences, which is especially true for ES knowledge bases [35]. For these reasons, it is necessary to know the decision models in detail in order to make the correct clinical conclusion using ES. Thus, in a study by McCreery and Truelove [36], a detailed analysis of decision models, 11 in total, with the best application in specific branches of dentistry is presented.

Orthodontic ES for the analysis of Class II and Case 1 occlusions was presented in the study by Brown et al. (1991) [37]. He gives advice to the orthodontist to define the treatment plan. The first decade of ES for medicine are KBS for diagnosis and counseling of physicians regarding treatment plans [38]. It is believed that future research in this area should be directed towards clinical problems. Diagnosis with treatment planning is the ES model presented in a study by Grant and Freer [39], wherein the knowledge base includes 13 different bite models.

A knowledge-based system is presented in a study by Hammond and Freer [40] and is used for orthodontic analysis and synthesis. Its main feature is that for each new case, the existing knowledge base is expanded with it. A comparison of the decisions of ES and dentists is shown that the accuracy of the ES is 88%, which means that it is worse than the expert and can only be assigned a consulting role, not the final decision.

Twelve different models were used as a training tool for NN, on a clinical history sample of 238 mandibular third molars (approximately the same number of male and female patients, aged around 30 years), with output data on oral surgeon treatment plans [41]. Starting from the gold standard for this field (0.8 sensitivity), the ES showed a sensitivity of 0.78 and the oral surgeon 0.88 (not a significant difference), while the difference in specificity is even smaller (0.98 and 0.99 for an oral surgeon), which is also not significant. The conclusion is that it is possible to train the ANN to provide reliable support in defining the treatment plan for the lower third molar. A study by Brickley et al. [42] analyzed the responses of an ES, which is used as an orthodontic consultant for appliance planning. Otherwise, it is a rule-based ES, and the result is that ES answers are satisfactory with 95% accuracy.

EIC0-1 ES constitutes a set of rules (690), with which the orthodontist, using the Ripple-Down-Rules (RDR) knowledge engineering model, designs and supplements the knowledge base, thus increasing the quality of the response of the ES itself [43]. It is suitable for use in the clinic, and students can especially benefit from it when mastering and making decisions for planning orthodontic treatment.

A paper by Xie et al. [44] presented a decision-making model for orthodontic treatment of patients between the ages of 11 and 15, in which it is determined whether tooth extraction is required. ANN is used for training and decision making. Otherwise, it is a rule-based ES, and the result was that the ES answers were satisfactory on a sample of 200 patients (180 for ANN training and 20 for the test). Accuracy was 100% for trained cases and 80% for test cases.

Tinuke and Yetunde [45] demonstrated that ES can effectively automate dental and administrative procedures. They described two AI techniques for reasoning and inference, ANN and fuzzy logic.

Three Web ES are presented by Pasaribu et al. [46], Kurniawan [47], and Sidik et al. [48], which are used to assist the dentist in diagnosing the patient's oral health status. They are based on IF–THEN rules by which symptoms and diseases are related to a certainty factor. The results showed 99% accuracy of his diagnosis compared to the diagnosis of a specialist dentist. A model for the diagnosis of the oral condition of patients who need surgical treatment was based on the diagnosis using radiographic images [49]. The accuracy of this predictive model is achieved by the depth of the convolutional neural network (CNN), which was demonstrated by the experiment. The screening included 960 patients, and the ResNet-18, 34, 50, and 101 models were used, and the accuracy, sensitivity, and specificity of each model were evaluated. ResNet-18 performed best with an area under the curve of 0.979, followed by ResNets-34, 50, and 101 at 0.974, 0.945, and 0.944, respectively.

AI / machine learning (ML) are increasingly applied in the fields of orthodontic diagnosis, treatment planning, growth assessment, and treatment outcome prediction [50, 51]. The following ML algorithms are analyzed: Bayes model (supporting risk assessment in diagnosis), ANN (diagnosis by image analysis), support vector machine is used for skeletal pattern recognition, GA is used for condition prediction trends based on diagnosis, fuzzy logic is used to define the line of reasoning in sets where states are not determined. From these models, deep learning models are being developed today, which will only be applied in the near future, as a support to dentists.

A study by Prasad et al. [52] presented an intelligent model based on CNN for deep learning, for the automatic identification of landmarks on the patient's face (13 in total), by analyzing radiographic images, and in relation to irregular jaw positions and the diagnosis of such a condition. The sample consisted of 950 patients, and excellent results were obtained with a reliability of 95%, which is why this method is recommended for clinical practice.

It can be stated that the application of AI in dentistry is still at an early stage [53, 54]. However, the prospects of this technology are great for diagnosis, treatment planning, recovery monitoring, patient management and administrative tasks. Special breakthroughs are expected in computer-aided design (CAD) and computer-aided manufacturing (CAM), implantology, as well as robotic oral surgery. The analysis in a study by Tam-Nurseman et al. [55] shows that in dentistry a few symptoms are not enough for a diagnosis, and for these reasons, Bayesian rules were applied, which enables linking (ranking and correlation) of several symptoms for a single diagnosis. For these reasons, an improved model of Bayesian rules was developed, which showed good results in defining the diagnosis, with multiple simultaneous symptoms.

Diagnosis and treatment planning are the core of orthodontics, which orthodontists acquire with years of experience [47]. ML has the ability to learn by pattern recognition, and it achieves this in a very short time, ensuring reduced inference error and excluding inter-clinician inference variability, as well as good accuracy. In this study, on a sample of 700 patients, using a four-layer CNN, an accuracy of 97% was achieved [52, 56]. All this was related to the diagnosis and treatment plan in orthodontics. Automated cephalometric analysis is one of the main areas of application of AI in the field of orthodontics. WebCeph ES performs the determination of linear and angular cephalometric landmarks, obtained on a web basis by fully automated measurements of these parameters using this platform. The results of the research show that there was complete agreement between manual measurements and this ES, on a sample of 30 patients.

Systematic reviews analyzed different strategies using AI to improve diagnosis, planning and monitoring of orthodontic treatment [57, 58]. The works were analyzed in an interval of 10 years, and a total of 33 studies were included. The results show that AI is increasingly becoming a part of clinical practice, and in particular the deep learning model. A review paper by Prasad et al. [52] also provides an analysis of the application of AI in orthodontics for diagnostics, cephalometric assessment, tooth age determination, temporomandibular jaw (TMJ) assessment, treatment plan decision making and remote patient monitoring (Dentistry 4.0). However, in clinical application, the validation of the solution must still be done by an expert dentist.

As a conclusion of this analysis, we can state the following: (a) ES in dentistry have been a research direction for four decades, and during that time they have come from individual research ideas to important scientific research practice, with a perspective in clinical dentistry; (b) the application of ES (AI) in dentistry is considered good practice today; (c) deep learning from unstructured databases is the best method of applying ES (AI) in dentistry today.

EXPERT SYSTEMS FOR DENTISTRY IN SERBIA

It is with great pleasure that we can state that at the School of Dental Medicine in Belgrade, at the Clinic for Prosthetics, serious research in this field has been carried out since the beginning of the last decade of the last century, until today [59–62]. All this resulted in the first ES for prosthetist dentists in Serbia. It was a rule-based system (IF–THEN rules), and the knowledge base had 120 rules. The search of the knowledge base was based on the forward chaining model, from symptoms to diagnosis. It was of an experimental-laboratory nature, and later the knowledge from its development served in the wide application of the CAD/CAM system at this clinic, as well as at other clinics of the School of Dental Medicine in Belgrade.

EXPERT SYSTEMS AND ARTIFICIAL INTELLIGENCE IN DENTISTRY – WHAT NEXT

AI-based virtual dental assistants can perform several tasks in a dental practice with greater accuracy, fewer errors, and less manpower compared to humans [51, 52, 53]. They can be used to coordinate appointments, manage insurance and paperwork, and assist in clinical diagnosis or treatment planning. They are very useful in alerting the dentist to medical history, as well as to habits such as alcoholism and smoking. In dental emergencies, the patient has the option of emergency teleassistance, especially when the dentist is unavailable. Thus, a detailed virtual patient database can be created, which will go a long way in providing the ideal treatment for the patient himself.

ARTIFICIAL INTELLIGENCE IN DIAGNOSIS AND TREATMENT

AI can be used as an effective approach in the diagnosis and treatment of lesions of the oral cavity, and it can be used in the screening and classification of suspicious changes in the mucous membrane which go through premalignant and malignant conditions. Even tiny changes at the level of a single pixel are detected, which can go unnoticed by the naked eye. AI can accurately predict genetic predisposition to oral cancer for a large population.

ARTIFICIAL INTELLIGENCE IN ORAL AND MAXILLOFACIAL SURGERY

The biggest application of AI in oral surgery is the development of robotic surgery, wherein the movement of the human hand and human intelligence are simulated. Successful clinical applications in image-guided cranial surgery include oral implant surgery, tumor and foreign body removal, biopsy, and jaw surgery. Comparative studies of oral implant surgery indicate significantly higher accuracy compared to freehand manual surgery, even when performed by experienced surgeons. Shorter operation time, safer manipulation around delicate structures and greater intraoperative precision are obtained. Image-guided robotic surgery allows for more thorough surgical resection, potentially reducing the need for revision procedures.

ARTIFICIAL INTELLIGENCE IN PROSTHETIC DENTISTRY

In order to provide the patient with an ideal aesthetic prosthesis, various factors such as anthropological calculations, facial measurements, ethnicity and patient preferences are integrated by the AI-based virtual prosthetic design assistant. It integrates computational design, knowledge-based systems (ES) and databases, using logic-based representation (AI) as a unifying medium. CAD/CAM application in dentistry is a process by which a finished dental restoration is achieved by a fine milling process of finished ceramic blocks. It is used in the production of inlays, onlays, crowns as well as crowns and bridges. CAD/CAM technique essentially creates two-dimensional and three-dimensional models and their materialization by numerically controlled processing on the machine. This approach replaced the time-consuming and laborious process of conventional casting and reduced the component of human error in the final prosthesis.

ARTIFICIAL INTELLIGENCE IN ORTHODONTICS

Diagnosis and treatment planning can only be determined by analyzing X-rays and photographs with intraoral scanners and cameras. All this is achieved by a virtual dental assistant, which eliminates the need to take impressions of the patient's jaws, as well as several laboratory steps, and the results are much more accurate compared to human perception. Tooth movement and the final treatment outcome can be predicted using AI algorithms and statistical analysis based on ML.

References of the author of this work represent a research contribution to some of the trends mentioned ahead [63–70].

CONCLUSIONS AND FURTHER RESEARCH

ES and AI are research areas in dentistry that are in intensive development, especially in clinical practice. Thanks to the current state of development of machine learning and knowledge engineering techniques, all the conditions have been met to translate clinical procedures of the best diagnostic and treatment practices into virtual dental assistants, as the first stage of development and application of smart dentistry. On the other hand, the aforementioned conditions are created for the development and application of telestomatology or Dentistry 4.0.

The challenges are considerable, but all the previous analyses in this work show that we need multi-disciplinary work, and thus the knowledge of dentists, knowledge engineers, and AI experts.

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Ekspertni sistemi u stomatologiji

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SAŽETAK

Uvod Veštačka inteligencija (AI) danas predstavlja važan činilac društvenog, naučnog i ekonomskog razvoja. Njene široke mogućnosti primene obuhvataju i stomatologiju. Istorija AI duga je oko osam decenija, a posebna oblast njenog istraživanja i razvoja su i ekspertni sistemi, koji su predmet ovog rada, a odnose se na stomatologiju.

Cilj rada je da se analizira stanje razvoja i primene ekspertnih sistema (ES) u stomatologiji, sa predlogom mogućnosti njihove primene danas.

Metode Korišćenjem elemenata sistemske analize, izabran je reprezentativni uzorak članaka sa SCI, Web of Science i Scopus referenci (PubMed/MEDLINE baze podataka), koji su analizirani iz ugla vremenske dimenzije razvoja AI i ES.

Rezultati Rad je strukturisan tako da daje odgovore na sledeća pitanja: Šta je AI i kako se razvijala, kako su nastali i kako su se razvijali ES u stomatologiji, uključujući i Srbiju, šta su perspektive primene AI/ES u stomatologiji, i koji su mogući pravci budućih istraživanja u ovoj oblasti.

Zaključak AI i ES su u oblasti stomatologije iz ere eksperimentalnih istraživanja na granici da postanu dobra klinička praksa. Digitalizacija i model Industrije 4.0, koji su već široko rasprostranjeni, predstavljaju veliku podršku za bržu primenu ovih modela u stomatološkoj praksi.

Ključne reči: veštačka inteligencija; ekspertni sistemi; stomatologija

UVOD

Veštačka inteligencija (AI) je grana nauke o inteligenciji, koja može biti prirodna i veštačka. AI je nauka i inženjerstvo za stvaranje inteligentnih mašina i softverskih sistema. Ove dve oblasti istraživanja su povezane i doprinosile su jedna drugoj tokom prethodnih osam decenija. Uspesi u prirodnoj inteligenciji postavili su čvrste temelje za istraživanje AI: neuronske mreže (ANN), genetski algoritmi (GA) itd., dok su napredni AI alati pomogli da se ubrzaju nova otkrića u prirodnoj inteligenciji [1, 2]. Dakle, postoji istorija AI, duga osam decenija, koja je danas obećavajuća više nego ikad, što se odnosi i na stomatologiju.

Ovaj pregledni rad ima za cilj da čitaocima stavi na uvid osnovne činjenice i znanja o razvoju i primeni ES u stomatologiji. Počeci primene se odnose, pre svega, na AI, koja sama za sebe ima istoriju razvoja, takođe detaljno analiziranu u ovom radu. Zašto? Zato što su ES bili dobra osnova za primenu alata i tehnika AI u stomatologiji, posebno dubokog učenja u poslednjoj dekadi ovog veka. Ovaj rad je namenjen naučnicima, istraživačima i studentima koji žele da dobiju konciznu informaciju o početku razvoja nove naučne grane u stomatologiji, pametne stomatologije.

Ova sistemska analiza je vršena prema metodologiji PRISMA [3], a naša pitanja su bila: Q1. Kako se ES koriste u stomatologiji? i Q2. Kako ES poboljšavaju donošenje odluka o dijagnozi, planiranju lečenja, praćenju napretka lečenja i ocene uspešnosti terapije? Za ova pitanja bili su definisani: vremenski period analize, tip studije, modeli ES, metodologija pretrage i ocena kvaliteta studije. Uzorak je obuhvatio 268 radova, a postavljene kriterijume su zadovoljila 32 rada.

Ovaj rad ima nekoliko celina: (i) kako je nastala i razvijala se AI, (ii) pregled razvoja ES za stomatologiju do danas, uključujući i Srbiju, (iii) izazovi i budući razvoj ES za stomatologiju, (iv) zaključci i buduća istraživanja.

KRATKA ISTORIJA AI

Pre nego što iznesemo detalje o ES u stomatologiji, neophodno je da ukratko analiziramo istoriju AI, koja je prikazana u Tabeli 1 [1, 2, 4]. Ona obuhvata interval od osam decenija (1940–2020. god.) i ima četiri etape razvoja, kako je to navedeno u donjoj tabeli.

Može se reći da istorija AI počinje od ranih 40-ih godina prošlog veka. Počelo je sa binarnim ANN modelom [5] koji su 1943. godine kreirali V. McCulloch i V. Pitts sa Univerziteta u Ilinoisu. Iako je njihov model samo razmatrao binarno stanje (tj. uključeno/isključeno za svaki neuron), ovaj model je korišćen kao osnova za istraživanje ANN-a kasnih 80-ih godina prošlog veka. Godine 1950. britanski matematičar A. Tjuring je predložio poznati Tjuringov test, pomoću koga se utvrđuje da li mašine mogu da misle [6]. Tjuringov test je izvođen putem kompjuterske komunikacije, koja uključuje ispitivača, čoveka (ispitivani), učesnika u eksperimentu i kompjuter, koji su međusobno razdvojeni, ali komunikaciono povezani. Ispitivač može postaviti bilo kakva pitanja. Ako ispitivač ne može razlikovati mašinu od čoveka na osnovu njihovih odgovora, kompjuter je položio test. Godine 1951. M. Minski i D. Edmonds [7], dva diplomirana studenta sa Univerziteta Prinston, napravili su prvi neuronski računar koji simulira mrežu od 40 neurona.

Važna prekretnica u razvoju AI je bio prva radionica o AI, održana 1956. godine na Dartmut koledžu, pod vođstvom J. Makartija [8]. Ova radionica označila je kraj „mračnog doba" AI i početak uspona AI u istoriji veštačke inteligencije. Termin veštačka inteligencija tada je predložio J. Makarti, i on je još uvek u upotrebi. On se kasnije preselio u Masačusetski institut za tehnologiju (MIT), gde je 1958. definisao prvi jezik veštačke inteligencije, LISP, koji se i danas koristi. Jedan od najambicioznijih projekata u ovoj oblasti bio je General Problem Solver (GPS), koji su 1961. godine stvorili A. Njuel i H. Sajmon sa Univerziteta Karnegi Melon [9]. GPS je zasnovan na formalnoj logici i može da generiše beskonačan broj operatora koji pokušavaju da pronađu rešenje; međutim, neefikasan je u rešavanju komplikovanih problema. Godine 1965, L. Zadeh sa Univerziteta u Berkliju objavio je čuveni rad „Fuzzi skupovi“, koji je osnova teorije rasplinutih skupova [10], ili neizvesnog odlučivanja.

Prvi ekspertni sistem, Dendral [11], razvijen je na Univerzitetu Stanford 1969. u okviru projekta koji je finansirala Nacionalna uprava za aeronautiku i svemirska istraživanja (NASA), a vodio ga je Dž. Lederberg, dobitnik Nobelove nagrade za genetiku. Međutim, u to vreme većina projekata AI mogla je da reši samo probleme sa igrama, a ne stvarne probleme, zbog čega su mnogi projekti u Sjedinjenim Američkim Državama, Velikoj Britaniji i nekoliko drugih zemalja propali, odnosno bili beskorisni. Tako su istraživanja AI ušla u tkz. „AI zimu“.

Uprkos smanjenom finansiranju, istraživanja AI su se nastavila, tako da su 1970. god., A. Brajson i Y. Ho [12] predložili model propagacije unazad za učenje neuronske mreže. Štaviše, prvi GA je predložio 1975. god. J. Holand sa Univerziteta u Mičigenu, koji je koristio selekciju, ukrštanje i mutaciju kao genetske operatore za optimizaciju [13] i tako razvio model GA. Isti tim koji je razvio ES Dendral [14] na Univerzitetu Stanford, razvio je 1976. godine MYCIN, koji je zasnovan na pravilima IF–THEN, kao ekspertni sistem za dijagnostiku bolesti krvi pomoću 600 pravila, ako (IF) – onda (THEN). Istraživanja su pokazala da on radi bolje od mlađeg lekara [15].

Posle 30 godina, ponovo su započela istraživanja na neuronskim mrežama, kao važnoj oblasti AI. Počeo je novi period, u kome je AI postala nauka. Bilo je to 1982. godine, kada je J. Hopfild objavio svoje Hopfildove mreže, koje su i danas popularne [16]. Godine 1986, propagacija unazad je postala prvi implementirani algoritam učenja u ANN, 16 godina nakon objave ovog modela [17]. Takođe, ova godina je i početak primene distribuirane AI (DAI) kroz paralelno distribuiranu obradu znanja. Posle 22 godine, teorija rasplinutih skupova ili fuzzi logika uspešno je ugrađena u upravljanje radom mašina za pranje sudova i mašina za pranje veša 1987. god., japanskih kompanija koje su proizvodile ove aparate za domaćinstvo. Godine 1992, J. Koza je predložio genetsko programiranje za manipulaciju simboličkim kodom koji je generisan na LISP jeziku [18]. Bazirani na idejama DAI i veštačkog života, inteligentni agenti su postepeno dobili oblik sredinom 1990-ih. Krajem 1990-ih, hibridni sistemi fuzzy logike, ANN i GA postali su popularni alati za rešavanje složenih problema. Posle toga su se pojavili različiti novi pristupi AI, uključujući ACO, optimizaciju jezera čestica (PSO), veštačku optimizaciju imuniteta (AIO) i DNK računarstvo, kao i inteligentni agenti [19]. Potencijal AI u budućnosti – kao što je stomatologija – ostaje veliki i u ovom trenutku nepredvidiv.

Prvi popularni AI alat bio je softver za igranje šaha, kompjuterski program Deep Blue, koji je kreirala korporacija International Business Machines (IBM) [20]. Gari Kasparov, tadašnji svetski šampion u šahu, igrao je protiv njega 1997. god. u egzibicionom meču i izgubio rezultatom 2,5 : 3,5. Još jedan rani primer je robot Honda ASIMO iz 2005. godine, koji je mogao da se penje stepenicama. Da bi se robot kretao u nestrukturisanom okruženju i njime komandovao čovek, potrebne su sposobnosti obrade prirodnog jezika, računarska vizija, percepcija, prepoznavanje objekata, mašinsko učenje i kontrola pokreta tokom rada. Nedavno, 2016. godine, AlphaGo kompanije DeepMind pobedio je svetskog šampiona L. Sedola u četiri od pet igara, koristeći računarstvo u oblaku, podržano učenjem i Monte Karlo algoritmom za pretragu u kombinaciji sa dubokom neuronskom mrežom za donošenje odluka [21]. Njegova novija verzija, AlphaGo Zero [4, 22], nadmašila je sposobnost AlphaGo-a za samo tri dana kroz samoučenje od nule. Novi iskorak u ovoj oblasti predstavlja inteligentna platforma IBM Watson.

Najnoviji pristup predstavlja ChatGTP, opšta platforma za korišćenje AI u različitim oblastima, uključujući i stomatologiju. Ovo je jedan od budućih pravaca razvoja ove oblasti u stomatologiji.

Danas se tehnike i sistemi AI mogu koristiti u različitim oblastima – od šahovskih partija i upravljanja robotima, preko dijagnoze bolesti, autopilota u avionima, pametnog projektovanja, pa sve do pametne stomatologije. Pored AI tehnika prikazanih u Tabeli 2, mašinsko učenje i duboko učenje pokazuju mnogo toga obećavajućeg za pametnu stomatologiju. Ova tabela klasifikuje tipične modele mašinskog učenja na osnovu toga da li su nadgledani, polunadgledani ili nenadgledani, diskriminativni ili generativni, kao i prema tome da li se odnose na standardno učenje ili duboko učenje. Modeli koji se primenjuju u stomatologiji obojeni su crvenom bojom.

Naime, nadgledano učenje pronalazi relacije između ulaza i izlaza nad označenim skupovima podataka u toku obučavanja sistema. Kod nenadgledanog učenja, model izdvaja realacije, odnosno zakonitosti iz podataka, bez mapiranja ulaza na izlaze. Polunadgledano učenje kombinuje nadgledano i nenadgledano učenje tako što koristi i označene i neoznačene podatke. Pored toga, grana mašinskog učenja koja se naročito ističe po rezultatima poslednjih godina je duboko mašinsko učenje. Uopšteno rečeno, radi se o primeni neuronskih mreža sa većim brojem slojeva. Još jedna klasifikacija koja je vrlo aktuelna poslednjih godina razlikuje diskriminativne i generativne modele. Diskriminativni modeli imaju za cilj da prepoznaju razlike između različitih tipova podataka, odnosno uče koje pojedinosti odvajaju jednu klasu podataka od druge. Generativni modeli pak nastoje da nauče distribuciju podataka i generišu nove podatke [23, 24].

EKSPERTNI SISTEMI U STOMATOLOGIJI – PREGLED RAZVOJA

Ekspertni sistemi (ES) su inteligentni računarski programi koji rešavaju probleme na način na koji to čine eksperti, i predstavljaju jednu od najznačajnijih oblasti istraživanja veštačke inteligencije [1, 4]. Opisani su kao „kompjuterizovano znanje“, a Britansko kompjutersko društvo je definisalo ES potpunije kao: ... stvaranje u računaru komponente zasnovane na znanju iz ekspertske veštine u takvom obliku da sistem može ponuditi inteligentne savete ili doneti inteligentnu odluku o predmetnoj oblasti [23]. ES rešavaju realne probleme iz različitih oblasti, koji bi inače zahtevali ljudsku ekspertizu. Cilj je da računarski program uvek daje korektne odgovore u datoj oblasti, ne lošije od eksperta, ali je to teško dostižno. Zato se postavlja manje ambiciozan cilj, traži se da sistem pruži pomoć u odlučivanju.

ES su odigrali veliku ulogu u razvoju i primeni modela AI (Tabela 3). Međutim, kako pokazuje analiza u donjoj tabeli, na scenu ponovo stupaju nove generacije ES zasnovanih na dubokom znanju.

Ranije je rečeno da je Mysin bio prvi ES koji su koristili lekari [15, 25–29], a u vezi sa tim sve je počelo razvojem prvog

ES – Dendral [14, 11], koji se koristio za rešavanje specifičnog zadatka u nauci: pomoći organskim hemičarima u identifikaciji nepoznatih organskih molekula analizom njihovih masenih spektara, uz korišćenje znanja iz hemije. Softverski program Dendral smatra se prvim ES, jer je automatizovao proces donošenja odluka i definisao ponašanje organskih hemičara u rešavanju problema. Projekat se sastojao od dva programa: Heuristic Dendral i Meta-Dendral i nekoliko podprograma. Napisani su u programskom jeziku Lisp, koji se smatra jezikom AI zbog svoje fleksibilnosti. Mnogi ES su izvedeni iz Dendrala, uključujući MYCIN, Molgen, Prospector, Kscon i Steamer.

MYCIN je bio prvi AI program za pretraživanje unazad, kojim je identifikovao bakterije koje izazivaju teške infekcije, kao što su bakteremija i meningitis i preporučivao antibiotike sa dozom prilagođenom telesnoj težini pacijenta. Sam naziv ovog ES potiče od samih antibiotika, jer mnogi antibiotici imaju sufiks "-mycin". Sistem MYCIN je takođe korišćen za dijagnozu bolesti zgrušavanja krvi. Njegova baza znanja bila je definisana pravilima, a način pretraživanja i povezivanja pravila radi zaključivanja i danas predstavlja primer dobrog modela rezonovanja (od simtoma (posledica) ka uzroku(cima).

Detaljna analiza literature pokazuje da je prvi ES u stomatologiji razvijen za oralnu stomatologiju 1983. god. (Tabela 4) [30]. Bio je to skup softverskih modula koji su se koristili za dijagnozu kliničkih stanja i upravljačkih hipoteza iz baze znanja, koja je razvijena na osnovu relevantnih informacija iz medicinske literature. Ovi moduli su bili: Problem-Knowledge Coupler, Coupler Editor, Mreža znanja i kompjuterizovani medicinski karton orijentisan na probleme. On je sadržavao jedan deo koji se odnosio na oralnu stomatologiju.

Sledeći model je razvijen 1986. god. [31]. Radi se o sistemu zasnovanom na znanju, koji takođe funkcioniše na bazi pravila. Ortodonti su definisali određeni broj karakterističnih tačaka, ili orijentira, na rendgenskom snimku ljudske lobanje koje se koriste za proučavanje rasta ili kao dijagnostička pomoć. Originalna slika je prethodno obrađena operatorom predfiltriranja (medijanski filter), a zatim detektorom ivica (Mero-Vassi operator). Zatim se primenjuje algoritam za praćenje linija zasnovan na znanju, koji uključuje sistem sa organizovanim skupovima pravila i jednostavnim tumačem. U algoritmu zaključivanja primenjuje se apriorno znanje, koje uzima u obzir činjenice bioloških oblika lica, koji mogu značajno da variraju od jednog do drugog pacijenta. Zbog toga algoritam putem pravila uzima u obzir objektivne kriterijume kvaliteta. Ovde se posebno napominje da su prva pozitivna iskustva u primeni ovog ES kasnije iskorišćena, uključujući i današnje vreme, za razvoj naprednih ES u ovoj oblasti.

Primer ES u studiji koju je sproveo Abbey [32] razvijen je za medicinu, ali je imao primenu i u stomatologiji. Ovaj ES je sistem zasnovan na znanju, koji generiše promenljive podatke od pacijenta i povezuje ih sa velikom fiksnom bazom znanja, koja je projektovana tako da obuhvata specifične probleme pacijenta. Rezultati u vidu savetodavnih dijagnoza i planova lečenja na raspolaganju su stomatologu kliničaru i odnose se na oralnu stomatologiju.

Ovaj ES (Orad) koristi Bajesove teoreme za ocenu radiografskog snimka pacijenata sa intrakoštanim lezijama, radi postavljanja dijagnoze [33]. U bazi znanja opisano je 98 lezija vilice, prema njihovoj prevalenci i distribuciji, kao i prema starosti, polu, rasi, prisustvu bola, broju, veličini i lokalizaciji lezija, povezanosti sa zubima itd. Korisnik prati meni od 16 pitanja kako bi se okarakterisala konkretna lezija. ES kao izlaz daje listu lezija poređanih prema procenjenoj verovatnoći. Ispitivanja pokazuju da je ovaj ES koristan kao pomoć kliničarima u formulisanju diferencijalnih dijagnoza.

Korišćenjem programskog jezika za fazzy logiku (FRIL), razvijen je konsultanski ES za ortodonciju [34]. On pomaže stomatolozima opšte prakse da korišćenjem ES ocene stanje oblika zubnog luka kod dece i na osnovu toga ga upute ortodontu za detaljnu dijagnozu i dalje lečenje. Cilj je da mladom pacijentu kasnije pravilno izrastu i budu raspoređeni stalni zubi.

Donošenje odluka u kliničkoj stomatologiji je skopčano sa različitim i velikim brojem uticaja, što posebno važi i za baze znanja kod ES [35]. Iz tih razloga, potrebno je detaljno poznavati modele odlučivanja da bi se doneo pravilni klinički zaključak pomoću ES. Tako je u studiji koju su sproveli McCreery i Truelove [36] prikazana detaljna analiza 11 modela odlučivanja sa najboljom primenom u specifičnim granama stomatologije.

Ortodontski ES za analizu zagrižaja klase II i slučaja 1 prikazan je u studiji koju su sproveli Brown i sar. (1991) [37]. On daje savete ortodontu za definisanje plana lečenja. Prva dekada ES za medicinu su sistemi zasnovani na znanju za dijagnozu i savetovanje lekara u vezi sa planovima lečenja [38]. Smatra se da bi buduća istraživanja u ovoj oblasti trebalo da budu usmerena ka kliničkim problemima. Dijagnoza sa planiranjem lečenja je model ES prikazan u studiji koju su sproveli Grant i Freer [39], u kojoj baza znanja obuhvata 13 različitih modela zagrižaja.

Sistem na bazi znanja prikazan je u studiji koju su sproveli Hammond i Freer [40] i koristi se za ortodontsku analizu i sintezu. Njegova osnovna karakteristika je da se za svaki novi slučaj postojeća baza znanja njime proširi. Poređenjem odluka ES i stomatologa pokazano je da je tačnost ES 88%, što znači da je lošiji od eksperta i njemu se može dodeliti samo konsultantska uloga, ne i konačna odluka.

Kao alat za obučavanje neuronske mreže (NN) korišćeno je 12 različitih modela, na uzorku kliničke istorije od 238 donjih trećih molara (približno istog broja muških i ženskih pacijenta, uzrasta oko 30 god.), sa izlaznim podacima o planovima tretmana oralnog hirurga [41]. Polazeći od zlatnog standarda za ovu oblast (osetljivost 0,8), ES je pokazao osetljivost od 0,78, a oralni hirurg od 0,88 (razlika nije značajna), dok je razlika u specifičnosti još manja (0,98 za ES i 0,99 za oralnog hirurga), što takođe nije značajno. Zaključak je da je moguće obučiti NN da pruža pouzdanu podršku pri definisanju plana lečenja za donji treći molar. Studija koju su sproveli Brickley i saradnici [42] analizirala je odgovore ES, koji se koristi kao konsultant u ortodonciji za planiranje aparata. Inače, radi se o ES na bazi pravila, a rezultati pokazuju da su odgovori ES zadovoljavajući, sa 95% tačnosti.

EIC0-1 ES čini skup pravila (690) pomoću kojih stomatolog ortodont, koristeći model inženjerstva znanja Ripple-Dovn-Rules (RDR), dizajnira i dopunjuje bazu znanja, čime povećava kvalitet odgovora samog ES [43]. Pogodan je za upotrebu na klinici, a posebne koristi od njega mogu da imaju studenti pri usavršavanju i donošenju odluka u planiranju ortodontskog tretmana.

U radu čiji su autori Xie i saradnici [44] prikazan je model za donošenje odluka za ortodontski tretman pacijenata između 11. i 15. godina, kod kojih se utvrđuje da li je potrebna ekstrakcija zuba. Za obuku i donošenje odluka koristi se veštačka neuronska mreža (ANN). Inače, radi se o ES na bazi pravila, a rezultati su pokazali da su odgovori ES zadovoljavajući na uzorku od 200 pacijenata (180 za obuku ANN, a 20 za testiranje). Tačnost je iznosila 100% za obučene slučajeve, a 80% za test primer.

Sledeći primer je pokazao da ES može efikasno da automatizuje stomatološke i administrativne procedure [45]. On koristi dve tehnike AI za rezonovanje i zaključivanje – ANN i fazzy logiku.

Tri veb ES predstavili su Pasaribu i saradnici [46], Kurniawan [47] i Sadik i saradnici [48]. Oni se koriste za pomoć stomatologu pri dijagnozi oralnog zdravlja pacijenta. Zasnovani su na pravilima (AKO –ONDA) u kojima su simptomi i bolesti povezani sa faktorom izvesnosti (CF). Rezultati su pokazali 99% tačnosti njegove dijagnoze u poređenju sa dijagnozom stomatologa specijaliste. Model za dijagnozu oralnog stanja pacijenata kojima je potrebno hirurško lečenje [49] zasnovan je dijagnostici pomoću radiografskih snimaka. Tačnost ovog prediktivnog modela postiže se dubinom CNN, što je eksperimentom i pokazano. Skrining je obuhvatio 960 pacijenata, a korišćeni su modeli ResNet-18, 34, 50 i 101, pri čemu su ocenjivani tačnost, osetljivost i specifičnost svakog modela. ResNet-18 je imao najbolje performanse sa površinom ispod krive od 0,979, zatim ResNets-34, 50 i 101 sa vrednostima 0,974, 0,945 i 0,944, respektivno.

AI i mašinsko učenje (ML) sve se više primenjuju u oblastima ortodontske dijagnoze, planiranja lečenja, procene rasta i predviđanja ishoda lečenja [50, 51]. Analiziraju se sledeći algoritmi ML: Bejsov model (podrška oceni rizika u dijagnozi), NN (dijagnoza analizom snimaka), mašina vektora podrške (MVP) (koristi se za prepoznavanje skeletnih uzoraka), genetski algoritam (GA)(koristi se za trendove predviđanja stanja na osnovu dijagnoze), fazzy logika (FL) (koristi se za definisanje linije rezonovanja u skupovima gde nisu determinisana stanja). Iz ovih modela se danas razvijaju modeli dubokog učenja (Deep ML), koji će se u bliskoj budućnosti i jedino primenjivati, kao podrška stomatolozima.

Studija Prasada i saradnika [52] prikazala je inteligentni model zasnovan na CNN za duboko učenje, za automatsku identifikaciju orijentira na licu pacijenta (ukupno 13), analizom radiografskih snimaka, a u vezi sa nepravilnim položajima vilica i dijagnozom takvog stanja. Uzorak je obuhvatao 950 pacijenata, a uz pouzdanost od 95% dobijeni su odlični rezultati, zbog čega se ovaj metod preporučuje i za kliničku praksu.

Može se konstatovati da je primena AI u stomatologiji još uvek u ranoj fazi razvoja [53, 54]. Međutim, perspektive ove tehnologije su velike za dijagnozu, planiranje lečenja, praćenje oporavka, upravljanje pacijentima i administrativne poslove. Posebni pomaci se očekuju u CAD/CAM modeliranju, implantologiji, kao i u robotskoj oralnoj hirurgiji. Analiza u studiji koju su sproveli Tam-Nurseman i saradnici [55] pokazuje da u stomatologiji nekoliko simptoma nije dovoljno za dijagnozu, pa su iz tih razloga primenjena Bajesova pravila, koja omogućuju povezivanje (rangiranje i korelaciju) više simptoma za jednu dijagnozu. Iz ovih razloga je razvijen unapređeni model Bajesovih pravila, koja su pokazala dobre rezultate u definisanju dijagnoze, sa više istovremenih simptoma.

Dijagnoza i planiranje lečenja su srž ortodoncije, koju ortodonti dobijaju višegodišnjim iskustvom [47]. Mašinsko učenje (ML) ima sposobnost učenja prepoznavanjem obrazaca, a to postiže u veoma kratkom roku, smanjujući verovatnoću greške u zaključivanju i isključujući varijabilnost zaključivanja među kliničarima, kao i dobru tačnost. U ovoj studiji je na uzorku od 700 pacijenata, korišćenjem četvoroslojne CNN, postignuta tačnost od 97% [52, 56]. Sve ovo se odnosilo na dijagnozu i plan lečenja u ortodonciji. Automatizovana cefalometrijska analiza je jedna od glavnih oblasti primene AI u oblasti ortodoncije. WebCeph ES vrši određivanje linearnih i ugaonih cefalometrijskih orijentira, dobijenih na veb bazi potpuno automatizovanim merenjima ovih parametara pomoću ove platforme. Rezultati istraživanja pokazuju da je dobijena potpuna saglasnost između merenja ručnim putem i pomoću ovog ES, na uzorku od 30 pacijenata.

Sistematski pregled [57, 58] analizira različite strategije koje koriste AI u poboljšanju dijagnoze, planiranja i praćenja lečenja u ortodonciji. Analizirani su radovi u intervalu od 10 godina, a ukupno su obuhvaćene 33 studije. Rezultati pokazuju da AI sve više postaje deo kliničke prakse, a posebno model dubokog učenja. Pregledni rad Prasada i saradnika [52] takođe daje analizu primene AI u ortodonciji u oblastima dijagnostike, cefalometrijske ocene, određivanja starosti zuba, temporomandibularne ocene vilica (TMJ), donošenja odluka o planu lečenja i daljinskog praćenja pacijenata (Stomatologija 4.0). Međutim, u kliničkoj primeni, još uvek, validaciju rešenja mora da uradi ekspert stomatolog.

Kao zaključak ove analize možemo da konstatujemo sledeće: (a) ES u stomatologiji su istraživački pravac već četiri decenije, i za to vreme su od pojedinih istraživačkih ideja došli do važne naučnoistraživačke prakse, sa perspektivom u kliničkoj stomatologiji, (b) ES se danas smatraju dobrom praksom primene AI u stomatologiji, i (c) duboko učenje iz nestrukturisanih baza podataka je najbolji metod današnje primene ES (AI) u stomatologiji.

EKSPERTNI SISTEMI ZA STOMATOLOGIJU U SRBIJI

Sa velikim zadovoljstvom možemo istaći da se na Stomatološkom fakultetu u Beogradu, na Klinici za protetiku, ozbiljna istraživanja u ovoj oblasti rade od početka poslednje decenije prošlog veka, pa sve do danas [59–62]. Sve to je rezultiralo i prvim ES za stomatologa protetičara u Srbiji. On je bio sistem zasnovan na pravilima (pravila AKO–ONDA), a baza znanja je imala 120 pravila. Pretraživanje baze znanja je bilo po modelu pretraživanja unapred, od simptoma ka dijagnozi. On je bio eksperimentalno-laboratorijskog karaktera, a kasnije su ta znanja iz njegovog razvoja poslužila u širokoj primeni CAD/CAM sistema na ovoj klinici, kao i drugim klinikama Stomatološkog fakulteta u Beogradu.

EKSPERTNI SISTEMI I VEŠTAČKA INTELIGENCIJA U STOMATOLOGIJI – ŠTA DALJE

Virtuelni stomatološki asistenti zasnovani na AI mogu da obavljaju nekoliko zadataka u stomatološkoj praksi sa većom preciznošću, manje grešaka i manje radne snage u poređenju sa ljudima [51, 52, 53]. Mogu da se koristiti za koordinaciju zakazivanja termina, upravljanje osiguranjem i papirologijom, kao pomoć u kliničkoj dijagnozi ili planiranju lečenja. Veoma su korisni da upozoravaju stomatologa o istoriji bolesti, kao i navikama poput alkoholizma i pušenja. U hitnim stomatološkim slučajevima, pacijent ima mogućnost hitne teleasistencije, posebno kada je stomatolog nedostupan. Tako se može kreirati detaljna virtuelna baza podataka o pacijentu, koja će mnogo pomoći u pružanju idealnog tretmana za samog pacijenta.

VEŠTAČKA INTELIGENCIJA U DIJAGNOZI I LEČENJU

AI se može koristiti kao efikasan pristup u dijagnostici i lečenju lezija usne duplje, kao i u skriningu i klasifikaciji sumnjivih promena sluzokože, koja prolazi kroz premaligna i maligna stanja. Detektuju se čak i sitne promene na nivou jednog piksela koje mogu ostati neprimećene golim okom. AI može tačno predvideti genetsku predispoziciju za oralni karcinom na nivou velike populacije.

VEŠTAČKA INTELIGENCIJA U ORALNOJ I MAKSILOFACIJALNOJ HIRURGIJI

Najveća primena veštačke inteligencije u oralnoj hirurgiji jeste razvoj robotske hirurgije, u kojoj se simulira kretanje ljudske ruke i ljudska inteligencija. Uspešna klinička primena u hirurgiji vođenom slikom u predelu lobanje obuhvata hirurgiju oralnih implantata, uklanjanje tumora i stranih tela, biopsiju i operaciju vilica. Uporedne studije oralne implantološke hirurgije ukazuju na znatno veću tačnost u poređenju sa ručnim zahvatom slobodnom rukom, čak i ako ga izvode iskusni hirurzi. Dobija se kraće trajaje operacije, sigurnija manipulacija oko delikatnih struktura i veća intraoperativna preciznost. Robotska operacija vođena slikom omogućava temeljniju hiruršku resekciju, što potencijalno smanjuje potrebu za revizionim procedurama.

VEŠTAČKA INTELIGENCIJA U PROTETSKOJ STOMATOLOGIJI

Da bi se pacijentu pružila idealna estetska proteza, virtuelni asistent dizajna za upotrebu u protetici na bazi AI integrisao je različite faktore poput antropoloških proračuna, merenja lica, etničke pripadnosti i preferencija pacijenata. On integriše kompjuterski dizajn, sisteme zasnovane na znanju (ES) i baze podataka, koristeći logički zasnovanu reprezentaciju (AI) kao objedinjujući medijum. Primena CAD/CAM tehnologije u stomatologiji je proces kojim se postiže gotova dentalna restauracija finim procesom glodanja gotovih keramičkih blokova. Koristi se u proizvodnji inleja, onleja, krunica i mostova. CAD/CAM tehnika u suštini stvara dvodimenzionalne i trodimenzionalne modele i njihovu materijalizaciju numerički kontrolisanom obradom na mašini. Ovaj pristup je zamenio dugotrajan i naporan proces konvencionalnog livenja i smanjio komponentu ljudske greške u finalnoj protezi.

VEŠTAČKA INTELIGENCIJA U ORTODONCIJI

Dijagnoza i planiranje lečenja mogu se utvrditi isključivo analizom rendgenskih snimaka i fotografija intraoralnim skenerima i kamerama. Sve ovo se postiže virtuelnim stomatološkim asistentom, čime se eliminiše potreba za uzimanjem otisaka vilica pacijenta, kao i za nekoliko laboratorijskih koraka, a rezultati su mnogo tačniji u poređenju sa ljudskom percepcijom. Pomeranje zuba i konačni ishod lečenja mogu se predvideti korišćenjem algoritama AI i statističke analize na bazi učenja (ML).

Ovde svakako treba dodati i neke reference autora ovog rada koje predstavljaju istraživački doprinos nekim od trendova opisanih u prethodnim delovima teksta [63–70].

ZAKLJUČCI I DALJA ISTRAŽIVANJA

ES i AI su istraživačke oblasti u stomatologiji koje se intenzivno razvijaju, posebno u kliničkoj praksi. Zahvaljujući današnjem stanju razvoja mašinskog učenja i tehnika inženjerstva znanja, stekli su se svi uslovi da se kliničke procedure najbolje prakse dijagnostike i lečenja prevedu u virtuelne stomatološke asistente, kao prvu fazu razvoja i primene pametne stomatologije. Sa druge strane, time se stvaraju uslovi za razvoj i primenu telestomatologije ili Stomatologije 4.0.

Izazovi su veliki, ali sve prethodne analize u ovom radu pokazuju da nam je potreban multidisciplinaran rad, a time i znanja stomatologa, inženjera znanja i eksperata za AI, što ovaj rad i pokazuje.