Biomaterials Journal
http://www.biomatj.com
Online ISSN: 2812-5045

Type of the Paper (Review Article)

Artificial Intelligence In Dentistry

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Citation: *Salma K.Rizk . Artificial Intelligence In Dentistry . Biomat. J., 2 (2),29 – 45 (2023).*

https://doi.org/10.5281/znodo.5829408

Received: 10 February 2023
Accepted: 20 February 2023
Published: 28 February 2023

Abstract: The term "artificial intelligence" (AI) refers to the idea of machines being capable of performing human tasks. It describes how technology is used to develop a software or a machine that can easily mimic human intelligence and perform specific activities. John McCarthy, a mathematician coined the term artificial intelligence in 1955, and widely recognized as the father of artificial intelligence. He chose this term to explain the potential of machines to perform tasks that can fall in the range of "intelligent" activities. In the following review article different applications of artificial intelligence in dentistry, achievements, limitations and challenges will be discussed.

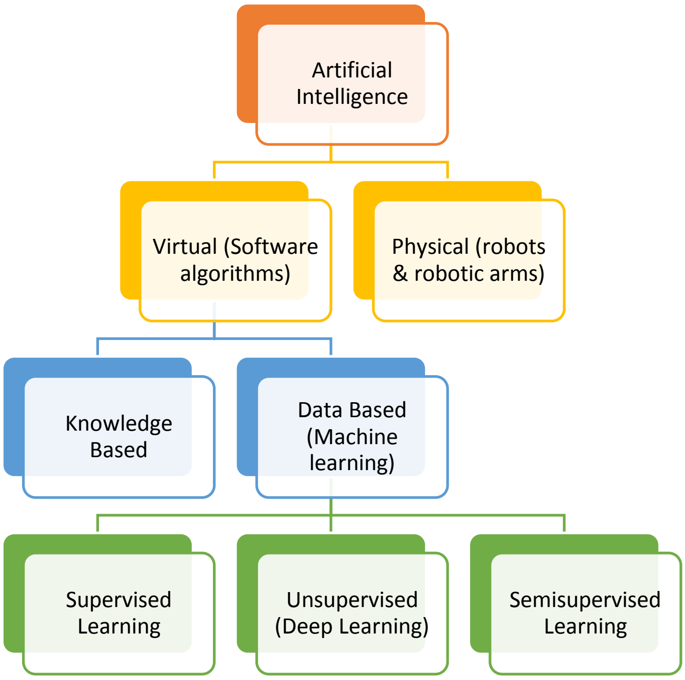
Keywords: *Artificial intelligence, applications of AI & Dental AI*

I. Introduction to artificial intelligence

The term "artificial intelligence" (AI) refers to the idea of machines being capable of performing human tasks. It describes how technology is used to develop a software or a machine that can easily mimic human intelligence and perform specific activities. (1, 2)

John McCarthy, a mathematician coined the term artificial intelligence in 1955, and widely recognized as the father of artificial intelligence. He chose this term to explain the potential of machines to perform tasks that can fall in the range of "intelligent" activities.(3)

AI is a branch of applied computer science that provides machines with the ability to mimic intelligent human behavior. Two types of AI are available for general health care delivery: **physical** and **virtual.** Physical applications are represented by sophisticated robots or automated robotic arms.Virtual components are software-type algorithms that support clinical decision making. (4)



Attempts at implementing AI were initially based on the assumption that human intelligence can be fully digitized and integrated into machines.

In dentistry, the applications of AI are mostly virtual, employing AI algorithms to distinguish between lesions and normal structures, prioritize risk factors, and simulate and evaluate prospective results. Virtual AI methodologies are divided into **knowledge-based** and **data-driven** AI according to the Barcelona Declaration for the Proper Development and Usage of Artificial Intelligence in Europe. (4)

Knowledge-based AI attempts to model human knowledge and is built in a top-down fashion from the self-reported concepts and knowledge that humans use to solve problems. However, knowledge acquisition and formalization are 2 major bottlenecks, which consume development time and require significant initial effort. (4)

Conversely, **data-driven AI**, commonly known as **machine learning** (ML), built in a bottom-up approach by training mathematical models with data derived from human activities. Because of the large amount of dental data available in electronic form, data-driven AI receives a lot of attention in dentistry. (4)

Data-driven AI or ML may be divided as supervised, unsupervised, and semisupervised learning. On **the supervised** platform, algorithms employ manually labeled training data sets to learn the correlations between data instances and labels, yielding the desired and known outcomes. It is defined by its use of labeled datasets to train algorithms to **classify data or predict outcomes** accurately. It is frequently mentioned that supervised learning is limited by the lack of annotated data. (4)

Examples:

- **Support vector machines** (SVMs) set up an imaginary high-dimensional space, place samples according to their features, and separate them by a hyperplane, resulting in data classification.
- **Decision tree (**DT) a hierarchical data structure used for classification.
- **Random forest** (RF) combines the output of multiple decision trees to reach a single result. It handles both classification and regression problems.
- **Artificial neural network** (ANN) is an attempt to simulate the network of neurons that make up a human brain so that the computer will be able to learn things and make decisions in a human like manner. ANNs are created by programming regular computers to behave as interconnected brain cells. The greatest advantage of these systems is that they have capability to solve the problems that are too complex to be solved by conventional methods. They are useful in various areas of medicinal science like diagnosis of diseases, biomedical identification, image analysis and data analysis. In dental practice also the clinical support systems are actively progressing.

A study done by Kim et al. used Artificial neural network to build a model that can predict toothache on the basis of association between toothache and daily toothbrushing frequency, toothbrushing time, use of dental floss, toothbrush replacement pattern, undergoing scaling and other factors like diet and exercise. This successful study aided in the development of a **toothache predictive model** with great accuracy. This model recognizes adequate eating habits, oral hygiene, and stress prevention as the most important factors in preventing toothaches.(5)

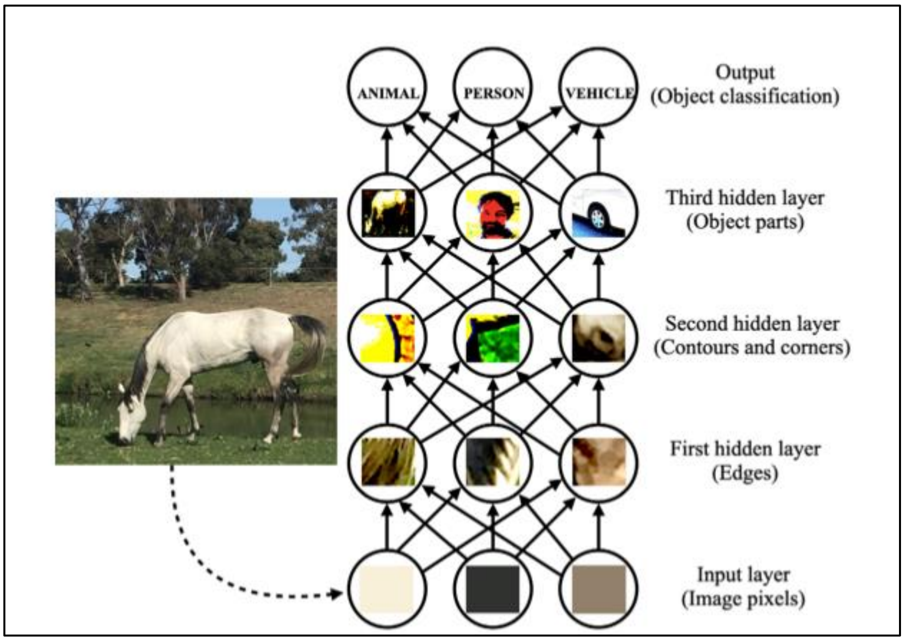


Fig 1: an artificial neural network for object identification

Unsupervised learning uses machine learning algorithms to analyze and cluster unlabeled datasets. These algorithms discover hidden patterns or data groupings without the need for human intervention, yielding unknown results.

- **Deep neural networks**, commonly known as deep learning (DL), is a subset of ML that can be operated in unsupervised scenarios. The term “deep” refers to multiple neural layers between the input and output layers. **Convolutional neural networks** (CNNs) are the most widely used DL architecture in dentistry, employing a convolutional process to learn features contained within data. The purpose of deep learning is **to construct a neural network that automatically identifies patterns to improve feature detection.** Unsupervised learning has also been criticized for failing to identify the initial pattern.

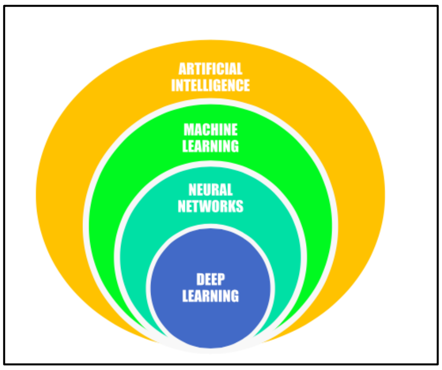


Fig 2: Key aspects of artificial intelligence(2)

Semisupervised learning is an amalgamation of supervised and unsupervised learning that analyzes a collection of data while augmenting the pattern recognition abilities with a small amount of labeled data. (4)

Smart and Intelligent Materials

Smart materials are **materials that are manipulated to respond in a controllable and reversible way by modifying some of their properties as a result of external stimuli** such as certain mechanical stress or a certain temperature.(6)

Smart materials have the ability to perceive and respond but not to self-optimize and improve, whereas intelligent materials perceive and analyze to summarize the experience and adapt to optimize the responsive performance.

Intelligent material is self-aware, and responds purposefully. intelligent materials should have the ability to be aware of external stimuli and learn from it to optimize response behaviors for achieving goals to the greatest extent. (7)

II. Applications of Artificial Intelligence in Dentistry

Two types of AI are available for dental health care delivery: **physical** and **virtual.** Physical applications are represented by sophisticated robots or automated robotic arms.Virtual components are software-type algorithms that support clinical decision making.

A) Applications of Virtual AI in dentistry:

i. Diagnosis:

Oral and Maxillofacial lesions. Machine learning algorithms, including SVM, ANN, RF, have been experimentally investigated for their ability to identify cysts, benign tumors, oral cancer, and lymph node metastasis.(4)

- Yilmaz et al. 2017 found that CBCT with SVM was 94% accurate in differentiating periapical cysts from keratocystic odontogenic tumors.(8)
- Sunny et al. 2019 Utilized CNN to score the malignancy of cytology images derived from a telemedicine platform, this model showed high sensitivity in detecting oral malignant (93%) and high-grade potential malignant (73%) lesions. (9)

Despite these excellent results, contemporary AI models for oral and maxillofacial surgery diagnosis focus on only 1 type of data, such as radiographic results or cytopathologic images. For highly accurate diagnosis, models that integrate more medical information about the patient are required.

Cariology and Endodontics. With the ability to perform automated lesion segmentation, Deep Learning with CNN has become the predominant AI component used in cariology and endodontic diagnostics. The segmentation process divides radiographs or images into multiple non overlapping regions using sets of rules, such as similar pixels or intrinsic features, to convert them into a meaningful form that can be conveniently analyzed. A number of studies have explored automated detec- tion of periapical radiolucencies using either panoramic radiographs or CBCTs. Computer vision and neural networks facilitate interpretation of CBCTs at a level uninterpretable to human vision. Early detection of periapical lesions might prevent complications and improve patient outcomes. (4, 10)

Deep Learning segments CBCT voxels into lesion, tooth structure, bone, restorative materials, and background, achieving results comparable to those of clinicians in diagnosing periapical lesions.

Focusing on the binary presence or absence of lesions. Volumetric measurement in CBCT, following DL-based segmentation, was reported to be comparable to the results obtained from manual segmentation of periapical lesions.(4,18)

Periodontics. Although periodontal disease is a complex inflammatory disease contributed by multiple causal factors simultaneously and interactively. Focusing on periapical radiographs, CNN achieved 81.0% and 76.7% accuracy in diagnosing periodontally compromised premolars and molars. However, due to the hysteresis of imaging characteristics and the visual field of periapical radiographs, this technique cannot distinguish incipient lesions or make a final diagnosis of periodontal disease. (4,22)

DT and SVM performed well in classifying healthy periodontium, gingivitis, chronic periodontitis, and aggressive periodontitis by integrating a patient's medical history, clinical information, and radiographs.

Temporomandibular Joint Disorder. Clinical clues from a patient's complaint and history are important for diagnosing temporomandibular joint disorders (TMDs). Natural language processing is a technology that transforms natural human language into structured computer language. A natural language processing–based model was successful in differentiating TMD-mimicking conditions from genuine TMDs, according to the frequency of word usage in the patient's chief complaint and mouth-opening size. (4,23)

ii. Treatment:

Prosthodontics. Integrating AI with CAD/CAM improves its chair-side application. ANNs based on panoramic radiographs, periapical radiographs, micro–computed tomography images, and 3-dimensional scanning of dental surfaces have been explored for tooth segmentation and classification. With >90% accuracy, such automatic classification is instrumental for bridging the gap between data acquisition and manufacturing in CAD/CAM technology. (4)

3D printing

Dental research has expanded the scope of 3D printing to a wide range of applications including surgical guides, orthodontic brackets and metal framework for removable partial dentures. Researchers are exploring methods to further improve dimensional accuracy of 3D printing, one of which is the implementation of ML algorithms to **learn** shape deviations from past printing jobs, **predict** shape distortions and **compensate** for these deviations in future printing jobs. This has the potential to reduce costs, time and the number of visits required for accurate fitting. (4)

B) Applications of physical AI in dentistry:

Dentronics is a hypernym of the range of advanced dental technologies, including medical robotics and artificial intelligence.

Robotics is an interdisciplinary field that integrates computer science and engineering. Robotics is defined as the "intelligent connection between perception and action". by artificial intelligence, robots are able to reason about current situations and new events in order to adapt to new circumstances autonomously. The inherent advantages of robots are their high accuracy and precision, high work efficiency, and stability.

1. Robots in Implant & Maxillofacial Surgeries.

- **Robots in implant surgeries:**

The development of computer-assisted implant surgery based on the concept of prosthetic-driven implantology and CT-scan analysis have been reviewed.

A surgical robotic application is an invasive robotic assistant for dental implantology. It was permitted for operative use by the FDA (Food and Drug Administration) in March 2017. The product is called ***Yomi*** and is produced by *Neocis* (Neocis Inc., Miami, USA). Based on 3D- data from a CT the dentist plans the implant position. During surgery the robotic arm drills the hole in the jawbone and places the implant according to the planning while the dentist can follow the position of the bur in real-time, owing to the software, which allows the dentist to adjust placement position of the implant intraoperatively.(3)

Robotic-Guided Dental Implant Placement in Fully Edentulous Patients was done using yomi robots. A total of 58 implants were placed in 11 arches in 8 patients. Intraoperative outcomes captured included safety, efficacy, surgical time, and a Likert scale evaluation of user experience. No adverse events were reported, and user experience was rated highly with respect to the standard of care. First cases using Yomi robotic guidance in fully edentulous patients were notable for brief procedural times, compati- bility with minimally invasive soft tissue management and access to immediate loading of restorations for candidate patients. (11)

Other industrial robot systems (MELFA RV-3S, Mitsubishi Electric Corporation, Tokyo, Japan). Those robots have six degrees of freedom (DOF), a position repeatability of ±0.02 mm and showed an error of 1.42 ± 0.70 mm were also used in studies describing robot-assisted implant placement.(12)

- **Robots in Maxillofacial Surgeries.**

A lot of systems have been proposed comprising surgical robots with optical surgical navigation systems and some kinds of hard tissue lasers that are able to automatically perform an osteotomy operation according to a preformed surgical plan. During the operation, the robot is proposed to register patient movements by real-time tracking. Robotic surgical techniques are being used for milling of bone surfaces, drilling of holes, deep sawing osteotomy cuts, selecting osteosynthesis plates, bending and intraoperative positioning in a defined position, and orthognathic surgery planning.(13)

Advantages:

- Minimize human-related factors such as reduced concentration, trembling, distraction or reduced vision that affect the accuracy and safety in maxillofacial surgery.
- Enabled drilling of complex forms of dental implants thus enhancing flexibility in prosthetic rehabilitation in patients with reduced bone supply.

2. Robots in orthodontics:

- **Wire Bending and Customized CAD/CAM Appliance Robotics.**

Accurate arch wire bending is a key technology for fixed orthodontic treatment. Compared with the traditional manual bending system, the accuracy and efficiency of arch wire bending can be improved by using the robot with its precise posture control ability.

Different types of arch wire bending robots have been proposed in the last decade including the **Motoman** UP6 robot, optimizing bending process and properties, **LAMDA system** (Lingual Arch wire Manufacturing and Design Aid), bending only 1st-order bends in the XY plane, **Cartesian type** arch wire bending robot using the third-order and **arch wire bending robot** that could change the pincer automatically as needed . (13)

Moving on to the customized CAD/CAM full appliances including customized brackets and wires manufactured by robots, clinical outcomes were assessed in terms of effectiveness and efficiency in different CAD/CAM systems in comparison to conventional approaches, showing premise in improving or at least achieving similar outcomes to conventional appliances, it also **reduced overall treatment duration**. (14, 15)

- **Robotics in Automated Aligner Production.**

In 2011, Hilliard patented a robotic system for forming features in orthodontic aligners, including a control system, a platen for three-dimensional positioning of the aligner, a heating station for selectively heating a small region of the aligner, and a thermoforming station for manipulating the heated region to form a desired feature in the aligner. The control system can include a processor with CAD software to enable a user to design features for aligners. The present invention enables an automated process for installing activation features and other types of features needed for polymeric shell orthodontic aligners to receive auxiliary devices that serve to expand their usefulness, range, and duration of application. (13)

3. Rehabilitative Robots in Management of TMD.

Massaging robots and mouth training robots have been proposed for the implementation of safe and effective maxillofacial massage and exercises to treat patients with myofascial pain and limited mouth opening by decreasing muscle stiffness significantly. Suitable treatment regimens have been discussed and evaluated, reaching an efficacy of 70.3%. (13)

Different designs were suggested including shoulder- mounted robotic exoskeleton for better esthetics and portability, incorporating visual feedback into therapy routines to promote active participation with safety design considerations. Assisted motion of the jaw using EMG- based feedback systems accurately tracking the progress of a patient over time. (16)

4. Nano-/Microrobots

- **Nanorobotic Dentifrice (Dentifrobots).**

Subocclusal dwelling nanorobotic dentifrice delivered by mouthwash or toothpaste could patrol all supragingival and subgingival surfaces, performing continuous calculus debridement. with catalytic-ability to destroy biofilm so it is used for prevention of tooth decay or peri-implant infection.

These invisibly small dentifrobots would be inexpensive, safely deactivating themselves if swallowed, and would be programmed for better cleaning of the teeth.

- **Nano-sensors for Remote Monitoring of Removable Appliance Wear.**

Monitoring of Obstructive Sleep Apnea Oral Appliance Compliance. Sleep apnea monitoring devices are being developed for diagnostic and treatment applications. These can be a safe, reliable, effective, feasible, and affordable option to monitor a person's sleeping patterns and to objectively measure compliance in wearing the OSA oral appliances.

Monitoring of Compliance of Active and Passive Removable Appliance Wear. Compliance in removable appliance wear is a highly variable, multifactorial issue that requires objective measures to be safely addressed in research designs and in clinical practice. Electronic microsensors, such as the **Smart Retainer** and the **TheraMon** proved to be reliable and accurate enough to measure wear time of removable orthodontic appliances by identifying temperature changes, which are then transformed to wear time information. Moreover, they provide the basis for more individualized wear time recommendations for patients with removable appliances, resulting in a more efficient, shorter, and less painful orthodontic therapy. (17)

5. *Robots for Tooth preparation*

Tooth preparation for crowns and bridges is a routine task for dentists, even though it is still challenging. The challenge is to reduce the tooth sufficiently to create space for the prosthetic rehabilitation with a minimum of damage to sound tooth structure.

A mechatronic system to support the dentist in drilling has been tested in vitro and showed good results. The dentist‘s position accuracy was 53% better with the mechatronic system than without it. Yet, it has not been validated in a clinical setting.(18)

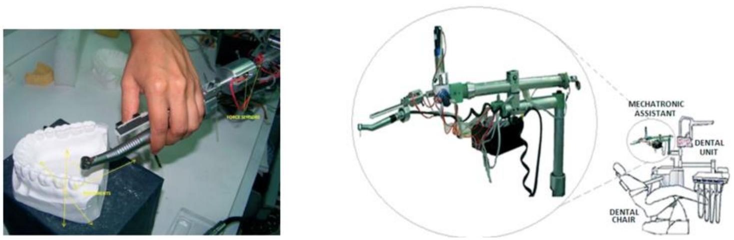


Fig 3: Mechatronic system attached to drill & Mechatronic system attached to dental unit

Yuan et al. described a robotic tooth preparation system with the following hardware components: (19)

- An intraoral 3D scanner to obtain the 3D data of the patient's target tooth, adjacent teeth, opposing teeth and the teeth fixture.

- Computer-aided design (CAD)/computer-aided manufacturing (CAM) software for designing the target preparation shape and generating a 3D motion path of the laser
- An effective low-heat laser suitable for hard tissue preparation.
- 6 DoF robot arm
- A tooth fixture connecting the robotic device with the target tooth and protecting the adjacent teeth from laser cutting.

The developed robotic device achieved precise 3D motion control of a laser focal point and is small enough to be used in the narrow workspace of the oral cavity. which can meet the requirement of typical dental operations.

Another tooth preparation system for veneers with a rotating diamond instrument mounted on a robotic arm was compared to human hand crown prep in an invitro study and showed better results than the tooth preparation carried out by the dentist.(19)

6. Robots for Root Canal Treatment.

Root canal treatment is a procedure which is based on high accuracy. Usually, a dentist specialized in endodontics works using magnification to assure adequate view of the root canal.

Nelson et al. published the idea of a **robotic system for assistance** during root canal treatment. The so-called "**vending machine**" was supposed to supply the dentist with the necessary root canal instruments during treatment in order to reduce deflection from the operating site. (21)

7. Educational robotics

A humanoid full-body patient simulation system **(SIMROID**) is standing 165 cm tall. It comes with a metal skeleton and vinyl chloride-based gum pattern of skin.It was tested in a study among dental students to find out whether a robotic patient was more realistic for the students to familiarize with real patients than the usually used dummies.

The "**Hanako**" is an interesting contribution to education in dentistry as it imitates human in its actions and expressions. It can verbally express pain, roll its eyes, blink, shake its head in pain, perform movements of jaw, tongue, elbow and wrist. It can even simulate a vomiting reflex with a uvula sensor, and also simulate functions to induce bleeding and saliva flow.

A haptic-based tooth drilling simulator was introduced for dental education with an implemented collision detection system to give force sensation to the user and make the virtual reality (VR) experience more realistic. Moreover, haptic devices for training of dental implant placement or oral anesthesia

It was found that best learning of dental basic motor skills in trainees receiving a combination of VR training with haptic feedback and human instructor verbal feedback.

The **ROBOTUTOR** is robotic educational equipment. That was was developed as an alternative to a clinician to demonstrate tooth-cleaning techniques to patients. It is a robotic device to train and show brushing techniques. A study among patients showed that the ROBOTUTOR was the most attractive method according to patient evaluation or dental health care education compared to other methods (clinician or video audio tutorial).

8. X-ray imaging robots

Positioning of the film/sensor and the X-ray source was proposed to be executed by a 6 Degree of Freedom robotic arm and was found to have no adverse effects. Results showed that the robotic system was superior to the mechanical alignment approach, due to its excellent accuracy and repeatability.(4)

9. Robotics in tissue engineering

In an attempt to improve conventional tissue culture methods and expand them to large-scale manufacturing, advanced robotics are used in manufacturing. Not only could robotic manufacturing produce a larger scale of cells without the need for training personnel, but fabrication could be performed in a closed system, reducing the risk of contamination and thus further saving costs by eliminating the need to discard contaminated cells.

Moreover, using machine learning algorithms and imaging techniques, manufacturing robots could be trained to identify cells in a culture that have successfully undergone genetic modification or differentiation and then isolate them, thus improving the efficiency of stem cell-derived cells for tissue engineering. (24)

III. Achievements of AI in dentistry

- Assists the clinicians so they can offer **high-quality dental care** to their patients.
- Dentists can use AI systems as an **ancillary tool for increasing the accuracy** of diagnosis, treatment planning, and predicting the treatment outcomes.
- Non-specialty dentists can receive **diagnostic support** via the deep-learning systems.
- Automated systems can save a lot of **time** and increase the **efficiency** of the clinicians
- The use of these systems for **secondary opinions** can improve the accuracy of diagnosis. (2)

IV. Limitations and Challenges

- **Data Acquisition**
  - Insufficient data
  - The lack of information on data processing & measuring
  - Sample size used for training and testing as well as the information for reference and comparative tests are deficient & sometimes unclear.

It is necessary to improve data quantity, quality, and readability by standardizing methodology in data reporting. Establishing an open-access standard data base, which contains comprehensive demographic, clinical, experimental, and treatment data, would be a crucial task in the next stage of AI development to facilitate evaluation and comparison of different algorithms. (4)

- **Interpretability**

Data-driven AI calculates output in a purely computational manner; however, it fails to illustrate the decision-making process in a medically acknowledgeable format. The lack of interpretability and transparency reflects the black-box nature of many ML approaches.

Interpretability matters for 2 reasons. First, ensuring that the algorithm is a reasonable interpretation of medical incidents is important for the **rapport between technology and humans**. Failure to explain the inner working will inevitably disrupt practitioners' trust in the clinical value of AI.

Second, the lack of transparency and interpretability makes it difficult to predict failures and generalize specific algorithms for similar contexts. (4)

Computing Power

Extracting information from constantly updating medical and dental databases for the application of AI requires continuous upgrading of processing power. Because the computational power of classical computers has been largely saturated, the insufficient computational resources in data processing have become one of the obstacles that constrain the efficacy of AI. (4)

Ethical Considerations

Development of AI should ensure that such intelligent technologies do no harm to humans. Incorporating AI into health care would inevitably replace some established services and potentially exacerbate current health inequalities. These ethical paradoxes emphasize the need to establish clear guidelines for the manner in which AI is applied clinically.

Judgment of legal responsibility is another ethical dilemma. At present, AI is not accountable. The physician takes total responsibility for each patient and for how information is used. Applying the same social and ethical norms acceptable to humans is inappropriate when the border of human responsibility is increasingly blurred by the advent of chatbot-based, unsupervised AI–based diagnosis. (4)

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