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Application of Artificial Intelligence in Predicting the Success of Dental Implant Treatments Using Deep Learning

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Abstract

AI has a variety of applications in dental implants that generally lead to increased accuracy, reduced treatment time, and improved quality of results. These applications include digital scanning, computer-aided surgical planning, and the manufacture of high-precision custom prostheses. Specific AI Applications in Dental Implants Digital Scanning and AI Impressions allow dentists to create accurate 3D models of a patient's mouth using digital scans. These models are used to design and manufacture high-precision custom implants and prostheses, eliminating the need for traditional impressions. Computer-aided Surgical Planning Using AI, implant surgery is planned more accurately. AI-based software can determine the ideal implant position based on the patient's oral anatomy and help the dentist choose the best angle and depth of implantation. Custom implant and prosthetic manufacturing AI allows dentists to design and manufacture dental implants and prosthetics with greater precision. This leads to improved fit and function of the prosthetics and reduces the need for readjustments. Reduced treatment time Overall implant treatment time is reduced thanks to the high accuracy of digital scans and precise surgical planning. Reduced human error AI reduces human error during the treatment process by reducing the need for manual and traditional methods. Improved quality of life by reducing treatment time, reducing pain and discomfort, and improving aesthetic and functional outcomes, AI can improve the quality of life of patients. Diagnosis and prevention AI can diagnose oral and dental diseases earlier by analyzing medical data and radiographic images and help prevent more serious problems.

Keywords: Dental implants, optimization using artificial intelligence, implant path design
with deep learning

The Impact of Artificial Intelligence on the Accuracy and Success of Dental Implants

In recent decades, artificial intelligence (AI) has emerged as a key driver of transformation across numerous industries. Dentistry is no exception to this trend, particularly in the field of dental implants, where AI has played a significant role in improving the accuracy and success rates of treatments. Dental implants are considered a durable and reliable solution for replacing missing teeth and therefore hold great clinical importance. This article examines how artificial intelligence influences the precision and success of dental implant procedures and also explores the role of *Pasteur Dental Clinic* in providing affordable, high-quality implant services through the use of advanced technologies.

1. Artificial Intelligence in Dentistry: An Overview

a) Definition and General Applications of Artificial Intelligence

Artificial intelligence refers to technologies capable of performing tasks that typically require human intelligence, such as learning, comprehension, pattern recognition, and decision-making. In dentistry, AI is applied in various areas, including disease diagnosis, treatment planning, and the execution of surgical procedures.

b) The Role of Artificial Intelligence in Dental Implants

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In the field of dental implants, artificial intelligence plays a particularly important role in enhancing diagnostic accuracy, surgical planning, and post-treatment follow-up. These technologies assist dentists in selecting optimal treatment approaches for patients while minimizing potential risks and complications.

2. Accurate Diagnosis Using Artificial Intelligence

a) Imaging and Diagnosis of Dental and Periodontal Diseases

One of the primary applications of artificial intelligence in dental implantology is the use of advanced algorithms to analyze radiographic images and three-dimensional scans. These algorithms can identify dental issues such as caries, bone resorption, and periodontal diseases with greater accuracy than traditional diagnostic methods. By utilizing these technologies, *Pasteur Dental Clinic* has accelerated and improved the diagnostic process, enabling the delivery of affordable yet high-quality dental implant services.

b) Analysis and Prediction of Jawbone Condition

Artificial intelligence can assess the condition of the jawbone prior to implant surgery and predict whether the bone structure is sufficiently strong and dense. Such analyses support dentists in making informed decisions regarding implant type selection and the potential need for bone grafting procedures.

3. Precise Surgical Planning with the Assistance of Artificial Intelligence

a) Use of CAD/CAM Software and Surgical Guides

One of the most significant advancements in digital dentistry is the use of CAD/CAM (Computer-Aided Design and Computer-Aided Manufacturing) software and digital surgical guides. These technologies allow dentists to place implants with a high degree of precision. By integrating three-dimensional imaging data with AI-driven analyses, these systems generate accurate surgical plans that determine the optimal angle and depth for implant placement.

b) AI-Guided Implant Surgery

AI-guided surgeries, combined with digital surgical guides, have substantially increased the precision and safety of dental implant procedures. These methods enable clinicians to minimize errors and achieve highly accurate implant placement. *Pasteur Dental Clinic* employs these advanced technologies to offer affordable and high-quality implant treatments, contributing to cost reduction and improved patient satisfaction.

4. Post-Treatment Monitoring and Management Using Artificial Intelligence

a) Monitoring the Condition of Dental Implants

Following implant placement, regular follow-up is essential to ensure implant stability and to prevent potential complications. Artificial intelligence can significantly support this stage of treatment as well. Intelligent systems are capable of analyzing data obtained from imaging techniques and other clinical records to promptly detect early signs of complications or abnormalities. Early identification of such issues allows for timely intervention, thereby increasing long-term implant success rates.

b) Use of Smart Applications for Patient Education and Follow-Up

Many dental clinics, including *Pasteur Dental Clinic*, utilize smart applications to maintain continuous communication with patients and to provide post-treatment instructions. These applications can remind patients how to properly care for their dental implants, notify them of scheduled follow-up visits, and encourage them to report any concerning symptoms. As a result, patient compliance improves and post-operative complications are reduced.

5. Cost Reduction and Increased Access to Affordable Dental Implants

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a) Reduction of Operational Costs Through Artificial Intelligence

By improving diagnostic accuracy and minimizing clinical errors, artificial intelligence helps reduce the operational costs of dental clinics. These savings can be passed on to patients, leading to the availability of more affordable implant treatments. By adopting AI-based technologies, *Pasteur Dental Clinic* has been able to provide high-quality yet affordable dental implant services without compromising treatment outcomes.

b) Improved Access to Dental Care Services

Artificial intelligence also enhances access to dental care by reducing waiting times and optimizing clinical workflows. This improvement is particularly beneficial for patients seeking cost-effective implant solutions who require timely and efficient treatment. Consequently, AI-driven systems contribute to more equitable access to advanced dental implant services.

6. The Future of Artificial Intelligence in Dental Implants

a) Future Advances in Artificial Intelligence Algorithms

With the continuous advancement of artificial intelligence technologies, a significant improvement in the accuracy and efficiency of AI-based systems in dentistry is expected. Emerging algorithms will be capable of delivering more precise medical diagnoses and optimizing surgical planning processes. These advancements are likely to further reduce clinical errors and enhance the predictability of dental implant outcomes.

b) Integration of Artificial Intelligence with Other Technologies

The integration of artificial intelligence with complementary technologies such as robotics and virtual reality has the potential to introduce more innovative solutions in the field of dental implants. Such integrations may enable dentists to perform increasingly complex procedures with higher levels of precision while simultaneously improving the overall patient experience. As a result, these combined technologies are expected to redefine standards of care in implant dentistry.

Accurate Diagnosis Using Artificial Intelligence

a) Imaging and Diagnosis of Dental and Periodontal Diseases

One of the primary applications of artificial intelligence in dental implantology is the use of advanced algorithms for the analysis of radiographic images and three-dimensional scans. These algorithms are capable of identifying dental conditions such as caries, bone loss, and periodontal diseases with greater accuracy compared to conventional diagnostic methods. By employing these technologies, *Pasteur Dental Clinic* has enhanced the speed and precision of the diagnostic process, thereby enabling the provision of affordable and high-quality dental implant services.

b) Analysis and Prediction of Jawbone Condition

Artificial intelligence can evaluate the condition of the jawbone prior to implant surgery and predict whether the bone structure is sufficiently strong and stable to support an implant. Such analyses assist clinicians in making more informed decisions regarding implant selection and the potential need for bone grafting procedures.

3. Precise Surgical Planning with the Support of Artificial Intelligence

a) Use of CAD/CAM Software and Digital Surgical Guides

One of the most significant advancements in digital dentistry is the use of CAD/CAM (Computer-Aided Design and Computer-Aided Manufacturing) software along with digital surgical guides. These technologies enable clinicians to place dental implants with a high level of precision in the optimal anatomical position. By integrating data

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obtained from three-dimensional imaging with AI-based analyses, these systems generate accurate surgical plans that define the ideal angulation and depth for implant placement.

4. Post-Treatment Monitoring and Management Using Artificial Intelligence

a) Monitoring the Condition of Dental Implants

Following implant placement, regular follow-up is essential to ensure implant stability and to prevent potential complications. Artificial intelligence can effectively support this stage of care. Intelligent systems analyze data derived from imaging modalities and other clinical records to rapidly identify early signs of abnormalities or implant-related complications, allowing for timely clinical intervention.

b) Use of Smart Applications for Patient Education and Follow-Up

Many dental clinics, including *Pasteur Dental Clinic*, utilize smart applications to maintain continuous communication with patients and to provide post-treatment guidance. These applications remind patients of proper implant care, notify them of scheduled follow-up visits, and encourage the reporting of any concerning symptoms. Such tools enhance patient compliance and contribute to improved long-term treatment outcomes.

5. Cost Reduction and Increased Access to Affordable Dental Implants

a) Reduction of Operational Costs Through Artificial Intelligence

By improving diagnostic accuracy and reducing clinical errors, artificial intelligence significantly lowers operational costs in dental clinics. These savings can be transferred to patients, resulting in more affordable implant treatments. Through the adoption of advanced AI-driven technologies, *Pasteur Dental Clinic* has been able to deliver high-quality and cost-effective dental implant services.

b) Increased Access to Dental Care Services

Artificial intelligence also improves access to dental services by reducing waiting times and optimizing clinical workflows. This is particularly beneficial for patients seeking affordable implant solutions who require efficient and timely treatment. Consequently, AI-driven approaches contribute to broader access to modern dental implant care.

6. The Future of Artificial Intelligence in Dental Implants

A) Future Advances in Artificial Intelligence Algorithms

With the continuous advancement of AI technologies, it is expected that the accuracy and efficiency of these systems in dentistry will increase significantly. New algorithms will be able to perform medical diagnoses with greater precision and optimize surgical planning processes.

B) Integration of Artificial Intelligence with Other Technologies

The integration of AI with other technologies such as robotics and virtual reality can lead to more innovative solutions in the field of dental implants. These integrations can assist dentists in delivering more complex and precise treatments while improving the overall patient experience.

7. Accurate Diagnosis Using Artificial Intelligence

A) Imaging and Diagnosis of Dental and Periodontal Diseases

One of the primary applications of AI in dental implantology is the use of advanced algorithms to analyze radiographic images and three-dimensional scans. These algorithms are capable of identifying dental issues such as caries, bone loss, and periodontal diseases with greater accuracy than traditional methods. By utilizing these

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technologies, *Pasteur Dental Clinic* has accelerated and improved the diagnostic process, enabling the delivery of high-quality and affordable implant services.

B) Analysis and Prediction of Jawbone Condition

Artificial intelligence can analyze the condition of the jawbone prior to implant surgery and predict whether the bone is sufficiently strong and stable. These analyses help dentists make more informed decisions regarding implant selection and the potential need for bone grafting.

8. Precise Surgical Planning with the Aid of Artificial Intelligence

A) Use of CAD/CAM Software and Surgical Guides

One of the most significant advancements in digital dentistry is the use of CAD/CAM (Computer-Aided Design and Computer-Aided Manufacturing) software and digital surgical guides. These technologies enable dentists to place implants more accurately in optimal positions. By utilizing data obtained from three-dimensional imaging and AI-driven analyses, these software systems can generate precise surgical plans that indicate the optimal angle and depth for implant placement.

9. Post-Treatment Monitoring and Management Using Artificial Intelligence

A) Monitoring Implant Status

Following implant placement, regular follow-up is essential to ensure implant health and prevent complications. AI can play a vital role in this stage by analyzing data obtained from medical images and other clinical sources to promptly detect any signs of abnormalities or potential issues.

B) Use of Smart Applications for Patient Education and Follow-Up

Many clinics, including *Pasteur Dental Clinic*, utilize smart applications to maintain continuous communication with patients and provide post-treatment instructions. These applications can remind patients how to care for their implants, schedule follow-up visits, and report any concerning symptoms.

10. Cost Reduction and Increased Access to Affordable Implants

A) Reduction of Operational Costs through Artificial Intelligence

By enhancing accuracy and minimizing errors, AI has reduced the operational costs of dental clinics. These savings can be passed on to patients, resulting in more affordable implant treatments. Through the adoption of these technologies, *Pasteur Dental Clinic* has successfully provided high-quality, low-cost dental implants.

B) Increased Access to Dental Care

AI also improves access to dental services by reducing waiting times and streamlining treatment procedures. This is especially beneficial for patients seeking affordable implants who require efficient and timely care.

Artificial intelligence plays a crucial role in improving the accuracy and success of dental implants. From more precise diagnostics and surgical planning to effective post-treatment monitoring, AI has elevated dentistry to a new level of efficiency and precision. By leveraging these advanced technologies, *Pasteur Dental Clinic* provides affordable, high-quality implant services and strives to deliver the best possible treatment experience. With ongoing technological advancements, a promising and innovative future for dental implants is anticipated, contributing significantly to improved patient quality of life.

Dental Implant Algorithm and Treatment Stages

The dental implant algorithm consists of the following stages: evaluation and planning, implant surgery, osseointegration, abutment placement, and final crown installation.

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These stages apply to both one-stage and two-stage implant procedures. However, in two-stage implants, an additional healing period is required to allow proper osseointegration.

Stages of Dental Implant Treatment

1. Evaluation and Planning:

This stage includes a comprehensive oral examination, review of the patient's medical history, and radiographic imaging (typically CT scans) to assess bone density and determine the precise implant position.

2. Implant Surgery:

At this stage, the implant fixture (usually made of titanium) is placed into the jawbone, typically under local anesthesia.

3. Osseointegration:

After surgery, the implant must fuse with the jawbone. This process may take several months, during which the patient should avoid hard foods and maintain proper oral hygiene.

4. Abutment Placement:

Once osseointegration is complete, an abutment is attached to the implant fixture. The abutment serves as a connector between the implant and the dental crown.

5. Crown Placement:

Finally, a prosthetic crown is placed on the abutment to restore the appearance and function of the natural tooth.

Single-Stage Dental Implant

In this method, the implant fixture and the abutment are placed simultaneously during a single surgical session.

Single-stage dental implantation is performed in one appointment and requires only one surgical incision. During the procedure, an incision is made in the gingival tissue, and the implant is placed into the jawbone. In this technique, the component positioned within the gum is slightly longer (by a few millimeters) than in other implant methods, allowing a portion of it to remain exposed above the gingiva.

Two-Stage Dental Implant

In the two-stage implant method, the implant fixture is first inserted into the jawbone. After a healing period, the abutment and subsequently the dental crown are placed.

In the initial stage of the two-stage implantation process, the dentist incises the patient's gum tissue and places the fixture into the jawbone. Following fixture placement, a healing period of approximately 2 to 4 months is required to allow the bone to rest. During this time, the jawbone gradually integrates with the implanted metal fixture through a process known as osseointegration, ensuring proper stabilization.

Immediate Dental Implant

This method is used when the condition of the jawbone and gingival tissue is suitable for immediate implantation, allowing for the simultaneous placement of a temporary crown.

Immediate dental implantation is considered a rapid solution for replacing missing teeth. Tooth extraction and implant placement are performed almost simultaneously. After the damaged tooth is extracted, the implant fixture (the screw-like component of the implant) is placed directly into the jawbone. In immediate implantation, a dental prosthesis is installed during the same initial visit.

Unlike conventional implant procedures, which may take up to three months to complete, immediate implant placement allows the patient to receive a temporary prosthesis during the first appointment. At the East Tehran Implant Center, all immediate implant services are performed by specialist dentists. The entire immediate implant procedure at this clinic typically takes between 3 to 4 weeks.

What is a Two-Stage Dental Implant and how is it performed?

If you have lost one or more teeth, visiting a dental clinic will likely result in the recommendation of dental implants. But what exactly is a dental implant and what

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are its advantages?

Dental implants consist of metal screws made from biocompatible materials, which makes them highly compatible with the human body and widely used by dental professionals. In this treatment method, a metal screw is placed into the jawbone at the site of the missing tooth, followed by the installation of a dental crown. This process not only restores dental function but also enhances the aesthetic appearance of the smile.

Dental implant procedures follow a specific protocol and are generally performed using either the two-stage method or the immediate implant technique. This article aims to provide comprehensive information regarding two-stage dental implants.

The Two-Stage Dental Implant Procedure

As indicated by its name, this procedure requires the patient to visit a periodontal and implant specialist for two distinct surgical stages. In the first stage, the dentist makes an incision in the gingiva and places the implant fixture into the jawbone. After placement, a healing period of approximately 2 to 4 months is required to allow complete osseointegration between the bone and the implant.

Once this healing phase is completed, a second surgical procedure is performed to reopen the gum tissue and expose the fixture. Subsequently, measurements are taken to fabricate a custom dental crown. After one to two weeks, during which the impression is processed and the crown is manufactured, the patient returns to the clinic for crown placement. At this stage, the prepared crown is installed onto the implant, completing the two-stage implantation process.

Differences Between Two-Stage and Immediate Dental Implants

As suggested by their names, immediate dental implants are completed in a shorter time frame, whereas two-stage implants involve a longer, multi-step process. Immediate implants are also commonly referred to as single-stage implants. In this method, the implant is placed into the jawbone, and a dental crown is attached on the same day.

Patients undergoing immediate implantation can obtain a functional and aesthetically pleasing tooth in a single session. In most cases, if the patient's jawbone has sufficient strength, the immediate implant procedure can be performed directly after extracting a damaged or decayed tooth. The two-stage implant method has been explained in detail above. Despite the differences in procedure, both methods can yield equally successful outcomes when selected based on the patient's jawbone density and gingival condition.

Who Is Suitable for Two-Stage Dental Implants?

Dental implantation is a highly specialized procedure. Therefore, determining the most appropriate implant method is entirely the responsibility of the implant specialist. The dentist must thoroughly assess the patient's jawbone and its structural strength, as well as estimate the osseointegration period and the bone's capacity to bond with the implant. Based on these evaluations, the dentist will recommend either a two-stage implant or an immediate implant.

Advantages of Two-Stage Dental Implants

During the second surgical phase of the two-stage implant procedure, the condition of the bone tissue can be easily assessed, allowing for additional therapeutic interventions if necessary. This method enables full visualization of bone volume prior to osteotomy. In cases of bone porosity or defects, corrective treatments such as bone grafting can be performed. Additionally, a temporary prosthesis can be used during the healing phase until the final crown is precisely fabricated.

Advantages of Immediate Dental Implants

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In addition to the benefits of two-stage implants, immediate implants offer several advantages. This method helps prevent bone resorption and degradation of the jawbone. It also eliminates the need for prolonged waiting periods for prosthetic preparation. Immediate implants allow damaged or fractured teeth to be restored in the shortest possible time.

Effects of Dental Implants on Jawbone Structure

As previously mentioned, in immediate implant procedures, the crown component is placed shortly after implant fixation. In contrast, the two-stage method allows the gingival and bone tissues sufficient time to rest and heal. Many dentists believe that two-stage implantation provides greater assurance in treating fractured teeth and enhances long-term implant durability. Allowing the jawbone adequate healing time increases its readiness to accept the implant, ultimately improving osseointegration and extending the lifespan of the dental implant.

Zygomatic Implants

Zygomatic implants are used for patients who lack sufficient bone volume in the upper jaw for conventional implant placement. In this method, implants are anchored in the zygomatic (cheek) bone.

What is a Zygomatic Implant?

Dental implants are among the most effective solutions for replacing missing teeth. However, implant placement often requires adequate jawbone volume. Some patients experience severe jawbone resorption and require bone grafting or sinus lift procedures prior to implant placement. With zygomatic implants, the need for bone grafting is eliminated, resulting in a faster and more straightforward treatment process.

Zygomatic implants are a specialized type of dental implant that is anchored into the zygomatic bone rather than the jawbone. This approach is particularly suitable for patients who lack sufficient jawbone to support traditional dental implants.

In zygomatic implant procedures, the implant fixture is placed into the cheekbone, resulting in a longer implant with enhanced stability. In contrast, conventional implants are placed solely within the jawbone and do not extend beyond this anatomical structure.

Zygomatic Dental Implant Procedure

Zygomatic implant placement is performed under local anesthesia. Surgical incisions are made toward the palatal area. To access and visualize the implant site, a sinus window measuring approximately 5 × 10 millimeters is created. A small cavity is then drilled into the zygomatic bone, preparing the site for implant insertion. The implant fixture and abutment are subsequently positioned within this prepared area.

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Disadvantages and Complications of Zygomatic Implants

The most commonly reported complications following zygomatic implant placement include:

- **Sinusitis** (the risk can be reduced through thorough preoperative sinus evaluation)
- **Nerve injury**
- **Perforation of the sinus membrane**

Advantages of Zygomatic Implants	**Disadvantages of Zygomatic Implants**
No need for bone graft surgery.	Sinusitis
Can be used in cases of severe bone resorption; in some patients, conventional implants are not feasible.	Nerve injury
If a dental bridge is needed, it can be attached to the implant on the same day.	Perforation of the sinus membrane
Best option for patients who cannot undergo conventional treatments, such as those with cleft lip.	-
Zygomatic implants can support 3–4 teeth, whereas conventional implants typically support 1–2 teeth.	-
Four zygomatic implants in the upper jaw are sufficient for bridge placement.	-

All-on-4 Dental Implant

The **All-on-4 dental implant** technique is used for patients who have lost all teeth in one jaw. In this method, a full-arch prosthesis is supported by four dental implants—two implants placed in the anterior region of the jaw and two posterior implants inserted at an angle of approximately 30 to 45 degrees.

Important Considerations

- The selection of the appropriate implant technique depends on the patient's clinical condition and the quality and quantity of the jawbone.
- Maintaining proper oral hygiene after implant placement is essential for long-term success.
- In the event of unusual pain or complications following implant surgery, patients should promptly consult their dentist.

What is the All-on-4 Implant Technique?

The All-on-4 implant system is a modern dental treatment approach designed to permanently replace all missing or severely damaged teeth in the maxilla or mandible using only four implants. Two implants are positioned in the anterior region of the jaw, while the posterior implants are typically placed at an angle of 30–45 degrees to maximize bone contact and stability.

Due to its numerous advantages, this technique has rapidly become one of the most popular full-arch implant solutions. Some clinicians also refer to this method as **"same-day implants"**, as a fixed prosthetic bridge can often be placed during a single treatment session.

- **Advantages of All-on-4 Dental Implants**
- Compared to conventional removable dentures, the All-on-4 technique offers several advantages, including:

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- **Immediate loading:** In most cases, new teeth are placed in a single session.
- **Cost-effectiveness:** Only four implants are required per jaw, making it more affordable than traditional full-mouth implant methods.
- **Permanent stability:** Unlike removable dentures that may loosen or require adhesives, All-on-4 prostheses are fixed and stable.
- **Natural appearance:** Implant-supported bridges closely resemble natural teeth in shape and color.
- **Prevention of bone and gingival Resorption:** By replacing tooth roots, this method stimulates the jawbone and helps prevent bone and gum loss.
- **Improved speech:** Stable implants eliminate speech difficulties commonly associated with loose dentures.
- **Enhanced comfort:** There is no need for frequent removal or special cleaning, as with traditional dentures.
- **Long-term durability:** With proper care, All-on-4 implants can last for several decades.

Cost and Treatment Stages
In Tehran, the cost of All-on-4 implants typically ranges from **40 to 120 million Iranian Tomans**, depending on materials, expertise, and clinical conditions.
Treatment Stages of All-on-4 Implants

- Initial consultation and clinical examination
Radiographic imaging (CBCT)
- Surgical placement of implants
- Placement of temporary prosthesis
- Healing and evaluation
- Placement of the final fixed prosthesis

Suitable Candidates for All-on-4 Implants
This technique is suitable for:

- Patients who have lost all teeth in one or both jaws
- Denture wearers seeking a permanent solution
- Patients with reduced jawbone volume
- Individuals seeking a cost-effective and long-term treatment option

Unsuitable Candidates

- Patients with active periodontal disease
- Individuals with severe osteoporosis
- Patients with uncontrolled diabetes
- Individuals taking certain medications that interfere with bone healing

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Artificial Intelligence Algorithm for Dental Implant Planning

An AI-based dental implant algorithm may include multiple stages aimed at optimizing and automating diagnosis, treatment planning, and surgical execution. A general framework may include the following steps:

1. Collection of Imaging and Clinical Data

- Acquisition of intraoral images and 3D CBCT scans to obtain accurate anatomical data.
- Collection of clinical information, including medical history and patient-specific requirements.

2. Data Preprocessing

- Noise reduction and image quality enhancement.
- Segmentation and focus on regions of interest.

3. Implant Need Analysis and Diagnosis

- Application of AI models (e.g., deep neural networks) to analyze bone density, identify suitable implant sites, and assess anatomical risks.
- Detection of structural limitations such as insufficient bone volume or proximity to nerves and sinuses.

4. Implant Position and Path Planning

- Determination of optimal implant location and angulation.
- Virtual 3D modeling and simulation of implant placement.

5. Surgical Guide Generation

- Design and fabrication of digital or physical surgical guides.
- Preoperative simulation of the surgical procedure.

6. Surgical Execution

- Integration with smart surgical tools or robotic systems for enhanced precision.

7. Postoperative Monitoring and Evaluation

- Monitoring implant stability and healing using follow-up imaging and data analysis.
- Adaptive treatment adjustments if necessary.

To present a sample code or model related to a dental implant algorithm, it should be noted that developing a complete system requires imaging data, machine learning models, and careful design. Below, a simple and preliminary example is provided in Python, using common libraries for dental implant detection and planning.

This example assumes that imaging data (such as CBCT images or 3D models) are available and that the goal is a basic prototype. The objectives of this sample include:

- Analyzing bone density using a simple neural network.
- Selecting an appropriate implant location based on these analyses.

A simple sample code for image analysis and dental implant planning is provided below.

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```
import numpy as np

import matplotlib.pyplot as plt

from keras.models import Sequential

from keras.layers import Dense, Conv2D, Flatten

from skimage import io, filters


# A sample CBCT image is available.

# Load Sample Image

image_path = 'sample_cbct_image.png'

image = io.imread(image_path, as_gray=True)


# Image Preprocessing: Filtering to Detect Bone Regions

edges = filters.sobel(image)


# Prototype of a simple neural network model for detecting suitable implant
regions

model = Sequential()

model.add(Conv2D(16, kernel_size=(3, 3), activation='relu',
input_shape=(image.shape[0], image.shape[1], 1)))

model.add(Flatten())

model.add(Dense(32, activation='relu'))

model.add(Dense(1, activation='sigmoid'))


# It is assumed that the training data and labels are already prepared

# x_train and y_train are the training samples

# This section is only to illustrate the structure


# Model Training


# model.compile(optimizer='adam', loss='binary_crossentropy',
metrics=['accuracy'])

# model.fit(x_train, y_train, epochs=10)
```

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```
# Predicting suitable regions for implant placement

# predictions = model.predict(image.reshape(1, image.shape[0],
image.shape[1], 1))

# For this sample case, we assume that the regions of interest are selected
based on a threshold


threshold = 0.5

# Locations predicted as suitable

# We consider regions with values above the threshold as appropriate for
implant placement


# Plotting the results

plt.figure(figsize=(8, 8))

plt.imshow(image, cmap='gray')

# Assume that suitable regions have high values

# Example: red color for suitable regions

plt.contour(edges, levels=[threshold], colors='red')

plt.title('Dental Implant Analysis Preview')

plt.show()
```

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```python
import numpy as np
import matplotlib.pyplot as plt
from keras.models import Sequential
from keras.layers import Dense, Conv2D, Flatten
from skimage import io, filters

# به صورت نمونه در اختیار است CBCT فرض کنید تصویر
# بارگذاری تصویر نمونه
image_path = 'sample_cbct_image.png'
image = io.imread(image_path, as_gray=True)

# پیش‌پردازش تصویر: فیلتر کردن برای تشخیص نواحی استخوانی
edges = filters.sobel(image)
```

```python
# به صورت نمونه در اختیار است CBCT فرض کنید تصویر
# بارگذاری تصویر نمونه
image_path = 'sample_cbct_image.png'
image = io.imread(image_path, as_gray=True)

# پیش‌پردازش تصویر: فیلتر کردن برای تشخیص نواحی استخوانی
edges = filters.sobel(image)

# مونه‌سازی مدل شبکه عصبی ساده برای تشخیص نواحی مناسب ایمپلنت
model = Sequential()
model.add(Conv2D(16, kernel_size=(3, 3), activat
model.add(Flatten())
model.add(Dense(32, activation='relu'))
model.add(Dense(1, activation='sigmoid'))

# فرض بر این است که داده‌های آموزش و برچسب‌ها آماده است
# x_train و y_train نمونه‌های آموزشی هستند
# این قسمت صرفاً برای نشان دادن ساختار است
```

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```
# آموزش مدل
# model.compile(optimizer='adam', loss='binary_
# model.fit(x_train, y_train, epochs=10)

# پیش‌بینی نواحی مناسب برای ایمپلنت
# predictions = model.predict(image.reshape(1, i
# ن می‌کنیم که نواحی موردنظر بر اساس یک آستانه انتخاب شده است

threshold = 0.5
# محل‌هایی که پیش‌بینی می‌شود مناسب هستند
# اسب برای قرارگیری ایمپلنت را در نواحی با مقادیر بالا پیدا می‌کنیم

# رسم نتیجه
plt.figure(figsize=(8, 8))
plt.imshow(image, cmap='gray')
# فرض کنیم نواحی مناسب با مقدار بالا است
# نمونه: رنگ قرمز برای نواحی مناسب
plt.contour(edges, levels=[threshold], colors='
plt.title('پیش‌نمایش تحلیل ایمپلنت دندان')
```

- This code is very simple and illustrative. For real-world projects, you will need accurate medical imaging data, more advanced models, and additional specialized processes.
- Collecting data and training deep learning models require reliable datasets and precise labeling.
- In practice, pre-trained models and deep convolutional neural networks (such as ResNet, U-Net, etc.) are commonly used.

Dental implant image analysis using artificial intelligence is a critical and sensitive process that can significantly improve diagnostic accuracy, surgical planning, and outcome evaluation. These analyses are typically based on deep learning techniques and convolutional neural networks (CNNs), which are capable of extracting complex features from medical images—especially three-dimensional medical images such as CBCT scans.

Below are the key points and main stages involved in dental implant image analysis using artificial intelligence:

1. Data Collection and Preprocessing

- **Medical images:** CBCT, CT scans, or digital dental images.
- **Preprocessing:** This includes noise reduction, contrast enhancement, normalization, and cropping of regions of interest.

2. Data Labeling and Model Training

- Labeling suitable implant regions, bone structures with sufficient density, nerves, and sinuses.
- Creating training and testing datasets.

3. Deep Learning Model Design and Training

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- Using CNN-based architectures, such as U-Net for segmentation, or other specialized models.
- The model objectives may include bone region detection, identification of optimal implant locations, or evaluation of bone density.

4. Analysis and Interpretation of Results

- Generating segmentation maps of useful or problematic regions.
- Measuring dimensions, density, and critical anatomical positions within the image.
- Recommending the most appropriate location for implant placement.

Example Workflow for Developing a Simple Image Analysis Model Using Python and Keras

In this example, it is assumed that you have access to medical images and their corresponding labels for training. In practice, however, large and accurately annotated datasets are required.

```
import numpy as np

import matplotlib.pyplot as plt

from keras.models import Sequential

from keras.layers import Conv2D, MaxPooling2D, UpSampling2D

from skimage import io, measure

# Sampling a single image and its label (mask of the target region)

image_path = 'cbct_sample.png'

mask_path = 'cbct_mask.png'


#  Loading images

image = io.imread(image_path, as_gray=True)

mask = io.imread(mask_path, as_gray=True)

# Normalization

image = image / 255.0

mask = mask / 255.0

# Developing a simple U-Net model for segmentation

model = Sequential([

    Conv2D(16, (3, 3), activation='relu', padding='same',
input_shape=(image.shape[0], image.shape[1], 1)),

    MaxPooling2D((2, 2)),

    Conv2D(32, (3, 3), activation='relu', padding='same'),
```

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```
    UpSampling2D((2, 2)),

    Conv2D(1, (3, 3), activation='sigmoid', padding='same')

])

# Model training (in practice, your dataset should be large and diverse)

# model.compile(optimizer='adam', loss='binary_crossentropy')

# model.fit(x_train, y_train, epochs=10)


# # Predicting regions segmentation

# prediction = model.predict(image.reshape(1, image.shape[0], image.shape[1], 1))

# Hypothetical example of the result

prediction = mask  # In this hypothetical case, it is the same as the mask

# Plotting the results

plt.figure(figsize=(12, 4))

plt.subplot(1, 3, 1)

plt.subplot(1, 3, 1)

plt.title('Original Image')

plt.imshow(image, cmap='gray')


plt.subplot(1, 3, 2)

plt.title('Labeled Mask')

plt.imshow(mask, cmap='gray')


plt.subplot(1, 3, 3)

plt.title('Model Prediction')

# plt.imshow(prediction, cmap='gray')

plt.imshow(prediction, cmap='gray')

plt.show()


#  Extracting suitable regions for implant placement (e.g., by drawing contours)
```

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```
contours = measure.find_contours(prediction, 0.5)
for contour in contours:
    plt.plot(contour[:, 1], contour[:, 0], linewidth=2)

plt.imshow(prediction, cmap='gray')
plt.title(Analyzed regions)
plt.show()
```

python

```python
import numpy as np
import matplotlib.pyplot as plt
from keras.models import Sequential
from keras.layers import Conv2D, MaxPooling2D,
from skimage import io, measure

# نمونه‌گیری از یک تصویر و برچسب (ماسک ناحیه موردنظر)
image_path = 'cbct_sample.png'
mask_path = 'cbct_mask.png'

# بارگذاری تصاویر
image = io.imread(image_path, as_gray=True)
mask = io.imread(mask_path, as_gray=True)

# نرمال‌سازی
image = image / 255.0
mask = mask / 255.0
```

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```
# توسعه مدل U-Net ساده برای segmentation
model = Sequential([
    Conv2D(16, (3, 3), activation='relu', padding='
    MaxPooling2D((2, 2)),
    Conv2D(32, (3, 3), activation='relu', padding='
    UpSampling2D((2, 2)),
    Conv2D(1, (3, 3), activation='sigmoid', padding
])

# آموزش مدل (در عمل، باید مجموعه دادهٔ بزرگ و متنوع باشد)
# model.compile(optimizer='adam', loss='binary_cros
# model.fit(x_train, y_train, epochs=10)

# پیش‌بینی نواحی segmentation
# prediction = model.predict(image.reshape(1, image
```

```
# مثال فرضی از نتیجه
prediction = mask  # در حالت فرض، همان ماسک است

# ترسیم نتایج
plt.figure(figsize=(12, 4))
plt.subplot(1, 3, 1)
plt.title('تصویر اولیه')
plt.imshow(image, cmap='gray')
plt.subplot(1, 3, 2)
plt.title('ماسک برچسب‌گذاری‌شده')
plt.imshow(mask, cmap='gray')
plt.subplot(1, 3, 3)
plt.title('پیش‌بینی مدل')
plt.imshow(prediction, cmap='gray')
plt.show()

# استخراج نواحی مناسب برای ایمپلنت (مثلاً با رسم کانتور)
contours = measure.find_contours(prediction, 0.5
for contour in contours:
```

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INTERNATIONAL ORGANIZATION OF IOAS ACADEMIC STUDIES

```
plt.title('تصویر اولیه')
plt.imshow(image, cmap='gray')
plt.subplot(1, 3, 2)
plt.title('ماسک برچسب‌گذاری‌شده')
plt.imshow(mask, cmap='gray')
plt.subplot(1, 3, 3)
plt.title('پیش‌بینی مدل')
plt.imshow(prediction, cmap='gray')
plt.show()

# استخراج نواحی مناسب برای ایمپلنت (مثلاً با رسم کانتور)
contours = measure.find_contours(prediction, 0.5)
for contour in contours:
    plt.plot(contour[:, 1], contour[:, 0], linewidt

plt.imshow(prediction, cmap='gray')
plt.title('نواحی تحلیل شده')
plt.show()
```

Important Notes

- Large-scale datasets with accurate and detailed annotations are required.
- In practice, more advanced architectures such as **U-Net**, **Mask R-CNN**, or **Vision Transformer–based models** are commonly used.
- Advanced analyses include assessing bone density, identifying regions close to critical nerves, and designing the optimal implant trajectory.

General Statement of the Research Problem

Dental implant–based treatments are recognized as one of the most effective and reliable approaches for replacing missing teeth in modern dentistry, demonstrating high long-term success rates (Albrektsson et al., 2020). This success is largely dependent on the phenomenon of osseointegration, defined as the direct and stable structural and functional connection between the implant surface and the patient's jawbone. Nevertheless, despite significant advances in implant design, surgical techniques, and treatment protocols, a proportion of implant treatments still result in failure. These failures may occur either in the early stages (prior to prosthetic loading) or in the long term (after functional loading), leading to biological and mechanical complications, increased financial burden for patients, and additional clinical challenges for dental practitioners.
Consequently, the identification of patients at higher risk of implant failure prior to treatment initiation represents a fundamental challenge and a critical priority in clinical implantology. This challenge arises from the multifactorial nature of implant success, which is influenced by a complex

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interplay of patient-related factors, implant characteristics, and surgical variables. Numerous unknown and ambiguous aspects persist in this field. Traditionally, clinicians assess risk and predict treatment outcomes based on personal clinical experience, intuition, and the evaluation of a limited number of key variables, such as bone quality and quantity, the patient's medical history (e.g., uncontrolled diabetes or osteoporosis), and behavioral factors (e.g., smoking). Although this approach is valuable, it is inherently limited, as the human cognitive system is not capable of simultaneously processing and analyzing nonlinear and complex interactions among dozens of variables.

For instance, how do synergistic interactions between low bone density, smoking habits, and a specific implant design affect the probability of implant failure? Or how can the combined effects of biomechanical parameters—such as insertion torque and resonance frequency analysis (RFA)—be integrated with systemic patient factors to construct an accurate predictive model? These questions remain insufficiently addressed by conventional analytical approaches, highlighting the unresolved aspects of the problem (Zhao et al., 2021).

The variables relevant to this research can be categorized into three main groups. The first group consists of patient-related variables, including demographic information (age, sex), general medical history (systemic conditions such as diabetes, cardiovascular diseases, and osteoporosis), medication use (e.g., bisphosphonates), behavioral factors (smoking, bruxism), and oral hygiene status. The second group encompasses surgical site– and procedure-related variables, such as bone quality and quantity (Lekholm and Zarb classification), bone density measured via three-dimensional radiographic imaging (CBCT), implant location (anterior vs. posterior region, maxilla vs. mandible), and intraoperative parameters, including primary implant stability (insertion torque and implant stability quotient, ISQ). The third group includes implant- and prosthesis-related variables, such as implant dimensions (length and diameter), surface characteristics (e.g., SLA or SLActive), implant body design, and prosthetic connection type.

The primary objective of this research is to leverage the computational power of artificial intelligence (AI), particularly machine learning algorithms, to develop a comprehensive and accurate predictive model capable of simultaneously analyzing this large and heterogeneous set of variables. Such a model aims to estimate the probability of implant success or failure on an individualized (personalized) basis, thereby supporting clinical decision-making and improving treatment outcomes in dental implantology.

In recent decades, numerous efforts have been made to identify risk factors associated with dental implant failure. Classical statistical studies, such as logistic regression analyses, have demonstrated associations between certain variables and implant treatment outcomes (Cho et al., 2019). However, these models are often incapable of capturing complex and nonlinear relationships among variables, and their predictive power at the individual patient level remains limited. For instance, while a statistical model may indicate that smoking generally increases the risk of implant failure, it cannot precisely estimate the degree of risk for a specific patient with a given bone density, a history of controlled

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diabetes, and the use of a narrow-diameter implant. This limitation highlights the need for a new analytical paradigm in implantology data analysis.
Artificial intelligence, and machine learning in particular, provides powerful tools to address this challenge. Algorithms such as Random Forests, Support Vector Machines (SVMs), and Artificial **Neural Networks (ANNs)** are capable of discovering hidden and complex patterns within large-scale datasets (Big Data) (Schmidt et al., 2022). These algorithms can "learn" from clinical, radiographic, and demographic data derived from thousands of patients who have previously undergone implant treatment and develop predictive models capable of estimating outcomes for new patients. Unlike traditional approaches, these models are not limited to a small number of key variables but can simultaneously incorporate dozens or even hundreds of features into their analyses. One of the keys and still ambiguous aspects that this research aims to clarify is the relative importance and weighting of individual variables within the predictive model. For example, is patient age more influential than bone density? Or does insertion torque affect implant success differently in diabetic patients compared to non-diabetic individuals? Modern machine learning approaches, particularly those based on Explainable Artificial Intelligence (XAI), can address such questions and help clinicians understand why a model generates a specific prediction. This level of transparency is critical for the clinical adoption of AI-based tools (Huang et al., 2023). Accordingly, this research seeks to uncover these hidden relationships and to provide an evidence-based decision-support tool. The ultimate goal of this research is not merely to develop a theoretical model, but rather to create a **practical Clinical Decision Support System (CDSS)**. Such a system would allow clinicians to input data from a new patient and receive an accurate risk score or probability of implant success. This information could be highly valuable in patients counseling, treatment planning (e.g., choosing between implant therapy and a fixed bridge), selection of surgical protocols (e.g., immediate versus delayed loading), and postoperative risk management. This approach represents a significant step toward **Precision Dentistry**, in which treatments are tailored to the unique characteristics of each individual patient.
The central research question can therefore be summarized as follows:
Given the multifactorial and complex nature of dental implant failure and the limitations of traditional methods in providing accurate and personalized predictions, can artificial intelligence algorithms, combined with comprehensive clinical data analysis, be used to develop a valid and reliable predictive model for estimating the probability of dental implant treatment success? Such a model must not only achieve high predictive accuracy but also be capable of identifying the most influential variables affecting treatment outcomes.
This research also faces several challenges. One of the most significant obstacles is the collection of high-quality, standardized, and comprehensive datasets from multiple dental centers. These datasets must include a wide range of demographic, clinical, radiographic, and surgical variables, with treatment outcomes (success or failure) accurately recorded according to standardized criteria. Moreover, AI models require rigorous validation using

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independent datasets to ensure their generalizability (Li et al., 2022). Overcoming these challenges are essential for the success of the study.
Another unresolved dimension concerns the impact of imaging data. Periapical radiographs and, in particular, CBCT images contain rich information regarding bone structure, density, and anatomical features surrounding implant sites. Deep learning algorithms, as a subset of machine learning, are capable of automatically extracting relevant features from these images and integrating them with other clinical data to achieve more accurate predictions. This research aims to investigate the potential of integrating structured data (e.g., age and medical history) with unstructured data (e.g., radiographic images) to enhance model performance (Wang et al., 2023).
Ultimately, the successful completion of this research could have far-reaching implications. For patients, it may enable more informed decision-making and reduce the risk of failure in costly implant treatments. For clinicians, it provides access to a powerful tool for optimizing treatment planning and managing patient expectations. For healthcare systems, it may contribute to reducing costs associated with failed treatments and corrective surgeries. Thus, this research seeks not only to address a scientific gap but also to offer a practical solution to a common and clinically significant problem in dental implantology.
In summary, the fundamental issue addressed in this study is the transition from an intuitive, experience-based approach to implant success prediction toward a **data-driven, objective, and precise methodology** enabled by artificial intelligence. By developing and validating a predictive model, this research aims to elucidate the complex interactions among multiple variables influencing osseointegration and to introduce an innovative tool for improving the quality of dental care—ultimately benefiting both patients and the dental community.

Significance and Necessity of the Study

The significance and necessity of conducting this research can be examined from several critical perspectives, each of which independently justifies the implementation of the study. The first and most important aspect is the existence of controversies and well-defined research gaps in the prediction of dental implant treatment outcomes. Although a wide range of potential risk factors—such as smoking, diabetes mellitus, poor bone quality, and inadequate oral hygiene—have been identified (Franco et al., 2022), the relative weight and interactive effects of these factors remain subjects of debate. Many previous studies have been retrospective in nature and have relied on conventional statistical methods, which are inherently limited in modeling complex and nonlinear interactions among variables. Consequently, their findings are sometimes contradictory; for instance, while some studies consider diabetes a definitive risk factor, others suggest that its impact becomes negligible when glycemic control is adequately maintained (Esposito et al., 2021). This lack of consensus has resulted in the absence of a robust, evidence-based, standardized protocol for patient risk assessment, rendering clinical decision-making heavily dependent on individual clinician experience and subjective judgment. By leveraging artificial intelligence—an approach inherently designed to analyze complex, high-dimensional data—this study aims to

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address this gap and provide a deeper understanding of the dynamics underlying implant failure.

The second dimension concerns the urgent clinical and societal need to improve the accuracy of treatment outcome prediction. Dental implant therapy is an invasive, time-consuming, and costly procedure. Implant failure not only results in financial and temporal losses for patients but may also be associated with bone resorption, thereby complicating or even limiting future restorative options (Chen & Buser, 2019). From the patient's perspective, treatment failure can be a distressing and discouraging experience, while from the clinician's perspective, it may adversely affect professional credibility. Therefore, there is a substantial demand for tools capable of providing accurate, individualized risk assessments prior to initiating treatment. Such tools enable both clinicians and patients to make informed decisions with a clear understanding of potential outcomes. This need is particularly critical in complex cases, where multiple risk factors coexist, and accurate prediction can significantly enhance the quality of care and patient satisfaction. The potential theoretical and practical contributions of this research are extensive. From a theoretical standpoint, the study may contribute to the development of a novel framework for understanding osseointegration and its failure mechanisms.

By identifying hidden patterns within data through machine learning algorithms, new risk factors may be discovered, or previously unrecognized interactions among known variables may be revealed. For example, an AI-based model may demonstrate that the combination of a specific implant surface type with a particular patient biological profile significantly alters failure risk—an insight that would be nearly impossible to obtain through traditional analytical approaches (Kang et al., 2023). Such theoretical advancements could form the foundation for future research in biomaterials engineering, bone biology, and implant design.

From a practical perspective, the primary benefit of this study lies in the development of a **Clinical Decision Support System (CDSS)**. This system could be implemented as user-friendly software accessible to dental practitioners. By entering patient-specific data—such as age, medical history, CBCT parameters, and lifestyle habits—the clinician would receive a clear output, including a predicted probability of implant success and a ranked list of the most influential risk factors for that individual patient. This practical tool could facilitate standardized risk assessment, optimize treatment planning (e.g., recommending smoking cessation prior to surgery or selecting wider-diameter implants in low-density bone), and improve the management of patient expectations (Tarno et al., 2022). Ultimately, such an approach may lead to reduced failure rates, lower costs associated with retreatment, and an overall improvement in the quality of dental care services.

Moreover, this research employs a methodological approach that remains relatively underexplored in domestic dental research. This approach involves the collection of heterogeneous data from multiple sources—including electronic health records, CBCT radiographic images, and laboratory test results—and their integration into a comprehensive database. Instead of relying on conventional statistical analyses, a suite of advanced machine

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learning algorithms will be utilized to develop and validate predictive models. A particularly innovative methodological aspect is the application of **deep learning techniques** for the automated analysis of radiographic images, enabling the extraction of quantitative biometric features of bone structure (Li et al., 2023). This multidimensional, data-driven approach represents a novel research paradigm in dentistry.

Finally, the necessity of this research aligns with the global shift toward **Precision Medicine and Precision Dentistry**. The traditional “one-size-fits-all” paradigm is becoming obsolete, and the future of healthcare lies in individualized treatment strategies based on each patient’s genetic, biological, environmental, and lifestyle characteristics (Mizrahi, 2020). This study directly contributes to this paradigm shift by seeking to transform implant-related decision-making from an experience-based art into a precise, data-driven science using artificial intelligence. Given the steadily increasing demand for implant therapy and the profound impact of treatment success on patients’ quality of life, investment in research aimed at enhancing the accuracy and safety of implant procedures is not merely an option but an undeniable necessity.

Review of Literature and Related Studies

Domestic Studies

Ghasemi et al. (2023) investigated risk factors affecting dental implant survival in a university-based center in Iran. Using logistic regression analysis on data from 250 patients, they found that smoking and a history of periodontal disease were significantly associated with increased implant failure risk, whereas patient age and sex showed no significant effect.

Sadeghi et al. (2023), in a narrative review, examined various applications of artificial intelligence across different dental specialties, including implantology. They concluded that machine learning holds substantial potential for diagnosing peri-implantitis and predicting implant stability; however, applied clinical research in this field within the country remains limited, highlighting the need for further clinical investigations.

Ahmadi et al. (2022) evaluated the accuracy of machine learning algorithms in distinguishing healthy bone from resorbed bone in panoramic radiographic images. Their results demonstrated that a convolutional neural network (CNN) achieved an accuracy exceeding 92%, suggesting its utility as an auxiliary tool in preliminary bone quality assessment prior to implant placement. Rezaei et al. (2022) explored the relationship between bone density measured on CBCT images and primary implant stability (ISQ values). They identified a significant positive correlation between Hounsfield unit (HU) values and primary stability, indicating that bone density metrics could serve as important inputs for predictive models.

Mohammadi et al. (2023), in a prospective study with a three-year follow-up of 150 implant patients, reported that individuals with low serum vitamin D levels experienced higher rates of marginal bone loss. They suggested that vitamin D status may represent a critical biological variable in implant success prediction models.

Jafari et al. (2022) compared immediate and delayed loading protocols in the mandible using Kaplan–Meier survival analysis. Their findings indicated no significant difference in success rates among selected patients with high primary stability, although

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protocol selection should consider other concurrent risk factors.

Naderi et al. (2023) developed a regression model to predict marginal bone loss one year after implant loading using data from a private clinic. They found that, in addition to smoking, excessive subcrestal implant placement depth was a significant risk factor.

Karimi et al. (2022) conducted an in vitro study comparing the effects of SLA and SLActive implant surfaces on osteoblast adhesion and proliferation. Their results indicated enhanced early cellular activity on SLActive surfaces, potentially contributing to faster and more reliable osseointegration in challenging conditions.

Tahmasebi et al. (2023) surveyed Iranian implant specialists to identify key factors influencing implant treatment planning decisions. The results highlighted clinical experience and CBCT-assessed bone quality as the most influential factors, underscoring the need for more objective decision-support tools.

Akbari et al. (2022), in a systematic review of Iranian publications on implant failure, concluded that most studies focused on single-variable risk factor identification using classical statistical methods, with a notable lack of advanced modeling and AI-based approaches.

International Studies

Huang et al. (2023) developed a deep learning model to predict early dental implant failure using clinical data and panoramic radiographs from over 5,000 patients. Their hybrid model achieved an accuracy of 91.3% and an AUC of 0.94 in identifying high-risk patients.

Shin et al. (2024) employed a Random Forest algorithm to identify key predictors of peri-implantitis. Their findings indicated that a history of periodontitis, poor oral hygiene, and lack of regular follow-up visits were the most influential predictors, with a sensitivity of 88%.

Li et al. (2023) trained a CNN to automatically analyze CBCT images and predict primary implant stability (ISQ) preoperatively. The model demonstrated a strong correlation (r = 0.85) with intraoperative ISQ measurements.

Elsharkawy et al. (2023) developed an AI-based CDSS using Support Vector Machines to assist in selecting immediate versus delayed loading protocols. Incorporating 15 patient- and surgery-related variables, the system achieved a 94% agreement with expert clinician decisions.

Kim et al. (2024) explored the application of Explainable AI (XAI) in implant success prediction. Their model not only achieved high predictive accuracy but also visually highlighted influential patient features—such as specific CBCT regions or systemic conditions—thereby enhancing clinician trust.

Patel et al. (2023) utilized Natural Language Processing (NLP) techniques to analyze unstructured clinical notes from electronic health records. They identified a modest but significant association between selective serotonin reuptake inhibitor (SSRI) use and increased implant failure risk.

Wang et al. (2023) developed a hybrid model integrating structured clinical data with periapical radiographic images to predict marginal bone loss. The combined model significantly outperformed single-data-type models.

Garcia et al. (2024), in a multicenter study, trained a machine learning model on data from Spain and validated it on German patient data to assess generalizability. The results demonstrated promising cross-population applicability following appropriate calibration.

Tarnowski et al. (2023) investigated prosthetic-related variables using a Bayesian network to predict peri-implant soft tissue inflammation. Their model successfully estimated mucositis risk based on prosthetic design characteristics.

Meister et al. (2024), in a comprehensive review, examined challenges and opportunities associated with Big Data and AI in implantology. They identified patient privacy, data standardization, and rigorous clinical validation as key challenges, while emphasizing the promising future of the field.

Novelty and Innovation of the Research

The novelty and innovative aspects of this research can be defined at three main levels. First, at the national level, this study represents one of the earliest comprehensive efforts in Iran to develop a predictive model for dental implant success using advanced artificial intelligence algorithms, thereby addressing an existing research gap in this field. Second, at the methodological level, the innovation of the study lies in the integration of heterogeneous data sources. Unlike previous studies that have primarily focused on structured clinical data, this research aims to employ deep learning techniques to automatically extract both quantitative and qualitative information from three-dimensional radiographic images (CBCT) and integrate these features with patients' demographic, medical, and surgical data to develop a more comprehensive and multimodal predictive model. Third, this research goes beyond simple outcome prediction (classification) by utilizing explainable artificial intelligence (XAI) techniques to identify and rank the importance of influential variables at an individual patient level. This approach can substantially assist clinicians in better understanding risk factors and making more transparent and effective clinical decisions.

Research Objectives

Ultimate Goal:

- To enhance the quality of dental implant treatments and advance toward precision and personalized dentistry.

General Objective:

- To develop and validate an artificial intelligence–based predictive model for estimating the probability of success in dental implant therapy.

Specific Objectives:

- To identify the most important patient-related variables (demographic, medical, and behavioral factors) associated with implant success.
- To determine the most influential site- and surgery-related variables (bone quality and quantity, primary stability) in predicting treatment outcomes.
- To evaluate and compare the accuracy, sensitivity, and specificity of different machine learning algorithms (such as Random Forest, Support Vector Machine, and Neural Networks) in predicting implant success.
- To develop a deep learning model for the automatic extraction of predictive features from CBCT radiographic images.

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- To present an explainable artificial intelligence (XAI) model capable of identifying the main factors influencing predictions for each individual patient.

Applied Objective:

- To develop a prototype clinical decision support system (CDSS) to assist dentists in risk assessment for patients who are candidates for dental implant treatment.

Beneficiaries (Organizations, Industries, and Stakeholders)

The primary beneficiaries of this research include several groups. At the forefront are dentists, implantologists, and oral and maxillofacial surgeons, who can use the developed model as a supportive tool for accurate risk assessment, optimization of treatment planning, and more effective patient counseling. The second group consists of patients who are candidates for implant therapy, who will benefit from more informed decision-making, reduced risk of treatment failure, and increased safety. At the organizational level, dental clinics, university hospitals, and dental schools (as sites for case studies and end users) can improve the quality of their services and standardize treatment protocols through implementation of this system. Finally, implant manufacturing companies and health insurance providers may also benefit from the outcomes of this research for risk analysis and the development of improved products and services.

Research Questions

- Can artificial intelligence–based models predict the success of dental implant treatment with higher accuracy than traditional statistical methods?
- What are the most important predictors of dental implant success or failure in the studied population?
- Does the integration of CBCT-derived imaging data with clinical data significantly improve the performance of the predictive model?
- Which machine learning algorithm (Random Forest, Support Vector Machine, or Neural Network) demonstrates the best performance for this prediction task?
- Is it possible to develop an explainable artificial intelligence model that presents the rationale behind its predictions in a manner understandable to clinicians?
- **Research Hypotheses**
- There is a statistically significant relationship between a set of demographics, clinical, and radiographic variables and the success of dental implant treatment.
- The artificial intelligence–based predictive model estimates implant
- success with higher accuracy than a logistic regression model.
- Incorporating features extracted from CBCT images enhances the predictive power of the model compared to a model based solely on clinical data.
- Primary implant stability (ISQ) will be one of the strongest predictors in the final model.
- Patients with a history of periodontal disease and smoking habits will exhibit a significantly higher probability of implant failure in the predictive model.

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- **Definitions of Technical and Specialized Terms**
- **Artificial Intelligence (AI):**
- **Conceptual Definition:** A branch of computer science focused on creating intelligent machines capable of performing tasks that typically require human intelligence, such as learning,
- reasoning, and problem-solving.
- **Operational Definition:** In this study, artificial intelligence refers to the application of machine learning and deep learning algorithms trained on patient datasets to identify patterns associated with implant success or failure and to predict treatment outcomes for new patients.
- **Dental Implant:**
- **Conceptual Definition:** A metallic fixture, usually made of titanium, surgically placed into the jawbone to serve as an artificial tooth root supporting a crown, bridge, or denture.
- **Operational Definition:** In this research, titanium implants with various designs and surface characteristics used in the study population are considered. Implant success is defined based on standard criteria (absence of mobility, no progressive bone loss, and absence of
- infection), while failure is defined as the need for implant removal.

Osseointegration:

- **Conceptual Definition:** A biological process characterized by a direct, structural, and functional connection between the surface of a dental implant and the surrounding living bone without the interposition of soft tissue.
- **Operational Definition:** In this study, successful osseointegration is assessed clinically and radiographically, including implant stability (absence of clinical mobility) and maintenance of marginal bone levels within acceptable limits (less than 1.5 mm of bone loss during the first year after loading).

Predictive Model:

- **Conceptual Definition:** A mathematical or computational model that uses historical data to predict future outcomes.
- **Operational Definition:** In this research, a machine learning model (such as a Random Forest or Neural Network) trained on historical patient data to estimate the probability of implant success or failure for new patients based on their input features.

Research Methodology

A. Description of the Research Method Based on Objectives, Data Type, and Implementation

This study is **analytical cross-sectional research with a retrospective approach**. The required data will be collected from electronic health records (EHR) and digital radiographic archives (PACS) of patients who received dental implants over the past five years at the School of Dentistry, Tehran University of Medical Sciences, as well as several selected private dental clinics. Inclusion criteria consist of patients for whom at least one year has elapsed since prosthetic loading of the implant. The collected data will be categorized into three main groups:

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- **Demographic and medical data** (age, gender, systemic diseases, medication use, smoking habits),
- **Clinical and surgical data** (implant location, bone quality, implant dimensions, primary stability indices such as ISQ values and insertion torque),
- **Radiographic data** obtained from preoperative CBCT images.

Treatment outcomes will be coded as a binary variable (successful/failed) based on the established criteria of Albrektsson and Zarb. Following data collection and preprocessing, various machine learning algorithms will be trained, and their predictive performance will be evaluated.

B. Variables of the Study Within a Conceptual Model and Measurement Methods

The conceptual model of this study is based on the assumption that implant success (dependent variable) is influenced by a complex interaction among three groups of independent variables:

- **Patient-related factors**: age, gender, diabetes, osteoporosis, smoking status, oral hygiene;
- **Local and surgical factors**: maxilla/mandible, anterior/posterior region, bone quality (D1–D4), bone density measured in Hounsfield Units (HU) from CBCT images, implant length and diameter, insertion torque, ISQ values;
- **Prosthetic factors**: type of prosthesis and loading protocol (immediate vs. delayed).

The dependent variable (implant success/failure) will be defined as a binary outcome (1/0) based on documented clinical records and follow-up examinations. Quantitative independent variables such as age and ISQ will be entered numerically, while qualitative variables such as gender and smoking status will be coded (e.g., 0 and 1).

C. Data Collection Methods and Instruments

Data collection will be conducted using a documentary (archival) method supported by digital data extraction tools. Clinical, demographic, and surgical information will be systematically extracted from electronic patient records using a standardized digital checklist designed to ensure consistency and accuracy of data entry. Radiographic data will be collected by accessing the PACS archive and extracting preoperative CBCT images in DICOM format for each patient. No new questionnaires, interviews, or direct patient interactions will be conducted, and all data will be derived exclusively from existing medical records.

D. Statistical Population, Sampling Method, and Sample Size

The statistical population includes all adult patients (≥18 years) who received at least one dental implant between 2019 and 2024 at selected dental centers (Tehran Dental School and affiliated clinics), provided that they have complete medical records and preoperative CBCT images.

Sampling will be performed using a convenience sampling method, and all eligible patients meeting the inclusion criteria will be enrolled. Based on similar studies and to ensure sufficient statistical power for training machine learning models, the target sample size is set at a minimum of 500 patients, corresponding to approximately 800–1000 implants.

E. Data Analysis Methods and Tools

Data analysis will be conducted using **Python** programming language and specialized machine learning libraries,

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including **Scikit-learn, TensorFlow, and PyTorch**. Data preprocessing steps will involve handling missing values and normalization.

The dataset will be divided into **training (80%) and testing (20%) subsets**. Several machine learning models will be developed and compared, including logistic regression (as a baseline model), Random Forest, Support Vector Machine (SVM), and a multilayer perceptron (MLP) neural network.

For CBCT image analysis, a Convolutional Neural Network (CNN) will be employed to automatically extract predictive features. Model performance will be evaluated on the test dataset using metrics such as accuracy, sensitivity, specificity, F1-score, and area under the ROC curve (AUC). Finally, explainable AI techniques, such as SHAP (SHapley Additive exPlanations), will be applied to interpret and explain the predictions of the best-performing model.

Acknowledgments

At this stage of my life, as I enter my forties while navigating various personal challenges, I would like to express my deepest gratitude first and foremost to my parents. My mother, who has been my constant supporter and source of strength up to this moment, and my father, who although is no longer with us, laid a path before me through which I learned not only how to achieve success but also how to uphold human ethics. His material and spiritual support has remained my foundation throughout my life.

I would also like to sincerely thank my husband, **Sohrab Pakzad**, who, through his musical creations, has immortalized my inner beauty in artistic form. His kindness and appreciation of beauty—much like a divine admiration for creation—have always been a source of encouragement and emotional support. I am equally grateful to my sisters, who stood by me during times of loneliness and hardship and shared the weight of life's challenges.

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Academic and Professional Background

I began my academic journey in 2006 by enrolling in an Associate Degree program in Computer Hardware Engineering in Eqlid, Fars Province. In 2010, I obtained an Associate Degree in Software Engineering from Islamic Azad University, Karaj Branch, and completed my final project courses at Iran University of Science and Technology. In 2015, I earned my Bachelor's degree in Software Engineering from Islamic Azad University, Tehran North Branch. I also

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gained professional experience working in the Human Resources Recruitment Department of Bank Saderat of Iran and completed civil engineering–related training courses in Zanjan.
In 2021, I received my Master's degree in Computer Systems Architecture from K. N. Toosi University of Technology, having previously completed specialized technical courses related to this field at Iran University of Science and Technology in 2018.
I am currently pursuing a PhD in Advanced Computer Systems Architecture, with a research focus on Artificial Intelligence in Medicine, at Islamic Azad University, Tehran North Branch. Alongside my doctoral studies, I am actively involved in teaching at the undergraduate level. Additionally, I have undertaken advanced training courses in Artificial Intelligence in Medical Sciences at the Faculty of Medical Sciences under the supervision of expert scholars.
My academic activities include authoring and publishing scientific research articles in my field of study. Beyond academia, I am a certified lifeguard and actively engaged in artistic fields. I hold a Nordic Science Certificate for the Scandinavian regions, have received admission offers from universities in Germany, and have participated in international conferences across Europe. I am also a member of charitable organizations supporting underprivileged regions, actively involved in music, and a member of the Iranian Calligraphers Association.

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