GRADUATION PROJECT

Degree in Dentistry

TITLE:

USE AND PREDICTABILITY OF AI FOR CEPHALOMETRIC ANALYSIS IN ORTHODONTICS

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RESUMEN:

Introducción: En odontología, la inteligencia artificial se ha convertido en una herramienta que debe utilizarse de manera similar a cualquier otro instrumento clínico. Su importancia radica en su utilidad dentro del sistema sanitario, especialmente en la mejora de la predicción de los tratamientos y en el aumento de la precisión diagnóstica. **Objetivos:** El objetivo de este artículo es examinar los diferentes usos y la precisión de la inteligencia artificial en el análisis cefalométrico. **Metodología:** Este estudio revisa el uso y la capacidad predictiva del análisis cefalométrico en ortodoncia, con un enfoque en el papel clave que desempeña la inteligencia artificial. Los datos principales se obtuvieron de la Biblioteca CRAI, específicamente de la base de datos PubMed. Se consideraron artículos publicados en inglés, francés o español en los últimos 5 años. **Resultados:** Inicialmente se identificaron un total de 24 artículos, de los cuales 14 cumplieron con los criterios de inclusión y exclusión y fueron seleccionados para el análisis. Estos estudios evalúan el uso, la fiabilidad y la reproducibilidad de la inteligencia artificial en el análisis cefalométrico. En general, los resultados indican que los sistemas de inteligencia artificial presentan altos niveles de precisión y consistencia, comparables a los de clínicos experimentados. **Conclusiones:** La inteligencia artificial ayuda a los ortodoncistas a ahorrar tiempo y a apoyar la toma de decisiones. Sin embargo, no puede reemplazar el juicio humano. Los sistemas actuales de inteligencia artificial siguen siendo imperfectos, con posibles errores en la localización cefalométrica que requieren verificación manual, aunque estas discrepancias suelen ser clínicamente aceptables. Por lo tanto, la inteligencia artificial debe considerarse actualmente una herramienta de apoyo valiosa para los clínicos. Se espera que su papel se amplíe significativamente en el futuro a medida que las tecnologías continúen mejorando y se integren de forma más fluida en la clínica.

PALABRAS CLAVES:

Odontología, análisis cefalométrico, inteligencia artificial, ortodoncia, predicción.

ABSTRACT:

Introduction: In dentistry, artificial intelligence has become a tool to be used similarly to any other clinical instrument. Its importance lies in its usefulness in the healthcare system, particularly in improving treatments prediction and increasing diagnostic precision. **Objectives:** The aim of this article is to examine the different uses and the accuracy of artificial intelligence in cephalometric analysis. **Methodology:** This study reviews the use and the predictive capacity of cephalometric analysis in orthodontics, with a focus on the key role played by Artificial intelligence. The primary data were obtained from the CRAI Library, specifically from the PubMed databases. Articles published in English or French or Spanish in the last 5 years were considered for the analysis. **Results**: A total of 24 articles were initially identified, of which 14 articles met the inclusion and exclusion criteria, were selected for analysis. These studies evaluate the use, the reliability and reproducibility of artificial intelligence for cephalometric analysis. The findings generally indicate that artificial intelligence systems demonstrate high levels of accuracy and consistency, comparable to those of experienced clinicians. **Conclusions**: Artificial Intelligence helps orthodontists to save time and support clinical decision. However, it cannot replace human judgment. Current artificial intelligence systems remain imperfect, with possible errors in cephalometric placement that require manual verification, although these discrepancies are generally clinically acceptable. Therefore, artificial intelligence should currently be considered a valuable support tool for clinicians. Its role is expected to expand significantly in the future as technologies continue to improve and integrate more seamlessly into clinical practice.

KEYWORDS:

Dentistry, artificial intelligence, cephalometric analysis, orthodontics, predictability.

Table of contents:

1. INTRODUCTION: 1

1.1. General introduction: 1

1.2. Manual cephalometric analysis: 1

1.3. Origin of AI in medicine: 3

1.4. Advantages and inconvenients in manual cephalometric analysis: 4

1.5. Cephalometric analysis by AI in orthodontics: 5

1.5.1. Uses and explication of CNN: 5

1.5.2. Clinical Validation and Accuracy of models: 6

1.6. Differences between AI and manual cephalometric analysis: 6

1.6.1. Comparison Between AI and manual orthodontics: 7

1.6.2. Differences among AI systems: 8

1.6.3. Software evolutions: 9

1.6.4. Precision and clinical implications: 9

1.7. Advantages of using AI in cephalometric analysis: 9

2. OBJETIVES: 11

3. MATERIAL AND METHODS: 12

3.1. Identification of the PICO question 12

3.2. Eligibility criteria 12

3.2.1. Inclusion criteria 12

3.2.2. Exclusion criteria 13

3.3. Data sources and search 13

3.4. Data extraction 13

4. RESULTS: 14

4.1. Study selection: 14

4.2. Summary of results: 16

5. DISCUSSION: 25

5.1. Overall Accuracy of AI-based cephalometric landmarks detection: 25

5.2. Predictability and Reliability of AI Systems and Time efficiency: 25

5.3. Comparison Between AI and Orthodontists through 2D or 3D imaging: 26

5.4. Clinical Impact and Practical Applications: 27

5.5. Methodological Limitations of the Current Evidence: 27

6. CONCLUSIONS: 29

7. SUSTAINABILITY: 30

8. REFERENCES: 31

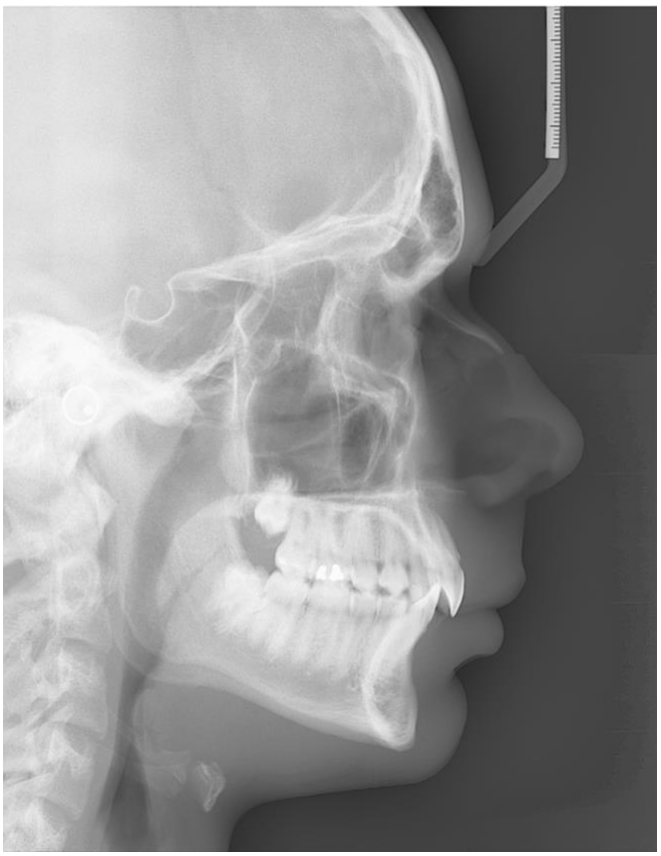
9. ANNEXES..... 35

1. INTRODUCTION:

1.1. General introduction:

In orthodontics, the cephalometric analysis also known as the analysis of human sagittal radiographs of the teeth and facial bones, is extremely important and plays a key role in this domain. Indeed, cephalometry is crucial for obtaining not only diagnostic but also a good prognostic information about the patient. Moreover, it allows us to obtain data on craniofacial morphology, growth patterns, and treatment planning. Orthodontists identify anatomical landmarks by placing specific points, and through the analysis of them, they can measure angles to assess patient's skeletal classes, dental relationships and facial aesthetics. Since everything can be measured, everything can therefore be planned to highlight the importance of performing a proper cephalometric analysis. This was done manually but nowadays; orthodontists would analyse cephalometric data through artificial methods. In the last years and decades, a lot of advances in digital imaging and artificial intelligence (AI) have enhanced the accuracy and precision of cephalometric analyses. This led to time savings and increasingly the aim for diagnostic and prognostics evaluations.

1.2. Manual cephalometric analysis:



Introduced in the 1930s the cephalometric analysis has become a very useful tool for orthodontists. Firstly, it aims to correct craniofacial discrepancies, moreover it can give a complementary diagnostic for aesthetic and functional analysis for orthodontist. Since this tool has appear; not only the eyes of the orthodontist were sufficient. Nowadays this is a mandatory tool for all the orthodontists (1). Standard cephalometric analysis is made by the orthodontist himself on two-dimensional (2D) sagittal cephalograms or three-dimensional (3D) like cone-beam computed tomography (CBCT) images.

One technic used in orthodontic diagnostic and prognostic is the analysis of lateral cephalometric radiographs. It makes it possible to evaluate the dental relationships between the upper and lower teeth and the skeletal bases, as well as the sagittal and vertical skeletal relationships of the maxilla, mandible, and cranial base (2). Example of a table with orthodontics landmarks Table 1: Cephalometric landmarks.

Table 1: Cephalometric landmarks

Anatomical landmarks	**Abbreviations**	**Definitions**
Sella	S	Centre of the pituitary fossa in the sphenoid bone
Nasion	N	Intersection of the nasofrontal suture with the internasal suture in the midsagittal plane
A point	A	Deepest point of the maxilla curve, location between anterior nasal spine (ANS) and the dental alveolus
Porion	Po	Highest point of the ear canal; most superior point of the external auditory meatus
Orbitale	Or	Lowest point of the orbital roof; most inferior point of the external part of the orbital cavity
Pogonion	Pg	Most anterior point on the midsagittal symphysis.
Gnathion	Gn	Midpoint between the most anterior and inferior point on the bony chin
Menton	Me	Most inferior point of the symphysis
Gonion	Go	Most convex point along the inferior border of the ramus

Subnasale	Sn	Point where the centre of the upper lip connects the nose
Soft tissue Pogonion	Pg'	Anterior point on the curve of the soft tissue chin

Cephalometric Planes:

Sella-Nasion plane	SN	Sella - Nasion
Frankfort-Horizontal	FH	Porion - Orbitale
Mandibular plane	Go - Me	Gonion - Menton

It is also useful for detecting for future problems in the airways due to the laterals radiographies in 2 dimensions radiographies (3). The 2D and the analyses require manual localization of anatomical landmarks with a pen and a dental guide plate, which is a time consuming task that can takes approximate 15 min per case for an orthodontist (4). Or 30 minutes depending on the previous experiences of the doctors (5). Nowadays, this is less done manually by humans, but orthodontists are increasingly using AI programs that calculate cephalometric angles for them. All orthodontists need to place the cephalometric points beforehand, and programs such as Dolphin or AudaxCeph calculate these angles (6).

1.3. Origin of AI in medicine:

For this reason, many Scientifics consider John McCarthy to be the father of artificial intelligence, having coined the term in 1955 and documented it during his workshop in 1956 (7). Firstly, used in medicine, AI is nowadays widely applied in radiology and cancerology, particularly for identifying lesions and analysing tissue samples to evaluate disease spread. It can be useful also in every branch of medicine for reducing the risk of cancers for example in stomach cancers in gastroenterology. In cardiology, artificial intelligence contributes significantly to the analysis of electrocardiogram (ECG) data. In medical radiology, where imaging is already digital and easily processed by computers, AI presents numerous opportunities for clinical application. By using large datasets that contain divers pathological patterns associated with disease or mortality, AI systems can perform cross-sectional comparisons and identify similar patterns in other patients. Similarly, the adoption of artificial intelligence in dentistry has increased considerably in recent years. AI tools can assist in diagnosing cavities or carious lesions that are otherwise difficult to

detect, as demineralization becomes visible only when it reaches approximately 40%. Furthermore, AI can support dentists in identifying periapical and periodontal conditions, classifying maxillofacial cysts and tumours, and locating cephalometric reference points in orthodontics analysis (2).

1.4. Advantages and inconvenients in manual cephalometric analysis:

In orthodontics, an accurate diagnosis and effective treatment planning depends mostly on a good cephalometric analysis. By using these teleradiographies, the clinicians can assess the patient's bone growth over time while developing an individualized treatment plan. Moreover, these radiographs allow evaluation not only of bone growth but also of the relationship between the soft and hard tissues that make up the patient's face. This technique and working tool, provide essential anatomical data that support both clinical evaluation and postoperative outcome analysis (4). It is important to take one's time as an orthodontist, because a well-planned and carefully managed case offers an excellent prognosis. Moreover, this approach significantly reduces the risk of treatment failure. We might spend an extra 30 minutes doing the job properly, but it greatly increases the prognosis of success. After all, mistakes are human and always possible but through preparation makes them far less likely. In orthodontics cephalometry, accurate diagnosis and effective treatment planning rely heavily on cephalometric analysis. By doing it manually landmarks are marked in order that all the orthodontists can interpret these values.

As it's done manually it has to be very precise because it can affect the results of the treatment and the prognosis. As the points need to be precises to the millimetre or to the good degree when orthodontists are tracing the lines this is a key moment in the approach of a treatment. Only a slight error of one of the parameters said before and this is all the treatment approach and prognosis that could be affected. Moreover, the human skull is a very complex structure with a lot of relief that plays a key role in orthodontics. If we use only the 2D approach for cephalometric analysis, this give more challenges to the doctors in order to visualize the good approach to have for the patients treatment (8).

To this, we can also add the fatigue and experience of orthodontist in their work, which can influence the accuracy in the technical execution of cephalometric analysis. But also the projection errors during the radiographs themselves or when the patient moved during the

radiographies (9).

1.5. Cephalometric analysis by AI in orthodontics:

As mentioned before, most of the actual orthodontist use the semi-automatic programs by placing the cephalometric points by themselves and the programs like CephX, WeDoCeph, and WebCeph or Nemoceph to calculate the angles and the value in few seconds (10). Traditionally performed by hands, this technique is now increasingly supported by computer-aided methods, appreciated for their speed and ease of use. A breakthrough came from *Arik et al*, who introduced deep convolutional neural networks (CNNs) into fully automated quantitative cephalometry. Their approach, which focuses on identifying anatomical landmarks and analysing pathological features, achieved higher accuracy in landmark detection compared to earlier methods (11). With improvements in diagnostic speed, accuracy, treatment planning and overall patient outcomes, AI technologies such as machine learning, artificial neural networks and deep learning have the potential to completely transform the way that healthcare is provided (12). Orthodontics has been the focus of more research and initiatives in recent years to determine whether algorithms may integrate some aspects of clinical practice because to the technology's rapid and wide range of applications (13).

This cephalometric analysis is therefore essential, as previously seen, for orthodontists. All of this is subject to inter- and intra-practitioner errors. Since the rise of artificial intelligence, one of its goals in orthodontics has been achieved notably through convolutional neural networks, which have made it possible to develop precise and rapid automatic methods for the detection of these points. Several recent studies have focused on the application of CNNs to automate this cephalometric analysis.

1.5.1. Uses and explication of CNN:

A Convolutional Neural Network (CNNs) in orthodontics, could be resumed as a computer system capable of recognizing patterns and characteristic features in a specific domain and interpreting them. Its functioning is relatively simple, if we were to illustrate it, it would be like a building with several floors: the first being convolutional layers, then dense layers and finally a prediction of the coordinates of the cephalometric landmarks. According to several authors, their CNN models allow automatic detection of cephalometric points with an accuracy

comparable to that of a human operator. Moreover, this represents a time-saving advantage while maintaining an acceptable level of accuracy in cephalometric landmark placement (1). This approach is part of a broader trend in the use of AI, not only in orthodontics but also among the general population. In orthodontics, it is used more specifically for diagnosis, treatment planning and the prediction of therapeutic outcomes (14).

1.5.2. Clinical Validation and Accuracy of models:

The comparison of the cephalometric study between the AI and an orthodontist who performs it manually differs very little. Indeed, a difference of less than 2 mm was found for the same patient, whether it was done by a human or by a CNN. This threshold, being small on human scale but large on the scale of a teleradiograph, remains nevertheless acceptable from an orthodontic point of view. Some landmarks remain difficult to identify, whether manually or digitally. This is why certain points may vary from one operator to another. These landmarks are particularly hard to access and cannot be reduced to a single, clinically precise point, but rather to a small area of a few square millimetres. Among these are the porion and the infraorbital region (15). All of this highlights the complexity of obtaining precise landmarks solely manually or through a CNN. This depends not only on the operator's knowledge but also on the quality of the teleradiograph and the performance level of the CNNs.

In addition to all this, new AI-based approaches are being developed for cephalometric analysis in orthodontics patients. Along with the conventional use of teleradiographs, these methods combine the use and analysis of clinical photographs and specialized software. Orthodontics is constantly evolving, practitioners are using an increasing variety of systems and becoming more versatile. This contributes to improving the precision of cephalometric diagnosis, thereby limiting errors and reducing the variability rate of measurement accuracy (16).

1.6. Differences between AI and manual cephalometric analysis:

As saw before, the cephalometric analysis is very important in orthodontics. This part is useful to compare the precision, the reliability and the consistency of CNNs versus manual tracing by orthodontics in cephalometric analysis. They should be equivalent from a lot of point of view, but studies still show discrepancies between them. Through this the landmarks obtain with AI are clinically acceptable, but they are still slight variations between the different landmarks. The

semi-automatic option where the clinician can modify the point the points obtain by the CNNs, is more accurate and faster than the conventional (17). Other programs as the Dolphin software shows differences close to 0 and about 95% of data points within the limits of agreement. However, the semi-automated ones present a greater precision than the full automated version. But they require a human intervention so more time consuming. The values for inter and intra-observer agreements exceeded 0.98 and 0.99. The semi-automated software offers comparable accuracy and aim to traditional software, but human correction still remain necessary for certain landmarks where it is complicated for AI to put them in the right place (6).

The incorporation of AI into dental diagnostics has led to the creation of commercially available AI programs. These systems are linked to a lot of previous orthodontics cases of labelled images, allowing them to recognize a pattern into a specific case. Moreover, it should be capable to identify the characteristics linked to specific anatomical landmarks. Originally, tracing software functioned by connecting points manually marked by the operator with lines. The software would then calculate angles and distances based on predefined algorithms. More recently , an innovation has emerged that enables fully automated detection of various cephalometric landmarks, eliminating dependence on the operation (18).

There are several software programs available on the market. Currently, three of them have been compared: WebCeph™, Cephio, and Ceppro DDH Inc. Not all software performs equally well. The best results are generally obtained with paid programs, whether on a monthly or yearly subscription basis. Free software tends to be less accurate than paid versions.
The quality of each program's database strongly influences both its precision and its processing speed. Overall accuracy remains high for well-defined landmarks such as Sella, but for more difficult points to identify, the precision varies depending on the software used (19).

1.6.1. Comparison Between AI and manual orthodontics:

Studies found no significant differences in the accuracy of AI detection for common reference points such as the nasion, orbital and Sella or for the soft tissue landmarks like the pterygomaxillary fissure. However, in some hard tissue landmarks including the posterior nasal spine, lower and upper incisors, the articular temporomandibular joint, and the pterygomaxillary fissure they show higher differences of values, even with the best CNNs. These

landmarks are more difficult to identify precisely because of anatomical complexity and the differences in X-ray projection between the two sides of the skull. Additionally, in patients with malocclusion, open root apices and dental crowding can reduce the accuracy of AI landmark detection for the upper and lower incisors (20). Related to this, there is also differences between practicians. All the practicians will not obtain the same values as their counterparts. This will depend on the precision of each practician; the experiences and many other factors could play a role. There are often greater differences between two human operators than between a single operator and AI (21).

1.6.2. Differences among AI systems:

Studies showed that both analysis methods were consistent with each other for skeletal and soft tissue measurements. Previous comparisons between manual and digital methods have reported mixed outcomes. Some reporting discrepancies in specific skeletal angles, while others found strong agreement overall supporting the reliability observed in this research (22).

For the AI and App based tools they are also differences. In the maxillary region, the automatic method produced slightly higher average values, showing a significant difference. The same in the mandibular region, a smaller but notable variation was observed. The CNN-based tracing tended to slightly overestimate some skeletal measurements, whereas manual tracing provided more precise results. Dental measurements showed overall agreement between techniques. The semi-automatic method proved to be a good compromise, combining precision and practicality and shows promise for future clinical implementation once further optimized (23).

Although AI-based and manual tracings generally yield comparable overall outcomes, some landmarks particularly Porion and Orbital tend to display greater variability. These differences can be attributed to several factors, including the quality and contrast of the radiographic image as mentioned before. Anatomical differences between patients and the subjective interpretation or experience level of the examiner. Moreover, the inherent limitations of the CNN training datasets. The main problem is that AI models have reached a high level of precision but are not yet autonomous, they require Human supervision which remains essential to validate and correct outputs. These findings highlight the complementarity between AI tools and clinical expertise and saving time. AI does not replace the clinician, but it is also important to highlight the dentist's evolving role in interpreting the information provided by AI.

1.6.3. Software evolutions:

As mentioned previously, cephalometric analysis was first performed manually, then became semi-automated with human assistance for the placement of certain landmarks. Finally, we are now moving toward a system in which everything is fully automated. The first software to appear were notably Dolphin and AudaxCeph, which still require human intervention, to be completely reliable. Later, new CNNs emerged in the field of orthodontics, considerably improving the speed of cephalometric landmarks detection.

AI is a promising tool to facilitate the cephalometric tracing process in routine clinical practice. It can analyse features; it has been trained to detect and becomes faster and more accurate as its dataset expands with new information. Studies have shown that AI errors are typically under 2 mm when placing landmarks, demonstrating an overall increase in precision (24).

1.6.4. Precision and clinical implications:

To verify the accuracy of these software programs, studies have been conducted to determine whether they are clinically acceptable. The precision of these programs is generally considered clinically acceptable, but it is not 100% perfect. Human supervision will always be necessary to verify the values obtained (25). AI therefore becomes just another tool for the practitioner. It doesn't replace them but assists in the diagnostic process, without being able to fully substitute for human analysis of the data. AI plays a key role in strengthening the relationship between patient and practitioner, ensuring a thorough and accurate assessment of each individual case (26).

1.7. Advantages of using AI in cephalometric analysis:

AI can outperform humans in several aspects. As mentioned previously, it can provide clinically acceptable and even highly precise cephalometric measurements for certain landmarks. Thanks to AI, it is possible to obtain accurate and consistent values while significantly reducing the time required compared to manual cephalometric analysis (15,18).

Indeed, the time saved by practitioners is an important advantage of using AI for cephalometric

analysis. AI can reduce the time required for analysis and landmark identification by 15 to 30 minutes. Additionally, some software programs are specifically designed to maximize speed without compromising the accuracy of the algorithms (27).

Another advantage compared to conventional manual cephalometric analysis is the reduction of errors caused by lack of experience. The use of AI can be extremely beneficial for dental or orthodontic students, helping them practice and verify whether landmarks are correctly positioned. AI-assisted and digital cephalometric training has been shown to significantly improve students' landmarking accuracy and learning efficiency (28).

2. OBJETIVES:

The aim of this article is to examine the different uses and the accuracy of artificial intelligence in cephalometric analysis. It tries to highlight how AI contributes to improving diagnostic precision by reducing human error and assisting clinicians in the interpretation and planning of orthodontic treatments.

3. MATERIAL AND METHODS:

This systematized review refers with the PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses, 2020).

3.1. Identification of the PICO question

To conduct a comprehensive electronic search for indexed articles on the use and prediction of AI in cephalometric analysis the following database was used: PubMed.

This search aimed to answer the following clinical question:

In orthodontics patients undergoing diagnostic evaluation, how does digital cephalometric analysis compare with manual tracing affect measurement accuracy, reliability and reproducibility?

This was based on the PICO questions:

P (population): Orthodontic patients.

I (intervention): AI for digital analysis.

C (comparison): Conventional manual cephalometric.

O (outcomes): Accuracy of measurements, intra- and inter-examiner reliability, reproducibility, and time efficiency.

3.2. Eligibility criteria

3.2.1. Inclusion criteria

Inclusion criteria consist of:

Study design: Clinical trials and randomized controlled trials, systematic review and meta-analysis; publications in English, Spanish or French, published between 2021 and 2026.

Population: Humans. Orthodontic patients. Young (<18years) and adult (≥18 years) patients.

Intervention: Studies evaluating cephalometric analysis.

Outcome: Accuracy of cephalometric measurements (cephalometric points and angular values). Intra-observer and inter-observer reliability. Reproducibility and consistency of the methods. Time required for tracing. Clinical relevance of discrepancies (diagnosis, treatment decisions).

3.2.2. Exclusion criteria

Exclusion criteria included: In vitro or animal studies. Letters to the editor, expert opinions, narrative reviews without methodological assessment. Articles that aren't pertinent in this study. Articles not available in full text or free to read. Studies published in languages other than English, Spanish, or French. Publications prior to 2021.

3.3. Data sources and search

A systematised and detailed electronic literature search was done throughs online databases (PubMed) to find relevant references using the following keywords in the databases: "AI", "cephalometric". The Boolean operators AND, OR and NOT were added to keywords to obtain precise search results. The search methodology in PubMed through the Biblioteca CRAI was: Cephalometric AND (ai or ia or artificial intelligence or machine learning). The search was made on the 28 of January 2026. Filters: from 2021-2026; English, Spanish, French and Academic journals (reviewed by a reading committee).

3.4. Data extraction

Data form eligible studies were extracted according to the following variables:

- Year of publication (from 2021 to nowadays) and authors.
- Study design (validation study, cross-sectional, cohort studies, randomized comparison, etc.).
- Sample size (number of patients and number of traces evaluated).
- Type of cephalometric analysis (manual vs digital; software used).
- Measurements evaluated (cephalometric points, angular values, skeletal/dental/soft tissue).
- Reliability and reproducibility indicators (software programs that really exists).
- Intra-examiner reliability.
- Inter-examiner reliability.
- ICC (intraclass correlation coefficient), standard deviation, measurement error
- Clinical impact (influence on diagnosis, skeletal classification, treatment decisions)
- Time efficiency of each method (when it was reported).
- Main conclusions regarding accuracy, reproducibility, and clinical relevance of discrepancies between manual and digital methods.

4. RESULTS:

4.1. Study selection:

110.934 articles were obtained from the primary search on PubMed by searching: "orthodontic". Among them, 427 became possible eligible articles via screening by titles/abstracts. However, some were excluded if they were not in English, Spanish or French, were off-topic or were published before 2021. The full-text articles were then obtained and carefully assessed. As a result, 14 articles met the inclusion criteria and were included in this review (*Figure 1 : PRISMA flow diagram of the search flow and title selection process during the systematised revie*).

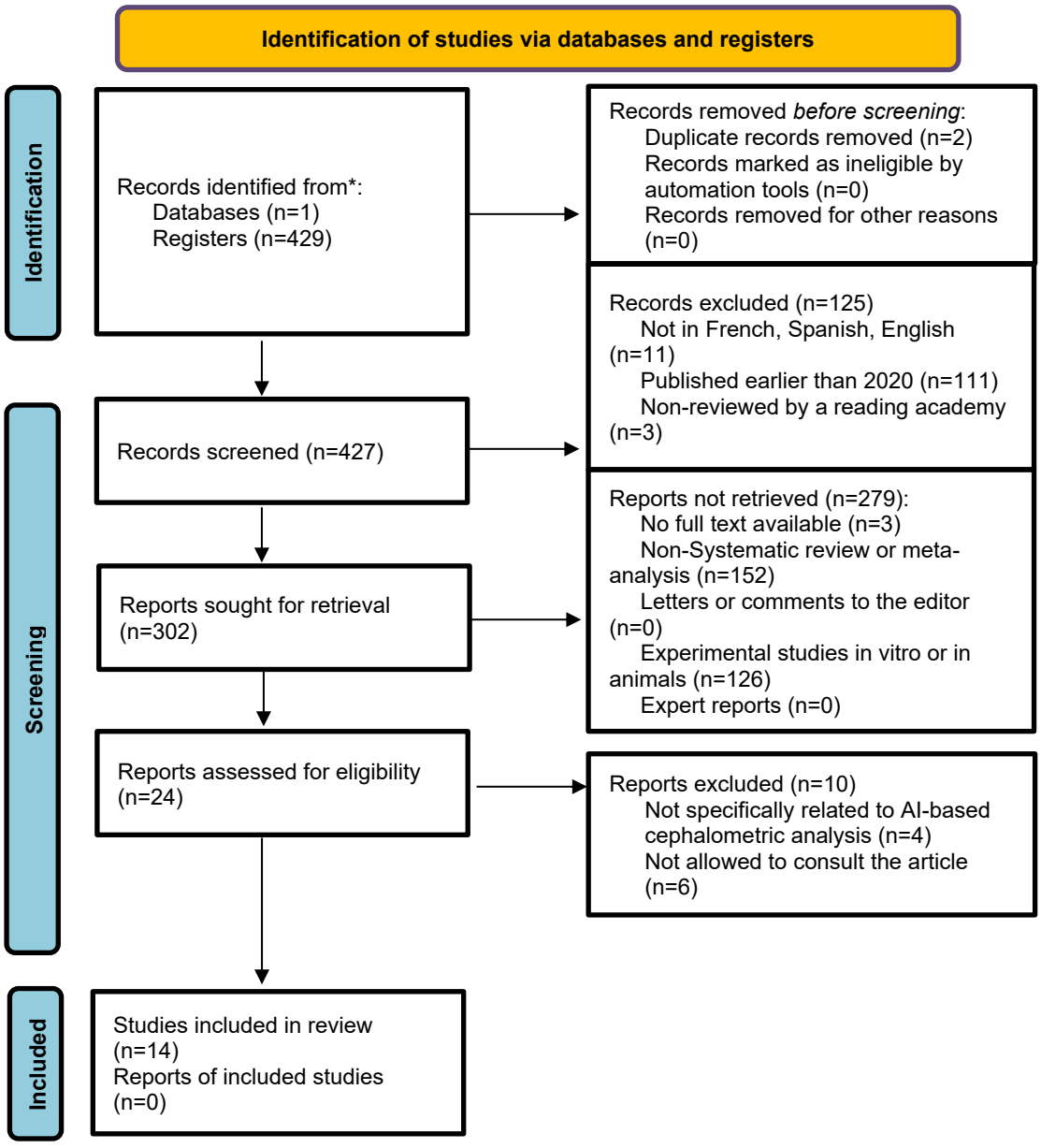


Figure 1 : PRISMA flow diagram of the search flow and title selection process during the systematised review. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews (29). BMJ 2021;372:n71. doi: 10.1136/bmj.n71

4.2. Summary of results:

The results are shown **Table 2**: Characteristics of studies reviewed and **Table 3**: Reliability, reproducibility and clinical outcomes.

***Table 2**: Characteristics of studies reviewed*

Authors and year of publications:	**Study design:**	**Sample size and n= studies:**	**Type of analysis:**	**Software used:**	**Measurements evaluated:**	**Time efficiency:**
Serafin et al., 2023 (30).	Systematic review and meta-analysis	N = 27 15 studies (qualitative) and 11 meta-analyses. Mean of images: 88; mean 47 landmarks	Manual landmarking vs automated deep learning landmarking	CNN-based deep learning (various models depending on included studies)	Learning architectures; 3D cephalometric landmarks; mean error in mm between manual and automated detection	Reported in 8 studies; automated detection reduced identification time
Mesquita et al., 2023 (31).	Systematic review and meta-analysis	N = 40 studies; total of 12,601 imaging exams (11,029 2D Ceph, 1,572 CBCT)	Manual vs AI-based automatic landmark detection (2D and 3D imagining)	Various AI systems including deep learning and handcrafted models	Cephalometric landmarks including: nasion, gonion, menton, orbitale, sella, ANS, PNS, pogonion, etc	Reported in some included studies. AI reduces analysis time compared to manual ones

Math et al., 2025 (32).	Systematic review	N = 16	Manual interpretation vs AI-assisted interpretation of radiographs including cephalometric landmark detection	Mainly CNN-based models; also, web-based AI software such as AssistDent and Diagnocat	Cephalometric landmarks and radiographic diagnostic interpretation accuracy	Reported in some studies; AI assistance reduced diagnostic interpretation time
Polizzi & Leonardi, 2024 (33).	Umbrella of systematic reviews	N = 11	Manual vs automatic AI landmark identification (2D and 3D imaging)	CNN, Machine learning (ML), deep learning algorithms	Cephalometric landmark identification accuracy	Not reported
Hendrickx et al., 2024 (4).	Systematic review and meta-analysis	N = 34; 34 studies included (27 2D, 7 CBCT)	Manual vs AI automated landmark identification	AI-based deep learning and machine learning algorithms	Cephalometric landmarks; mean radial error; success detection rate	Automated landmarking <1 min vs ~15 min manual
Chen et al., 2024 (34).	Systematic review and meta-analysis	N = 42 studies (23 meta-analysis and 19 systematic reviews)	Cephalometric analysis used to evaluate dentoskeletal changes	Not applicable (cephalometric measurement used as outcome tool)	Skeletal and dental measurements (SNA, SNB, ANB, overjet, overbite, U1-SN, L1-MP)	Not reported

Fang et al., 2023 (35).	Retrospective study	502 patients	Machine-learning–based detection of degenerative temporomandibular joint (DJD) vs manual cephalometry	Uceph v4.4.2 (manual tracing); LASSO	36 cephalometric parameters and points	Not reported
Krymovskyy et al., 2024 (36).	Systematic review	N = 37	deep learning vs manual for 3D landmarks in visualization/diagnosis	Invisalign, Clincheck Pro, Maestro 3D, Ormco Insignia, 3Shape OrthoAnalyzer, Dolphin, Anatomage	Publication trends 2016–2023; frequency of 3D technologies (3D scanning: 14 mentions; CAD/CAM: 5; CBCT: 4; 3D printing, Diagnostic performance of models on the training and validation sets, cephalometric landmarks	Not reported
Rauniyar S et al., 2023 (37).	Systematic review	N=7, 7 articles included	Manual tracing (MT) vs AI for cephalometric landmark detection	Machine learning, AI, cellular neural networks	Accuracy of cephalometric landmarks identified by AI/ML vs manual tracing	Not reported

Schwendicke et al., 2021 (38).	Systematic review and meta-analysis	N = 19	Deep Learning vs reference test (experts/annotators) for landmark detection	CNN	Landmark prediction error; proportion within 2 mm; mean error	Not reported
Junaid et al., 2022 (39).	Systematic review	N = 17, 17 full-text articles	AI-based automatic cephalometric analysis vs trained orthodontist	Deep learning-based convolutional neural networks (CNNs)	Accuracy, precision of AI landmark detection; diagnostic performance	AI provides quick outcome (simplifies analysis)
Londono et al., 2023 (40).	Systematic review and meta-analysis	Not specified	Machine Learning algorithms vs clinician performance for landmark prediction	Deep learning, convolutional neural networks (CNNs)	Accuracy of landmark detection/prediction; error reduction	ML algorithms save time
Ardila et al., 2025 (41).	Systematic review and meta-analysis	N = 7	AI-assisted educational interventions vs traditional	Cephalometric landmarking platforms; ChatGPT modules	Global Quality Scale (GQS) for AI content; diagnostic skills, learner engagement	Not reported

Ribas-Sabartés et al., 2024 (42).	Systematic review	N = 13	Manual/professional methods vs AI algorithms for landmark localization	Convolutional neural networks (CNN); YOLOv3 highlighted	Cephalometric landmarks (at least 13 per study); accuracy mean error.	AI generates results quicker than manual

Authors and year of publications:	Intra-examiner reliability (ICC):	Inter-examiner reliability (ICC):	Measurement error / SD:	Reliability of software:	Clinical impact:	Conclusions:
Serafin et al., 2023 (30).	Not reported	Not reported	Mean error approx. 0.49–2.44 mm depending on study	High accuracy for most landmarks	Improved diagnostic reproducibility	Automated landmark detection shows high accuracy
Mesquita et al., 2023 (31).	Reported in included studies but not pooled	Reported in included studies	Mean error approx. 2.05 mm; 79% within 2 mm	High agreement with manual methods	Clinically acceptable accuracy	AI is reliable but requires further validation
Math et al., 2025 (32).	Not reported	Improved observer consistency with AI	Not specifically quantified for cephalometry	AI improves diagnostic consistency	Improved diagnostic accuracy	AI enhances clinician performance but does not replace clinicians
Polizzi & Leonardi, 2024 (33).	Not reported	Not reported	AI error exceeded clinical threshold for some landmarks	Variable reliability depending on landmark and algorithm	Requires orthodontist supervision	AI not yet fully reliable for autonomous clinical use
Hendrickx et al., 2024 (4).	Not reported	Not reported	Mean error 1.39 mm for 2D landmark detection; 1.0–5.8 mm for 3D	High diagnostic accuracy	Improved efficiency and workflow	AI shows strong potential but requires further validation

Chen et al., 2024 (34).	Not reported	Not reported	Not applicable (focus on dentoskeletal treatment changes)	Not applicable	Cephalometric analysis useful for treatment evaluation	Cephalometric measurements effective for evaluating dentoskeletal changes
Fang et al., 2023 (35).	ICC intra-observer >0.75 (50 tracings repeated after 30 days)	ICC inter-observer >0.75	bias 0.08–0.61 mm (all P>0.05) → acceptable reproducibility; no explicit SD reported	High accuracy for most landmarks. Ceph score: (0.861-0.812) combined model (Ceph score + clinical features): (0.893 - 0.828).	Screening tool for DJD using routine lateral cephalograms; assists dentists/orthodontists in identifying high-risk patients in clinical practice	AI models show good reliability and calibration. AI may assist in clinical screening for temporomandibular joint disorder.
Krymovskyy et al., 2024 (36).	Not reported	Not reported	Quality of included articles assessed via Jadad scale but here not reported.	AI: "excellent accuracy results for automated 3D cephalometric landmarking"	Enables full digital replication of clinic operations, improved diagnostic accuracy	AI demonstrates excellent accuracy in 3D landmark detection.

Rauniyar S et al., 2023 (37).	Not reported	Not reported	Not reported	AI/ML: extremely positive/promising results vs manual tracing	AI as diagnostic aid/decision tool in orthodontics; reduces errors	AI landmark detection shows extremely positive results compared to manual tracing
Schwendicke et al., 2021 (38).	Not reported	Not reported	Mean error ~2 mm threshold (-0.581 mm; 95% CI -1.264 to 0.102 mm); proportion within 2 mm: 0.799 (95% CI 0.770–0.824)	relatively high accuracy	High accuracy for automated detection; need for robustness / generalizability	Digital Landmarking shows consistent high accuracy; mostly 2D focus; promising for 3D but sparse data.
Junaid et al., 2022 (39).	Not reported	Not reported	Not reported	precision like trained orthodontist	Simplifies analysis; quick outcome; great benefit to orthodontists	AI performance is comparable to trained orthodontists. Simplify and accelerates the processus.
Londono et al., 2023 (40).	Not reported	Not reported	Not reported	promise for landmark detection (accuracy varies among studies/clinicians)	Reduces errors; improves accuracy; saves time	Machine Learning promising for 2D landmark detection; accuracy varies but improves efficiency

Ardila et al., 2025 (41).	Not reported	Not reported	Not reported.	AI tools: moderate quality; enhances skills/engagement	Improves diagnostic skills, autonomy, satisfaction; barriers: limited integration, scepticism	AI promising in orthodontic education
Ribas-Sabartés et al., 2024 (42).	Not reported	Not reported	Mean error 1.04 ± 0.89 mm to 3.40 ± 1.57 mm (within clinical 2 mm range)	CNN-based: 64.3–97.3% accuracy; YOLOv3 improvements; quick/reproducible but inferior to orthodontists	Promising for landmark detection in 2D radiographs	CNN most effective AI for cephalometric points; AI is quick but less accurate than orthodontists.

***Table 3**: Reliability, reproducibility and clinical outcomes*

5. DISCUSSION:

5.1. Overall Accuracy of AI-based cephalometric landmarks detection:

Following these findings, several important patterns emerge and can be linked together. Most of the included studies report mean landmark detection errors ranging from approximately 0.5 mm to 2.5 mm when compared with the reference standard (4,30,38,42). In addition, many authors indicate that around 79-80% of landmarks fall within a 2 mm deviation, which is commonly regarded as the threshold for clinical acceptability in cephalometric analysis (31). Across the literature, convolutional neural network-based models tend to show the highest levels of accuracy compared with other artificial intelligence approaches. Another important observation is that 2D landmark detection appears more stable and reliable than 3D analysis, as some 3D studies report errors reaching up to 5.8 mm for certain landmarks (4).

However, accuracy is not consistent across all conditions and depends on several factors. Skeletal landmarks are usually more reliably than dental landmarks (34). The type of imagining modality also influences the aim of the landmark positions. With clear differences observed between conventional 2D lateral cephalograms and CBCT-based analysis. Moreover, studies using larger and more diverse datasets generally report better results.
These findings raise an important clinical question: is a 2 mm margin of error truly acceptable for every cephalometric landmark?

5.2. Predictability and Reliability of AI Systems and Time efficiency:

Based on the information obtained in Tables 2 and 3, a clear lack of data can be observed regarding the consistent reporting of parameters, particularly the intraclass correlation coefficient (ICC). Few studies directly assessed intra- and inter-examiner reliability, which represents an important limitation when evaluating the true reproducibility of AI-based cephalometric analysis versus manual cephalometric. In our review, we can see that ICC is greater than 0.75, indicating good reproducibility between different orthodontists (35). However, this remains one of the few studies proving explicit ICC parameter and the reported results should be interpreted with caution due to the lack of examples.

Many systematic reviews highlight a high level of agreement between AI systems and human experts. Yet pooled reliability parameters are frequently missing. This makes it difficult to fully assess reproducibility and limits the strength of the conclusions that can be understood. It

highlights an important point: manual landmark identification itself is subject to variability and is not exempt from methodological errors and limitations (33).
Although landmarking through AI tend to show stable performance overall, their predictability across different patient populations, imaging settings and datasets has not yet been thoroughly validated (4,37). The lack of standardized and consistently reported ICC data males it challenging to reach firm conclusions about their long-term reliability and broader clinical applicability.

Moreover, several reviews indicate that manual landmarking take between 10-15 minutes depending on the proper experience of the orthodontist. Whereas AI landmarking takes less than 1 minute which reduces significantly the time to make the cephalometry (4,42).
By reducing the time around 10 minutes this would improves the clinical workflow, but this doesn't mean that there is an improvement in diagnostic quality by using AI tools. Furthermore, there could be potential economic implications in orthodontics practices.

5.3. Comparison Between AI and Orthodontists through 2D or 3D imaging:

Artificial intelligence now performs almost as well as trained orthodontists when locating many landmarks on X-ray images (39). However, for some landmarks there is still errors that are too big to be clinically acceptable. Which means that the AI cannot be trusted completely. The current AI technology is not reliable enough for fully autonomous use in orthodontics and still requires direct supervision by a qualified orthodontist (33,42).

Moreover, orthodontists can used programs based on 3D and 2D imaging. Scientific evidence on AI for cephalometric landmark detection focuses on traditional 2D lateral cephalograms, where AI has shown strong and consistent performance. However, with the growing use of 3D imaging through CBCT, several programs and deep learning models now enable automated landmark identification directly in three dimensions (36).
While 3D landmark detection has great promise thanks to its ability to avoid superimpositions, distortions and projection errors common in 2D images, studies and reviews indicate higher variability in accuracy compared to 2D methods. Some recent analyses suggest that AI landmarking on 3D CBCT tends to be less precise overall than on 2D radiographs, with greater differences in some landmark positioning through several cases (4,31).
As a result, although progress is rapid and some models achieve clinically acceptable errors, 3D AI landmarking remains more variable and generally requires further refinement and human oversight for reliable clinical use (31).

5.4. Clinical Impact and Practical Applications:

Artificial intelligence brings several benefits to orthodontic practice, particularly in improving the reproducibility of cephalometric landmark identification and diagnosis. Multiple studies show that AI tools achieve higher consistency than manual tracing by human operators, with lower variability in repeated measurements (40,41).

AI shows strong screening potential, for example in detecting degenerative joint disorder (DJD) of the temporomandibular joint developed a machine-learning model that uses lateral cephalograms combined with clinical features for offering a quick way to identify potential issues early in orthodontic patients (35).

In educational applications, AI supports training and skill development. The work highlight how AI-integrated tools, such as digital platforms for cephalometric training, help students and practicians to improve landmarking by making it faster by providing instant feedback, verification and adjustment guidance (41).

However, important barriers still limit the clinical integration of these programs in the dental office. Real regulatory continue to challenge the routine use of these AI tools from a professional point of view. Many lack of full official approval specifically for diagnostic purposes in orthodontics, leaving orthodontists uncertain about relying on them legally and safely in daily practice.

Software differences also create inconsistencies. Performance varies noticeably between systems, which makes it tough to compare results reliably or trust they'll work the same way across different clinics and patient cases.

5.5. Methodological Limitations of the Current Evidence:

Meanwhile promoting accuracy in. many studies, systematic reviews and meta-analysis reveal significant methodological limitations that underrate the reliability of AI for cephalometric landmark detection.

A high risk of bias is frequently noticed, particularly in domains like patient or data selection and reference standards, with most included studies showing concerns in these areas due to non-representative sampling (4,37,38).

Heterogeneity of datasets is another problem: studies often rely on public or limited datasets with variations in image quality, patient demographics and imaging protocols, leading to inconsistent performance and reduced applicability through the real-world (31).

Many primary studies suffer from small sample sizes, which limits statistical power and increases the chance of overlapping, especially when training deep learning models on hundreds rather than thousands of diverse cases. There is notable lack of standardized landmark definitions across investigations, with different numbers of landmarks and varying annotation protocols, making direct comparisons between AI models difficult and contributing to outcome variability (38).

Errors in landmarking are not consistently reported: while mean radial error (MRE), successful detection rate (SDR) and intraclass correlation coefficients (ICC) appear in some papers, they are not uniformly reported, complicating evidence synthesis.

To resume, while AI shows technical promise, these limitations: high bias risk, dataset heterogeneity, small samples, non-standardized definitions, inconsistent metrics, potential publication bias and scarce external validation mean the current evidence base is of low, requiring more rigorous, large sample, externally validated studies before widespread clinical trust.

6. CONCLUSIONS:

In addition to saving time for the orthodontists, AI also helps in clinical decision-making for patient prognosis. While AI cannot fully replace human judgment, it can support and guide the clinician in choosing the most appropriate treatment options by using datasets and sometimes even suggesting solutions that had not been considered by the clinician himself. AI becomes much more than a simple measurement tool, offering value in multiple aspects of orthodontic practices.

Despite advances in the field of AI, a perfect program still does not exist, as perfection itself does not exist it is made up of details. Even the best programs cannot achieve this level of precision. A perfect AI program does not exist, at least; not yet. Some landmarks are very accurately represented by AI in cephalometry, but more complex points can be poorly positioned on radiographs, making them unreadable unless the points are manually adjusted. Ai is not yet perfect and still needs continuous improvement.

Not all software programs are equal. Whether comparing different AI systems or AI versus huma, performance, variations in the placement of certain cephalometric landmarks raise doubts about the reliability of the obtained measurements. Relying solely on AI is therefore a challenge, requiring a careful balance between approximation and precision. In orthodontics, where approximation cannot be taken as reliable, this uncertainty calls into the use of AI for cephalometric analysis.

AI could not replace humans in any scenario at present, as it still requires human verification. For complex and ambiguous cases, the clinician must make decisions that only them can make, not an AI.

Therefore, AI is currently more a useful tool for the practitioner rather than a replacement. However, this should be put into perspective: over the past few years, AI has enhanced significantly and it is possible that in the near or more distant future years or decades, algorithms could play a much larger role, potentially even replacing certain aspects of orthodontic decision-making.

7. SUSTAINABILITY:

The use of artificial intelligence in cephalometric analysis in orthodontics can contribute to several aspects of sustainability, particularly in terms of economic efficiency, environmental impact and social accessibility. By automating landmark identification and measurements, AI can significantly reduce the time required for cephalometric analysis. This increased efficiency may lower operational costs in orthodontics practices and improve workflow management, contributing to a more sustainable healthcare system.

From an environmental point of view, the digitalization and automation of diagnostic procedures can reduce the need for repeated radiographs caused by manual errors or imprecise measurements. This may help decrease unnecessary radiation exposure for patients and limit the use of additional resources. However, the use of AI may also have negative environmental impacts, as store large amount of data and running complex algorithms requires powerful data centres that consume significant amounts of energy and water for cooling.

Socially, AI-assisted diagnostic tools have the potential to improve access to orthodontic assessment by standardizing analyses and supporting clinicians in decision making especially in settings with limited specialist availability. However, the sustainability remains central to diagnosis and treatment planning.

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9. ANNEXES