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Review Article

AI in Cervical Vertebral Maturation Assessment – A Current Evidence and Future Perspectives

[1] Dr. Manjula Marimuthu, [2] Dr. Deenadayalan P., [3] Dr. Akshay Tandon, [4] Dr. Nidhi Angrish, [5] Dr. Katepogu Praveen, [6] Dr. Reshma Mohan and [7] Dr. Deepak Chandrasekharan *

[1] Post-Graduate, Department of Orthodontics and Dentofacial Orthopedics, SRM Kattankulathur Dental College & Hospital, SRM Institute of Technology, Kattankulathur-603203, Chengalpattu District, Tamil Nadu State, India.
[2] Professor, Department of Orthodontics and Dentofacial Orthopedics, SRM Kattankulathur Dental College & Hospital, SRM Institute of Technology, Kattankulathur-603203, Chengalpattu District, Tamil Nadu State, India.
[3] Associate Professor, Department of Orthodontics and Dentofacial Orthopedics, SRM Kattankulathur Dental College & Hospital, SRM Institute of Technology, Kattankulathur-603203, Chengalpattu District, Tamil Nadu State, India.
[4,5,6] Assistant Professor, Department of Orthodontics and Dentofacial Orthopedics, SRM Kattankulathur Dental College & Hospital, SRM Institute of Technology, Kattankulathur-603203, Chengalpattu District, Tamil Nadu State, India.
[7] Professor, HOD, Department of Orthodontics and Dentofacial Orthopedics, SRM Kattankulathur Dental College & Hospital, SRM Institute of Technology, Kattankulathur-603203, Chengalpattu District, Tamil Nadu State, India.

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***Corresponding author: Dr. Deepak Chandrasekharan**
Professor, Head of Department, Department of Orthodontics and Dentofacial Orthopedics, SRM Kattankulathur Dental College & Hospital, SRM Institute of Technology, Kattankulathur-603203, Chengalpattu District, Tamil Nadu State, India.

Abstract

Aim: *To review the current evidence and future perspectives on the application of artificial intelligence (AI), particularly machine learning (ML) and deep learning (DL), in cervical vertebral maturation (CVM) assessment for orthodontic diagnosis and treatment planning.*
Introduction: *Accurate evaluation of skeletal maturity is crucial in orthodontics for optimal treatment timing. Traditional CVM assessment on lateral cephalograms is subjective and prone to variability. AI techniques, especially convolutional neural networks (CNNs), offer potential improvements by providing automated, objective, and reproducible analysis.*
Methodology: *A comprehensive review of recent studies was conducted focusing on AI models used in CVM staging. Various ML algorithms—including artificial neural networks, logistic regression, support vector machines, and CNN architectures such as ResNet, Inception-ResNet, and U-Net—were analyzed for their accuracy, reliability, and clinical applicability in evaluating lateral cephalometric radiographs and CBCT scans.*
Results: *AI-driven models demonstrated high accuracy in classifying CVM stages, with CNN-based approaches often exceeding 90% accuracy. Larger datasets and integration of 3D imaging modalities improved model performance and clinical relevance. Novel models addressing interpretability and incorporating domain-specific filters showed promise for future clinical integration. Despite promising results, variability in study designs and sample sizes highlights the need for further validation.*
Conclusion: *AI applications significantly enhance the precision and consistency of CVM assessment in orthodontics, supporting better treatment timing and decision-making. Future research should focus on expanding diverse datasets, improving algorithm transparency, and validating across populations to facilitate clinical adoption. AI-driven CVM analysis has the potential to transform growth prediction and personalized orthodontic care.*

Keywords: *Artificial Intelligence, Cervical Vertebral Maturation, Orthodontics, Machine Learning, Deep Learning, Convolutional Neural Networks, Skeletal Maturity, Cephalometric Radiographs.*

INTRODUCTION:

Our profession has seen significant changes over the past few decades. Patients and professionals now have a new focus on orthodontic care thanks to the introduction of new and more aesthetically pleasing orthodontic treatment options, the shift to a fully digital workflow, the development of temporary anchorage devices, and new imaging techniques(1)

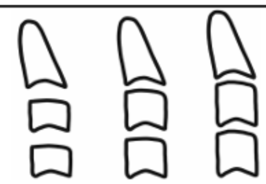
The application of artificial intelligence (AI) in orthodontics has significantly increased in recent years in an effort to improve the accuracy and efficiency of the diagnostic process. This information is essential for forecasting prognosis for treatment. The fact that medical professionals must ultimately diagnose patients and choose the best course of treatment based on their own expertise from years of experience and specialized education is unaffected by the addition of this AI-based knowledge. However, AI can be helpful when making quick clinical decisions. Due to the high accuracy of AI results, which in certain situations can also prevent human error, AI applications can help clinicians make better decisions and perform better.(2)

This review aims to thoroughly examine how artificial intelligence (AI), specifically machine learning (ML) and deep learning approaches, can be used to evaluate cervical vertebral maturation (CVM) in orthodontics. This review aims to assess the clinical utility, accuracy, and dependability of AI-driven models, particularly convolutional neural networks (CNNs), in identifying the stages of skeletal maturity from lateral cephalometric radiographs.

AI IN CERVICAL VERTEBRAL MATURATION

Orthodontics is especially well-suited for the application of AI because of its heavy reliance on imaging and focus on cephalometric analysis.(3) Since growth and maturation are directly related to how well orthodontic treatment works, they are important considerations in the field of orthodontics. Before reaching skeletal maturity, patients receiving orthodontic appliance treatment typically experience optimal growth and harmonious masticatory system development.(4) The amount of remaining growth cannot be accurately predicted by chronological age alone because teenage growth rates vary greatly. Skeletal age is a commonly used and trustworthy metric for assessing personal development, and it can be identified using two primary methods: wrist X-rays and cervical vertebral maturation (CVM)(5) .Stages of CVM are shown in figure 1.

Stages	CS 1	CS 2	CS 3
Inferior borders* (C2, C3, C4)	F, F, F	C, F, F	C, C, F
C3 morphology*	T	T	T
C4 morphology*	T	T	T



Stages	CS 4	CS 5	CS 6
Inferior borders* (C2, C3, C4)	C, C, C	C, C, C	C, C, C
C3 morphology*	RH	S	RV
C4 morphology*	RH	S	RV

Fig 1: The characteristics of different CVM stages. The inferior border and shape of cervical vertebra C2, C3 and C4 are important cues for CVMassessment. (6)

CVM has demonstrated accuracy and reliability in skeletal age assessment and makes use of lateral cephalograms that are commonly obtained during treatment planning. Bacetti in 2005 and Hassel and Farman in 1995 made additional changes to it(7). The process entails assessing the cervical vertebrae's growth and fusion, paying special attention to the second, third, and fourth vertebrae's morphology. Since its inception, the technique has been extensively applied in orthodontics to track skeletal growth and assist in determining the best time for orthodontic treatment. AI's integration into CVM evaluation may help physicians make the right diagnosis because it has already demonstrated its capacity to identify characteristics that human readers might miss.

Role of AI in CVMI Assessment(8)

1. Image Analysis & Feature Extraction

AI (fig 2), particularly Deep Learning (DL) using Convolutional Neural Networks (CNNs), can:

- Automatically detect and segment cervical vertebrae from lateral cephalometric X-rays.
- Extract relevant morphological features (e.g., vertebral shape, concavity) for staging CVMI.

2. Automated Staging

AI models are trained to classify images into **CVMI stages (I–VI)** using large datasets:

- Reduces inter-observer variability.
- Saves time in clinical settings.
- Offers high accuracy, sometimes comparable to experienced clinicians.

3. Integration into Digital Workflows

AI-powered tools can be integrated into:

- Orthodontic diagnostic software.
- Cephalometric analysis platforms.
- Mobile apps or cloud-based tools for tele dentistry.

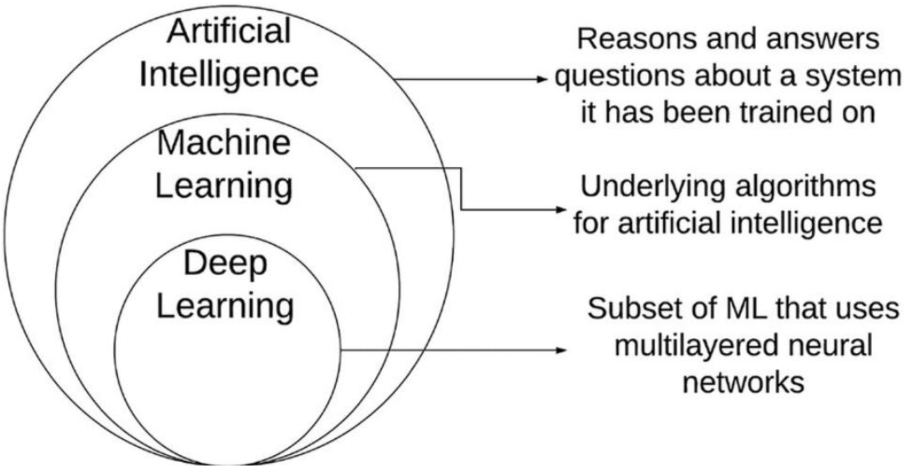


Fig 2: Model of artificial intelligence

The fundamental component of artificial intelligence is machine learning (ML). It uses algorithms to forecast results from data sets and incorporates ideas from a wide range of scientific fields. Its goal is to make it easier for computers to learn from data so they can solve problems without assistance from humans. Support vector machines (SVM), logistic regression (LR), naive Bayesian classifiers, decision trees (DT), random forests (RF), extreme learning machines (ELM), fuzzy k-nearest neighbors (FKNN), and convolution neural networks (CNN) are among the most widely used machine learning techniques.(9)

Neural networks are a set of algorithms that calculate signals through artificial neurons that try to imitate the functioning of human neurons.

Deep learning is an integral part of ML. It uses networks with different computer layers in deep neural networks to analyse input data. Its purpose is to build a neural network that can automati cally recognize patterns to improve feature detection.

Convolutional neural networks (CNNs) are increasingly applied for medical image diagnostics, most frequently for the detection, segmentation or classification of anatomical structures.(10) Deep learning has also recently been used for geometric feature learning and classification. Machine- learning approaches, which are algorithms trained to identify patterns in large data sets, are ideally suited to facilitate data- driven decision- making.(11)

COMMONLY USED CNN NETWORK:

- Alexnet
- VGG16
- Resnet
- U Net
- VGG19
- Googlenet
- V Net or Densenet

Evidence from various studies on AI algorithms used in CVM assessment:

In orthodontics, artificial intelligence (AI) has quickly become a potent tool, especially for evaluating cervical vertebral maturation (CVM), which is essential for assessing growth potential and choosing the best time to start treatment. Variability results from the subjective and examiner-dependent nature of conventional CVM assessment on lateral cephalograms. Researchers have increasingly used deep learning and machine learning (ML) approaches to automate and standardize CVM evaluation in order to get around these restrictions.

Using 300 cephalograms, Hatice Kok et al(12) (2019) compared several machine learning (ML) algorithms and discovered that artificial neural networks (ANN) were more accurate than logistic regression or k-nearest neighbors, while support vector machines and decision trees displayed varying degrees of accuracy. Similar to this, Lizhe Xie et al(13) (2021) showed the potential of logistic regression as a maturity evaluation index in craniofacial orthopedics by applying it to 447 CBCT scans. Convolutional neural networks (CNNs) gained prominence as deep learning progressed.

Hyejun Seo et al(14) (2021) tested a number of models on 600 cephalograms and found that Inception-ResNet-v2 performed the best, with an accuracy of up to 90%. Using 1,080 cephalograms, Jing Zhou et al(15) (2021) verified CNN-based evaluations against human examiners and found high agreement.Reliability was further confirmed by expanding datasets. For example, Haizhen Li et al (16)(2022) evaluated 6,079 cephalograms and determined that ResNet152 was the best model tested. Salih Furkan Atici et al(17) (2022) developed custom CNNs with directional filters that outperformed pre-trained networks, and Ni Liao et al(18)(2022) introduced the interpretable iCVM model. Dong-Wook Kim et al(19)(2021) highlighted AI's function in maximizing treatment timing by combining hand-wrist radiographs with cephalograms.

Suhae Kim et al(20)(2023) emphasized how various CNNs prioritize different craniofacial regions, while Hairui Li et al(21)(2023) developed the high-accuracy psc-CVM system more recently. In order to improve outcome planning, Nazila Ameli et al(22) (2023) applied U-Net to CBCT slices for 3D growth prediction.

Sandhita Agarwal et al(23) (2023) demonstrated strong performance of ResNet-50 and VGG-19. Beyond conventional imaging, Omid Moztarzadeh et al(24) (2023) proposed blockchain-based digital twins using MobileNetV2, suggesting future integration into the metaverse. Most recently, Miran Hikmat Mohammed et al(25)(2024) validated CNN-based multiclass classification as an accurate tool for CVM staging. Collectively, these studies confirm that AI, especially deep learning, provides accurate, reproducible, and clinically valuable support for growth assessment in orthodontics.

Three major stages can be distinguished in the development of AI applications in CVM assessment:

1. Conventional machine learning models like ANN and logistic regression had a modest level of success.
2. Using CNNs for deep learning on 2D cephalograms greatly improved accuracy and dependability.
3. More accurate, comprehensible, and clinically significant applications are being made possible by integration with 3D CBCT and new technologies.

With accuracies frequently surpassing 90%, models such as ResNet, Inception-ResNet, DenseNet, and U-Net have continuously shown superior performance. Additionally, the next step toward broader clinical translation is represented by interpretability-focused models (iCVM), custom CNNs with domain-specific filters (CNNDF), and blockchain-integrated platforms.

Emerging perspectives and future research directions

These developments suggest that AI tools could soon offer clinicians efficient, objective, and repeatable assistance in determining the best time to treat patients who are growing. AI has the potential to completely transform orthodontic growth prediction by offering repeatable, objective evaluations that maximize treatment timing. However, a number of important issues need to be resolved in future research before broad clinical adoption. To increase model robustness and generalizability, datasets must be expanded to include a variety of populations and skeletal maturity indices, such as hand-wrist radiographs, the Cervical Vertebral Maturation Index (CVMI), and newly discovered skeletal biomarkers. In order to promote clinician trust and ease integration into clinical workflows, it will also be essential to improve the interpretability of AI algorithms. Furthermore, to guarantee consistent and dependable performance, thorough crossvalidation across various demographic and ethnic groups is required. Personalized orthodontic growth predictions and better patient outcomes may be possible through collaborative, multi-center studies that integrate sophisticated machine learning with thorough skeletal maturity evaluations.

CONCLUSION:

The studies varied AI algorithms, sample sizes, and research designs, in spite of the encouraging outcomes, may have affected how broadly the results can be applied. Although some studies showed unclear risk, primarily because of a lack of thorough methodological descriptions, the risk of bias was generally low.

In summary, artificial intelligence (AI) holds great promise for improving the precision and dependability of CVM evaluations in orthodontics.AI performance and the limited number of high-quality studies suggest the need for further research.

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