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Precision, Prediction, Perfection: The AI Takeover in Orthodontics.

Deepika Yadav[1], Namrata Dogra[2], Khushal Sharma[3]

[1]Assistant Professor, Department of Orthodontics, Faculty of Dental Sciences, SGT University, India

[2]Professor, Department of Orthodontics, Faculty of Dental Sciences, SGT University, India

[3]Consultant, Swasthya Hospital, India

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ABSTRACT:

Recent years, artificial intelligence technology has been a revolutionary tool in health care system, an increase in application of the technology noted significantly in Orthodontics as well. AI is an outstanding tool to help orthodontists as it can be utilized from the beginning to diagnose till the planning of the treatment. Along with speeding up the diagnosis and treatment processes, automation can cut labour expenses to zero.

AI has shown promising results in enhancing the accuracy of diagnoses, treatment planning, and predicting treatment outcomes. Its usage in orthodontic practices worldwide has increased with the availability of various AI applications and tools.

We have witness the broadening of the application of AI in orthodontics, accompanied by advancements in its performance. Additionally, this review outlines the existing limitations within the field and offers future perspectives.

INTRODUCTION

The practice of dentistry has undergone significant transformation in recent years. It has become possible to create more recent technologies that imitate the way the human brain works[1].The concept of Turing machine was introduced in 1936 byAlan Turing, in order to simulate human calculation. The theory of computation and the Turing machine concept served as the fundamental building blocks for the creation of artificial intelligence (AI). John McCarthy first used the term "artificial intelligence" in 1956[2,3].

Inrecentyears,technologicaladvancementshavepavedthewayfor digitalization in orthodontics, which has largely improved and simplifieddiagnosticandtreatmentplanning workflows. Themainhighlights towards achieving a computer-based digital workflow in orthodontics havebeentheincorporationofthree-dimensional(3D)imagingdevices, computer-aided design and manufacturing platforms (CAD/CAM) and 3D printing.Such technologies offer faster, more precise and predictable treatmentwithlesspatientdiscomfort.

The expert system and machine learning are two important branches of AI. Unlike the knowledge-based expert system, which is established based on predetermined rules and knowledge, machine learning focuses on “learning” from training data to improve its capability[4,5]. In addition to its strong adaptability and generalization capabilities, machine learning is capable of processinglarge-scaledataandhasmoreopen-sourcealgorithms,whichmakesitoneof the most promising technologies in AI.

Artificial neural networks (ANNs), a sub-domain of machine learning, draw inspiration from the biological neural system of the human brain[6]. ANNs have been notably employedtoanalyseintricateconnectionsbetweenmassivedata[7].AnANNtypically has a minimum of three layers, namely, an input layer, an output layer, and at least one hiddenlayer[8].Neuronswithineachlayerareinterconnectedtoestablishanetwork of processors.ANNs encompassing multiple hidden layers are commonly referred to asdeep learning, which has demonstrated exceptional performance in computer vision tasks such

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as classification and segmentation[9].Deep learning is becoming increasingly popular due to its high feasibility and growing computing performance, as well as advancedmodel training algorithms[10]. In addition, one notable advantage of deep learning over traditional machine learning is that it allows automated feature extraction without manual intervention, enabling the better harnessing of the information within the data[11]. Convolutional neural networks (CNNs), one of the most widely used deep learning algorithms, exhibitparticularlyremarkableperformanceinhandlinghigh-resolutionimages[12-14]. InCNN,thehiddenlayersaresubstitutedwiththreedistinct functionallayers, namely, convolution layers, pooling layers, and fully connected layers. The convolution layers employ convolution kernels as filters to generate feature maps. The convolution process effectively reduces image complexity, making CNNs highly suitable for tasks like recognizing objects, shapes, and patterns.The pooling layers are commonly employed after convolutional layers to decrease the dimension of feature maps while retaining essential information.Following several iterations of convolutional and pooling layers, the outputs are integrated in the fully connected layers for further decision making.Consequently, thanks to the abovementioned three layers, CNNs outperform algorithms such as ANNs inimage-related tasks[8,13].(Fig. 1)

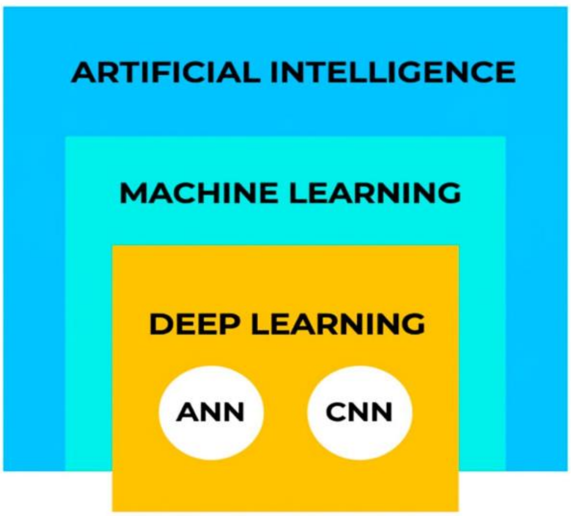

Figure1. SimplifiedAIdiagram.

This shift toward personalized orthodontic care powered by AI is a game-changer. AI-driven systems can optimize the design of orthodontic devices (like braces and aligners) for each patient, factoring in the unique This shift toward personalized orthodontic care powered by AI is a game-changer. AI-driven systems can optimize the design of orthodontic devices (like braces and aligners) for each patient, factoring in the unique characteristics of their teeth and jaw alignment. Asa result, patients can experience faster, more efficient treatments with fewer complications oradjustments[15,16].Thepredictive capabilitiesof AIalso offerthe potential toforecast howlongthetreatmentwilltake,makingtheprocessmoretransparentandreducingthe uncertainty that patients often face during orthodontic care. Furthermore, AI enables continuous monitoring of a patient's progress throughout the treatment journey[17,18]. Using advanced image recognition and predictive modeling, AI systems can assess whether tooth movement is proceeding as expected and provide real-time recommendations to adjust thetreatmentplanifneeded. Thislevelofprecisionandadaptabilityisdifficulttoachieve through traditional methods, making AI-powered solutions an exciting development in orthodontics[19].

1. AI IN ORTHODONTICS

The AI improves the landmark identification process especially in regards ofthe time required for this procedure, however clinicians still need to refine or manually correct the landmark positions beforerigorousassessments.Althougheffortsarebeing made to improve the robustness of the automatic landmark identification tools, the precision and accuracy of landmark identification still requires extensive training and tests beforea fully precise automated landmark identification can be achieved with AI (Fig.2).

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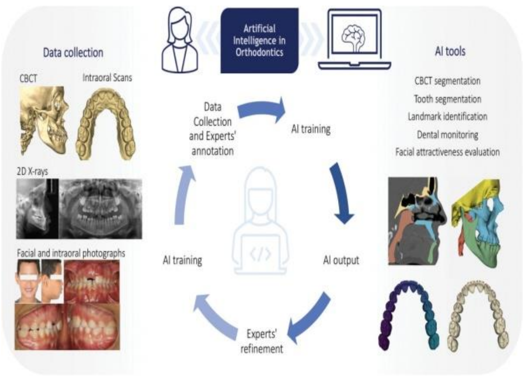

Figure2. SequenceofdevelopmentofAItoolsinorthodontics.

A series of studies have shown that AI can significantly enhance the efficiency of clinical orthodontic practice[20,21]. Several commercially available AI-driven software (3Shape Dental System 2.22.0.0, Uceph 4.2.1, Mastro 3D V6.0 etc.) programs have found widespread applications in orthodontic care. With the ongoing advancement of AI algorithms, computing capabilities and the growing availability datasets, the scope of AI applications in orthodonticsisexpanding,accompaniedbycontinuous performanceimprovement.StayingupdatedonthelatestdevelopmentsofAIapplicationsinorthodonticsthroughtimely summaries helps researchers gain a rapid and accurate understanding of this field.In addition,despiteobtainingencouragingresults,thereis stillsignificantroomforprogress intheapplicationofAIinorthodontics. Therefore,thisreviewprovidesacomprehensive summaryofthecurrentstateofAIapplicationsinorthodontics,encompassingdiagnosis, treatment planning, and clinical practice. Additionally, the review discusses the current limitations of AI and offers future perspectives, aiming to offer valuable insights for the integration of AI into orthodontic practice.

2.1 Diagnosisandtreatmentplanning

Orthodontic diagnosis is a difficult undertaking since it necessitates a complete simultaneous evaluation of various facial components from various angles. With the use of digital dentistry tools, patient information can now be gathered on a digital platform and turned into a database that can be utilized for both diagnosis and treatment.The evaluation burden has been significantly reduced and diagnostic variations have been avoided thanks to automation solutions that use AI and machine learning technology[22,23].

One such AI-based system, developed by Diagnocat Ltd. (San Francisco, CA, USA), utilizes CNNs and provides precise and comprehensive dental diagnostics.The system enables tooth segmentation and enumeration, oral pathology diagnosis (including periapical lesions and caries), and volumetric assessment.Several scientific papers have validatedthediagnosticperformanceofthisprogram,demonstratingitshighefficacyand accuracy[24-28].

2.2 Cephalometric Analysis

Currently AI-based cephalogram are replacing manual tracing and identification of land marks by saving timeand minimizing errors**.** The AI is largely used to recognize and analyze cephalometric landmarks, make extraction decisions, analyze faces, segment teeth and the mandible, determine bone ages, forecast orthognathic surgery and segment the temporomandibular joint.Automated cephalometric tracing was subsequentlyinvestigatedbyanumberofotherresearchers andfoundtobeeffective. Adeepconvolutionalneuralnetwork-basedanalysisfor automated cephalometric tracing was used by Lee et al.[29] The program developed has a high success rate (over 90%), according to the authors in the differential diagnosis of cephalometric landmarks.

Accurateandrepeatablelandmarkidentificationis crucial for reliable CA outcomes. Several studies have demonstrated the effectiveness of AI in identifying cephalometric landmarks. Although lateral radiography remains the most commonlyusedmethodinCA,recentAIadvancements havesparkedrenewedinterestin the use of cone-beam computed tomography (CBCT)[30].

2.3 Estimation of Growth and Development

The determination of patient'sgrowth spurt is critical for orthodontic treatment, especially for those who need functional and orthopedic treatment. Hand–wrist X-rays havebeen regarded as the most conventional and accurate way to determine skeletal age.In recentyears,severalstudieshavereportedcombiningAIwithhand–wristradiographsto predict skeletal age[31-33]. A number of research studies have revealed that the cervical vertebral maturation (CVM) method is also effective for growth estimation and highly correlates with the hand–wrist radiograph method[34-39].

Caution is advised when interpreting AI-assisted CVM assessment studies due to the limited number of expert readers used to establish the gold standard for evaluation. Errors made by these readers may have influenced the study results and subsequently impactedthe performance of the AI algorithm[40]. The lack of scientific evidence in meta-analyses highlights the need for a broader examination of the role of AI in CMR. A recent systematic review by The Angle Orthodontist reported that the model accuracy for test data ranged from 50% to more than 90%. The authors emphasized the importance of conducting new studies to develop robust models and reference standards that can be applied to external datasets.While these findings are encouraging, we anticipate that future advancements inAI technology will enhance the diagnostic accuracy of CMR tools, potentially making them comparable to wrist X-ray assessments for skeletal maturity.

2.4 TMJ examination & disorders

Osteoarthritis (OA) is a condition that affects joints and is characterized by the gradual deteriorationofjointcartilage,boneremodelling,andtheformationofosteoproliferative bodies[41].Temporomandibularjointosteoarthritis(TMJOA)isaspecifictypeoftemporomandibular disorder that can cause significant joint pain, dysfunction, and dental malocclusionandadecreaseinoverallqualityoflife[41]. TheexaminationofTMJfunctionandmorphologyiscrucialinorthodonticanddentaltreatments[42]. TMJOAisone ofthecausesofmalocclusionandfacialasymmetry[43,44]. Radiographicexamination, such as OPG/CBCT, confirms the presence of TMJOA by revealing bony changes[45], while MRI is the preferred modality for evaluating joint discs[42].

Recent studies have demonstrated the high diagnostic performance of AI in detecting and staging TMJOA[45-49].These studies have shown the potential for automated, detailed assessment of joint morphology using various imaging techniques, including OPG, CBCT andMRI.Therefore,theauthorsanticipatethattheuseofAIsystemsforTMJ diagnosticimagingwillcontributetofutureresearchoneearlydetectionandpersonalized treatments for OA.

2.5 Extraction decision making

One of the most challenging issues during orthodontic treatment is deciding whether extraction is mandatory in a particular case. A wrong decision about extraction could cause a series of irreversible problems like an unfavourable profile, improper occlusion and extraction-space closure difficulties. AI can contribute to reducing the likelihood of incorrect tooth extraction protocols. Several AI tools have been introduced in recent years to support therapeutic decisionmakinginorthodontics.

ANNs are the most utilized method to predict extraction diagnosis and patterns[50-55].Jungetal. BuiltanAIexpertsystemwithneural-networkmachinelearningbasedon 12 cephalometric variables and 6 additional indices, reaching a success rate of 93% and 84% in deciding extraction/non-extraction and detailed extraction patterns, respectively.In thisstudy,one-thirdofthelearningdatasetwaschosenasthevalidationsettopreventover-fitting[51].Lietal.adoptedamultilayerpercepteronANNandobtainedsimilarresults, withanaccuracyof94%and84.2%inthedeterminationofextractiondiagnosisandpatterns.

2.6 Orthognathic decision making & planning

Despite significant developments in orthodontics and surgery, there is a lack of clearly established criteria for qualifying patients for surgical procedures.This issue becomes particularly problematic in borderline cases, where the orthodontist faces the decision ofwhethertoreferthepatientforsurgicaltreatmentorcamouflagetreatment[56,57].

Lateralcephalogramsarethemostusedmethodinclinicalpracticetoassesssagittalskeletaldeformities.Severalstudieshaveusedlateralcephalogramsasthe inputdata,whetherusinganANNorCNN,andallachieved accuracyratesexceeding 90%[58,59]. Shin et al. adopted both lateral cephalograms and posteroanterior cephalogramsastheirtrainingdatatotakeboththesagittala

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ndlateralrelationshipof thejawsintoconsideration[60].TheproposedCNNmodelreachedanaccuracyof 95.4%inpredictingorthognathicsurgerydiagnosis.

AsystematicreviewbySalzaretal[61]furtherhighlightedthesignificantheterogeneity amongcurrentstudiesandthedifficultyingeneralizingtheirresults.Theauthorscautiously concluded that AI could be a valuable tool in orthognathic surgery planning, but further research is necessary.

2.7 Management of Impacted Canines

In order to achieve the best orthodontic and periodontal results, impacted canines require extensive therapeutic care. The length of the therapy depends on the difficulty level and how much the canine is displaced from the surrounding teeth. An intermediary stance between statistics andartificialintelligenceistakenbytheBayesianNetwork (BN)[62].

Based on the angular and linear measurements, panoramic and lateral cephalometric radiographs are helpful in predicting an impacted maxillary canine. The random forestmethodhadthebest degree ofaccuracyandcorrectly predicted thecanineeruptioncondition(83%).Incaseswith unilateralcanineimpaction,Wangetal.usedCBCTand amachine learning techniquecalled Learning-based multi-sourceIntegrationframeworkforSegmentation(LINKS)to quantify the variance in the maxilla.

2.8 Upper airway obstruction management

Skeletal deformity and airway obstruction mutually influence each other.Upper-airwayobstructioncanalterbreathing,whichcanaffectthenormaldevelopmentof craniofacial structures and potentially lead to malocclusion and other craniofacial abnormalities. Screening the presence of upper-airway obstruction, especially adenoid hypertrophy,iscriticalfororthodonticdiagnosisandtreatmentplanning.

Dong et al. proposed two deep learning algorithms, the hierarchical masks self-attention U- net(HMSAU-Net)and3D-ResNet,toautomaticallysegmentupperairwaysanddiagnose adenoid hypertrophy, respectively, from CBCT. Of note, a high accuracy of 0.912 was achieved by the adenoid hypertrophy diagnosis model[63].Inadditiontoadenoidhypertrophy,themorphologyandvolumeoftheupperairway are also important indicators for assessing upper-airway obstruction.By using a CNN model, Jeong et al.obtained promising results in automated upper-airway obstruction evaluation based on lateral cephalograms, with a positive predictive value of 0.90 and negative predictive value of 0.85[64].The segmentation of the airway from CBCT can provide a 3D view, enabling the more accurate detection of airway obstruction.Recent studies have shown continuous progress in airway segmentation, with deep learning, especially CNN algorithms, being the most commonly used.

2.9 In Treatment Outcome

Orthodontists face the challenge of selecting the most appropriate treatment strategy for each patient based on their individual expectations, socioeconomic conditions, cultural background, and skills. Currently,AIcanaidinpredicting dental, skeletal and facial changes, as well as patient’s experience of clear aligners, thereby guiding the treatment planning. Orthodontic tooth setup, initially proposed by Kesling, enables the visualization of thetreatmentprogressandfinalocclusion,butmanualtaskslike toothsegmentationand repositionarelabourintensive.Withthecontinuousadvancementsofdigitalorthodontics andartificialintelligence,automatedvirtualsetupshave beenwidelyapplied,especially in the field of clear aligners.Woo et al.compared the accuracy of three pieces of automateddigital-setupsoftwarewiththatofamanualsetupregardingsixdirectionsof tooth movement[65].

In a recent study by Tanikawa et al.[66], a DL model was used to predict the 3D outcomes of orthodontic and orthognathictreatmentinJapanesepatients,resultinginmeanerrorsof0.69 ± 0.28mmand 0.94 ± 0.43mmfortheorthodonticandsurgicalpatientgroups,respectively.Similarly,Park et al.[67] evaluated a DL algorithm that accurately predicted treatment outcomes in terms of3Dfacialchanges, withameanpredictionerrorof1.2 ± 1.01mm.A recent scoping review[68] revealed that AI models are not only efficient but alsoperformconventionalmethodsinorthognathictreatmentplanningandoutcome prediction.This review highlighted the reliability and reproducibility of these models, suggesting their potential to improve clinical outcomes, especially for less experienced practitioners.

2.10 Miscellaneous

The COVID-19 pandemic has brought attention to the importance of social distancing, remote work, and telemedicine. Orthodontic treatment typically lasts approximately 20 months and requires regular progress monitoring and potential complications. Traditional methods of monitoring can be time-consuming and repetitive. However, recent advancements in orthodontics,such as self-ligating systems and aligners,along withthe implementation of telemedicine, have led to the development of dental monitoring (DM)[69]. During the orthodontic treatment, orthodontists often come across various challenges, includingclinicalexpertiseinorthodonticsandpatientcommunicationandmanagement. The application of AI can help facilitate efficient and effective orthodontic treatment regardingpracticeguidance,remotecareandclinicaldocumentation.

Remotemonitoringallowsorthodontiststoremotelytrack treatmentprogressandprovide timely feedback based on photos or oral scans of the dentition, avoiding unnecessary visits, and bringing flexibility and convenience to patients. AIhasenhancedtheapplicationsandeffectivenessofremotemonitoringsoftware[70]. Clinical photos and radiographs are routinely taken for diagnosis and treatment monitoring.AI can aid in classifying and categorizing these images, thereby enhancing the efficiency of clinical practice. Ryu et al. applied CNNs to automatically classify facial and intraoral photographs, including four facial photos and five intraoral photos.The CNN model obtained an overall valid prediction rate of 98%[71].

2. Future Challenges

Orthodontic data sets represent a considerable privacy and security risk due to the sensitive nature of the data they contain—among others, clinical photographs that can make patientsidentifiable.Furthermore,differentdatamodalitiesare usually stored in isolated repositories, referred to as “data silos” (Rischke et al. 2022); accessing them and fusing them remains challenging.

ExplainabilityreferstotheblackboxphenomenonofAI.Deep learningalgorithmsinherentlylacktheabilitytoexplainmodel predictions. Thus, efforts have been undertaken that provide insight into this “black box.” AI-based end-to-end classificationoflateralcephalograms (eg. growthpattern,cervicalvertebrae maturation stages) is not inherently explainable.

Interoperabilitylaysthefoundationtoafrictionlessintegration ofAIintotheclinicalworkflow.Itsimplifiesthedevelopment of AI in orthodontics and streamlines the application in the clinicalworkflow Interoperabilitybecomes more crucial for the development and deployment of multimodalAI.Currently,however,themajorityofclinical note taking in orthodontics lacks standardization. This poses a significant challenge in consolidating these valuable data into datasetsformodeltraining.

Potential errors in automated diagnosis are a major challenge, as AI systems depend on the quality and comprehensiveness of their training data[72].If an AI model has been trained onadatasetthatlackscertaindentalconditions,itmayfailtorecognizeoraccurately diagnoseraremalocclusions,leadingtoincorrector suboptimal treatmentrecommendations.This highlights the need for continuous model improvement, where AI systems areregularly updated with diverse and high-quality datasets to enhance diagnostic accuracy.

Another challenge in AI-driven orthodontics is the high cost of implementation. AI- powered systems, including advanced imaging tools, treatment planning software, and cloud-basedAIservices,requiresubstantialfinancialinvestment[73]. Manyorthodontic practices, particularly smaller clinics, may find the cost of integrating AI prohibitive. To promotewidespreadadoption,AItechnologiesmustbe

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comemoreaffordableandaccessible, with flexible pricing models that allow clinics to adopt AI tools without significant financial strain.

Additionally, over-reliance on AI without orthodontist verification can lead to significant risks.AI-generated treatment plans should always be reviewed by a qualified orthodontist to validate their feasibility. Blindly following AI recommendations without criticalassessmentcouldresultinsuboptimalpatientcare, particularlyifanAImodelfails toconsidercertainbiomechanicalorpatient-specificfactors. AIshouldfunctionasa complementarytool,providingrecommendationsthatorthodontistscanrefinebasedon their clinical expertise.

3. Limitations

Despiteitsmanybenefits,AI-basedorthodontictoolsarenotwithoutlimitations. Overfittingisacommonissueinthewholefieldof AI.Thismeans the model performs excessively well in the training datasets but shows unsatisfactory performance in the testing dataset. Factors like data insufficiency, low data heterogeneity and excessive variables could all lead to overfitting. Methods like improving data samples, data augmentation, regularization, cross-validation and specific algorithms haveallbeenreportedtopreventoverfitting.

Although AI has been extensively explored in orthodontic treatment, there are still several other areas where it could be further investigated, for example, the automated detection of orthodontic treatment needs like the index of orthodontic treatment need (IOTN) and index of orthognathic functional treatment need (IOFTN). Currently, AI excels mostly in orthodontics diagnosis, yet it has limited guidance on the treatment process[73]. Orthodontists may encounter various challenges throughout the entire orthodontic treatment,includingcorrectingdeepoverbitesandavoidingbonedehiscenceorfenestration.Using AI to aid in preventing or addressing these issues could also be a potential area for future development. As clinical data continue to grow and AI computing power improves, there is no doubt that AI will significantly advance the field of orthodontics.

4. Conclusion

Undoubtedly, AI has the potential to revolutionize medicine, particularly in the field of diagnostic imaging, including orthodontics. The continuous advancement of AI algorithms that support pretreatment diagnostic processes allows the visualization of outcomes and facilitates decision making during treatment, placing orthodontics among the disciplines benefiting the most from the introduction of AI technology.

ByleveragingAI'ssophisticatedpredictivecapabilities ,orthodontistsareabletodevelop highly individualized treatment plans that not only improve patient outcomes but also significantlyreducetreatmenttimes.AI'sabilitytopredicttoothmovement,optimizealigner and brace design, and continuously monitor treatment progress allows for a more effective andstreamlinedapproachtoorthodonticcare.Despitethe manybenefits,challengessuch as data security, algorithmic bias, and the need for widespread adoption remain. These obstacles must be addressed to ensure that AI technologies are applied ethically and equitably across diverse patient populations.

As AI continues to evolve and integrate with other advancedtechnologieslikeroboticsand3Dprinting,the futureoforthodonticswilllikely become more accessible, cost-effective, and patient-centered. The ongoing development ofAIholdsthepromiseoftransformingnotonlythepatientexperiencebutalsotheoverall landscapeoforthodonticcare,leadingtobetterdentalhealthoutcomesonaglobalscale.

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