FINAL MANAGEMENT COMMITTEE MEETING

COST Action CA24147 – AID-AgE

AgEstimation project

COST Action CA24147

Artificial Intelligence Driven Dental AgEstimation Network (AID-AgE)

PROCEEDINGS BOOK

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FINAL MANAGEMENT COMMITTEE MEETING

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Artificial Intelligence Driven Dental AgEstimation Network (AID-AgE)

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Artificial Intelligence Driven Dental AgEstimation Network (AID-AgE)

FINAL MANAGEMENT COMMITTEE MEETING

COST Action CA24147 – AID-AgE

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Artificial Intelligence Driven Dental AgEstimation Network (AID-AgE)

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CONTENTS

PREFACE

Dear Readers and Participants,

The Cooperation in Science and Technology (COST) Action CA24147 – Artificial Intelligence Driven Dental AgEstimation Network (AID-AgE) is a European research network dedicated to advancing artificial intelligence (AI)-based methods for biological age estimation.

The Action officially commenced on 31 October 2025 in Brussels and will run until 30 October 2029. It is coordinated by Prof. Dr. Roberto Cameriere (Chair, Italy), together with Prof. Dr. Ayşe Gulsahi (Vice-Chair, Türkiye) and Prof. Dr. Cristiana Palmela Pereira (Scientific Grant Holder Representative, Portugal).

The primary objective of AID-AgE is to develop and validate AI-driven models for biological age assessment using biological markers, particularly dental structures analysed through radiographic imaging. By integrating advanced AI techniques with panoramic radiography (orthopantomography, OPG), periapical radiographs, and cone-beam computed tomography (CBCT), the Action seeks to improve the accuracy, reproducibility, and reliability of forensic and judicial age estimation.

Recognising that several European countries have already established national research initiatives in this field, AID-AgE aims to create a coherent and interoperable European framework that aligns scientific, technical, and legal perspectives. The Action promotes the exchange of knowledge, harmonisation of methodologies, and validation of AI-based models across different populations and jurisdictions.

AID-AgE bridges the gap between traditional radiographic approaches and emerging digital technologies by fostering an interdisciplinary network that brings together odontologists, radiologists, forensic anthropologists, computer scientists, legal scholars, and other experts. Through collaborative research, shared standards, and the ethical implementation of AI, the network seeks to establish a trustworthy, explainable, and scientifically validated European framework for forensic and judicial age estimation.

The project is organised through dedicated Working Groups focusing on data collection, AI model development, validation, software implementation, and clinical integration. AI models will be trained to analyse developmental indicators such as tooth mineralisation and root formation, with the aim of automating and enhancing the precision of established age estimation methods. The resulting software tools are being designed to be user-friendly and applicable in both medical and legal settings, while also accounting for genetic, environmental, and socio-economic factors that influence biological development.

In the long term, AID-AgE aspires to establish internationally accepted standards for AI-assisted dental age estimation, facilitating their adoption in clinical practice, forensic investigations, humanitarian missions, and judicial proceedings. By combining cutting-edge AI technologies with established forensic methodologies, the Action has the potential to transform current practice through more precise, reliable, and standardised age estimation procedures.

The Management Committee currently includes representatives from Albania, Bosnia and Herzegovina, Croatia, Cyprus, Czechia, France, Georgia, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Montenegro, the Netherlands, North Macedonia, Poland, Portugal, Romania, Serbia, Slovenia, Spain, Switzerland, and Türkiye, reflecting the Action's strong international and multidisciplinary character. A central pillar of the project is the education, training, and empowerment of early-career researchers, who represent the future of forensic odontology and forensic sciences.

Beyond Europe, the Action actively seeks to expand its international network by establishing partnerships with researchers and institutions in Africa, Asia, and Central and South America. Such collaborations are particularly important in addressing humanitarian and legal challenges related to human identification and age assessment in migration and disaster-response contexts.

The Technical Seminar and International Workshop in Lisbon, held on 7–8 September 2026, represents another important milestone in this collaborative effort. As part of a continuing series of AID-AgE meetings, the seminar provides an opportunity to exchange knowledge, strengthen scientific cooperation, and advance the development and validation of trustworthy AI-based tools for biological age estimation from radiographic images. Ultimately, these efforts contribute to the establishment of new European and global standards in forensic odontology founded on scientific excellence, transparency, and ethical responsibility.

We wish you a productive, inspiring, and enjoyable stay during the Final Management Committee Meeting in Lisbon.

Professor Hrvoje Brkić
Science Communication Coordinator

https://aidage.eu   https://be.linkedin.com/in/cost-action-2934103b3

Instagram https://www.instagram.com/cost_action_aid_ige/

PROGRAMME OVERVIEW

MONDAY, September 7, 2026

09:00 – 12:30 **MC MEETING**

09:00 – 10:00 Registration of COST Participants and Welcome Coffee

10:00 – 10:20 **Opening**

Professor Cristiana Palmela Pereira

Professor Marília Antunes

10:20 – 10:30 Working Group Progress Meeting: **WG1**

10:30 – 10:40 Working Group Progress Meeting: **WG2**

10:40 – 10:50 Working Group Progress Meeting: **WG3**

10:50 – 11:00 Working Group Progress Meeting: **WG4**

11:00 – 11:10 Working Group Progress Meeting: **WG5**

11:10 – 11:20 Working Group Progress Meeting: **WG6**

11:20 – 11:30 Working Group Progress Meeting: **WG7**

11:30 – 12:15 **Discussion**

12:15 – 12:30 All together photo

12:30 – 14:15 **Lunch break**

14:15 – 14:30 Registration of External Participants

14:30 – 17:30 **TECHNICAL SEMINAR**

14:30 – 14:45 **Opening**

Professor Cristiana Palmela Pereira

14:45 – 15:30 Teaching Machines to Read Teeth: A Primer on Neural Networks for Dental Age Estimation

Professor Carlos Grilo

15:30 – 16:00 **Coffee break**

16:00 – 16:20 Pilot Evaluation of Image Preprocessing and YOLO-Based Anatomical Cropping in Hand-Wrist Radiographs

Dr. Ana Rodrigues
Dr. Valon Nushi
Francisco Afonseca
Professor Rui Santos
Professor Cristiana Palmela Pereira

16:20 – 16:40 From Networking to Innovation: Lessons Learned from the MDVI COST Action

Dr. Petra Urbanová
Dr. Tomáš Rebok
Dr. Sarah Shrimpton
Professor Caroline Wilkinson

16:40 – 17:30 AID-AgE Application Demonstration

Professor Roberto Cameriere

TUESDAY, September 8, 2026

10:00 – 11:30 **MC MEETING**

11:30 – 12:00 **CORE GROUP MEETING**

12:00 – 13:45 **Lunch break**

13:45 – 14:00 Registration of External Participants

14:00 – 18:00 **INTERNATIONAL WORKSHOP AgEstimation at a Turning Point? The Role of AI and COST Action CA24147**

14:00 – 14:20 Medico-legal Age Assessment in Living Individuals: From Expert Examination to Artificial Intelligence-Assisted Decision Support

Professor Cristiana Palmela Pereira

14:20 – 14:40 Key Aspects of the Strategy COST Action AID-AgE

Professor Hrvoje Brkić

Professor Ivan Galić

14:40 – 15:30 **MAIN SESSION**

1. AgEstimation Project: History, Methods and Scientific Philosophy
2. AgEstimation in the AI Era: The New Platform

Professor Roberto Cameriere

15:30 – 16:00 **Coffee break**

16:00 – 18:00 **MAIN SESSION**

3. Practical Session

Professor Roberto Cameriere

WORKING GROUPS ACTIVITY REPORTS

WG1 – Medical Imaging Acquisition

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[3] Orthodontist, PhD

Keywords: Adult Age Estimation; Artificial Intelligence; Forensic Odontology; Panoramic Radiography; Third Molar.

Objective

Working Group 1 (WG1) of COST Action CA24147 – Artificial Intelligence Driven Dental AgEstimation Network (AID-AgE) is dedicated to the identification, collection and harmonisation of radiological material suitable for age estimation research and for the subsequent development and validation of artificial intelligence applications. Following the recent reorganisation of WG1 leadership, the current priority is to consolidate the resources already available within the network and to define a common strategy for expanding image collection across different countries and populations. The objective of this contribution is to present the current framework of WG1 activities and the priorities proposed for the next phase of the Action.

Discussion

AID-AgE already brings together researchers and institutions with access to radiological material from several European and non-European populations. At the same time, new data collection initiatives are being developed, with particular attention to African countries, including Algeria, Nigeria, Kenya, Namibia and Somalia. This geographical expansion is particularly important for increasing population diversity and reducing the lack of reference data for age estimation in some geographical areas.

For dental age estimation, panoramic radiographs represent one of the main sources of information, with third molar development providing an important indicator during late adolescence and the transition to adulthood.[1–5] Other skeletal indicators, including cervical vertebral maturation and knee epiphyseal development, may complement dental information in specific age ranges and around thresholds of medico-legal relevance.[6–8]

The next objective of WG1 will therefore not simply be to increase the number of available images, but to establish common criteria for their selection, quality assessment and organisation. Radiological material should be accompanied by a limited set of essential information, particularly chronological age, sex, and country or population of origin, while avoiding the collection of unnecessary personal information.

This activity necessarily requires close interaction with the other Working Groups. WG2 will have a central role in transforming the collected material into structured and usable datasets, while WG3 will need to define the technical requirements and image characteristics necessary for the development of AI tools. WG1 will therefore need to progressively adapt image collection and harmonisation to these requirements, while maintaining appropriate radiological standards and methodological consistency.

A further objective will be to define a shared protocol that can be used both by centres already involved in the network and by those joining at a later stage. Such a protocol should facilitate the inclusion of new countries, improve comparability between different data collections, and create the conditions for reproducible multicentre studies.

Conclusions

The next phase of WG1 should therefore mark the transition from the identification and initial collection of available radiological resources towards a coordinated, standardised and progressively expanding multinational image collection. Particular attention should be given to geographical diversity, the definition of common quality criteria, and close interaction with WG2 and WG3.

The ultimate aim is to provide AID-AgE with reliable and representative radiological material suitable for quantitative age estimation methods and for the development and validation of AI-supported models. AI-based approaches have already been investigated for the classification of third molar development around medico-legal age thresholds.[9]

From this perspective, AI may support and complement established quantitative methodologies while maintaining their underlying scientific principles.

Conflicts of interest

The authors declare no conflict of interests.

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WG2 – Dataset Creation and Annotation

Ksenija Zelić Mihajlović[1,2]

[1] Senior Research Associate, School of Dental Medicine, University of Belgrade, Belgrade, Serbia

[2] WG2 Leader

During the reporting period (31.10.2025-31.10.2026.), Working Group 2 (WG2 – Dataset Creation and Annotation) focused on activities that significantly contributed to capacity building, knowledge transfer, networking, and dissemination of the COST Action CA24147 – *Artificial Intelligence Driven Dental AgEstimation Network (AID-AgE)*. A substantial proportion of WG2 members actively participated in the planning and implementation of these activities, ensuring strong engagement of the consortium and attracting new researchers to the Action.

The major achievement of WG2 was the successful organization of the first face-to-face COST Action event—the Training School *Forensic and Radiographic Methods in AI-Based Age Estimation: Practical Application and Knowledge Transfer*, held in Belgrade, Serbia, on 11–12 May 2026. The first day consisted of lectures delivered by internationally recognized experts in dental age estimation and forensic odontology, including Prof. Roberto Cameriere (University of Macerata), Prof. Hrvoje Brkic (University of Zagreb), Prof. Cristiana Pamela Pereira (University of Lisbon), Prof. Ivan Galic (University of Split), Prof. Aida Selmanagic (University of Sarajevo), together with experts from the University of Belgrade (dr Ksenija Zelic Mihajlovic and Ksenija Djukic).

The second day was dedicated to practical workshops, where participants received hands-on training in both conventional dental age estimation methods and their implementation through an AI-supported digital platform. Participants learned how established age estimation techniques can be performed more efficiently using artificial intelligence and validated digital workflows. The workshops demonstrated that even participants with no previous experience in AI-assisted age estimation were able to quickly adopt the methodology and successfully complete practical exercises.

An additional workshop focused on skeletal material analysis, including both juvenile and adult skulls and skeletal specimens relevant to forensic anthropology and archaeology. Participants combined direct examination of skeletal material with radiographic image analysis and AI-assisted assessment, providing a comprehensive overview of multidisciplinary age estimation approaches.

The Training School proved to be highly successful, receiving excellent feedback from participants. Beyond the educational outcomes, it substantially strengthened networking within the Action. New collaborations were established among researchers from different countries and disciplines, many of which have continued through formal and informal communication following the event.

WG2 members were also actively involved in dissemination activities throughout the reporting period. The objectives of the COST Action and the importance of artificial intelligence in dental age estimation were presented at several national scientific meetings, including the Annual Symposium of Paediatric Preventive and Restorative Dentistry in Sombor(1,2), the CNN Conference hosted by the Faculty of Mechanical Engineering, University of Belgrade(3), Annual scientific meeting of Archaeological Society of Serbia in Leskovac and a conferences dedicated to artificial intelligence in social sciences hosted by Faculty of Philosophy, University of Novi Sad.(4,5) These activities increased the visibility of the Action, promoted interdisciplinary collaboration, and raised awareness of the growing role of artificial intelligence in forensic odontology, archaeology, and clinical dentistry.

Conflicts of interest

The author declares no conflict of interests.

Acknowledgements

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WG3 – AI Development and Engineering Group

Cristiana Palmela Pereira[1], Roberto Cameriere[2,3]

[1] Grant Holder Scientific Representative

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[3] COST Action Chair

WG3 is responsible for developing the artificial intelligence algorithms and computational models to be used for dental age assessment.(1-9)

Its tasks, as defined in the MoU, are:

- Designing and implementing machine learning and deep learning models specifically designed to the analysis of dental images;
- Collaborating closely with WG2 — Dataset Creation and Annotation Group to ensure that the datasets meet the technical requirements and to optimise model performance;
- Conducting iterative testing, evaluation, and refinement of the models to improve their accuracy, sensibility, and applicability;
- Exploring advanced computational approaches, including graph-based representations and Graph Neural Networks, whenever appropriate for modelling structured and relational data;
- Integrating the Dental Age Assessment Ontology as a structured knowledge framework to harmonise concepts, terminology, methods, developmental stages, anatomical features, legal age thresholds, and contextual variables used in dental age assessment;
- Investigating the combination of data-driven models with ontology-based knowledge to improve semantic interoperability, consistency, interpretability, and judicial decision support;
- Contributing to the development of explainable models suitable for clinical, forensic, and legal applications.

The potential use of Graph Neural Networks is supported by recent research demonstrating that complex structured information can be represented as graphs and processed using graph-based architectures. Graph-based representations and Graph Neural Networks may be explored to model complex relationships among imaging features, anatomical structures, developmental stages, age-related variables, and contextual information. These approaches may support the efficient analysis of structured data and the approximation of computationally demanding tasks. Their development should include reproducible preprocessing procedures, appropriate reference standards, independent testing, and rigorous evaluation using both internal and external datasets. Particular attention should be given to model generalisability across different populations, institutions, imaging modalities, and dataset sizes, as performance may decrease when models are applied to data that differ substantially from those used during training.

The Dental Age Assessment Ontology can complement image-based models by providing a machine-readable representation of the domain. It may support the standardisation of variables and outputs, the connection of radiographic findings with established dental age assessment methods, the documentation of the reasoning underlying an estimate, and the integration of chronological age, biological indicators, sex, population-related factors, uncertainty, and legally relevant age thresholds.(10)

The MoU establishes that WG3 will design, implement, and test the dental age assessment models between months 17 and 32 of the Action. These models will subsequently be assessed by WG4 — Clinical Validation Group, including comparison with conventional dental age assessment methods.

In summary, WG3 will transform the images, annotations, and structured knowledge prepared within the Action into computational models for dental age assessment. It will test and refine these models and contribute to their technical reliability, interpretability, semantic consistency, and readiness for subsequent clinical and forensic validation.

Conflicts of interest

The authors declare no conflict of interests.

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WG4 – Clinical Validation and Standardisation: Towards Harmonised Validation Frameworks for Artificial Intelligence-Driven Dental Age Estimation

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Keywords: Artificial Intelligence; Clinical Validation; Dental Age Estimation; Forensic Odontology; Standardisation.

Introduction

Traditional dental age estimation methods, such as those developed by Demirjian et al.(1) and Cameriere et al.(2), have long been used in forensic and clinical practice, relying on manual assessment of tooth mineralisation stages or root apex measurements. Artificial intelligence (AI) is rapidly transforming dental age estimation by offering new opportunities for automated image analysis and decision support.(3–6) However, the implementation of AI in forensic and clinical practice requires rigorous validation, reproducibility and harmonised evaluation methodologies.(3,4) Within COST Action CA24147 – Artificial Intelligence Driven Dental Age Estimation Network (AID-AgE), Working Group 4 (WG4) was established to address these challenges by promoting clinical validation and standardization across participating countries.(7)

Discussion

During the first Grant Period, WG4 contributed to the development of a collaborative framework for clinical validation within the AID-AgE network.(7) The Working Group promoted interdisciplinary dialogue between experts in forensic odontology, orthodontics, dentomaxillofacial radiology and artificial intelligence to identify methodological requirements for validating AI-driven dental age estimation systems. (3,4) Discussions focused on the importance of harmonised validation protocols, reproducible evaluation procedures, expert consensus and population-specific considerations when assessing AI performance.(3-6) WG4 also supported the identification of future priorities aimed at strengthening multicentre collaboration and facilitating the development of standardised methodologies applicable across different institutions and populations. These activities provide the scientific basis for future collaborative validation studies and contribute to the responsible implementation of AI technologies in forensic odontology.

Conclusions

Clinical validation represents a fundamental step in translating AI-based dental age estimation from research into routine forensic and clinical practice [3–6]. WG4 provides the methodological framework necessary to support reliable, reproducible and clinically meaningful validation strategies within AID-AgE [7]. Future activities will focus on harmonised validation protocols, expert-annotated reference datasets, multicentre collaboration and standardisation of biological age assessment methodologies to strengthen international research and improve the clinical applicability of artificial intelligence [3,4].

Conflicts of interest

The author declares no conflict of interests.

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WG5 – Data Management and Privacy

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Keywords: Radiographic Images; GDPR; Data Management; AID-AgE.

Objectives

Working Group 5 is responsible for the secure collection, transfer and handling of all acquired radiographic images and the accompanying personal information.(1,2) In particular, the role of this working group is to handle all the radiographs, and the complementary personal data, that will be used within the context of the Action, securely and in accordance with the privacy regulations, including the General Data Protection Regulation (GDPR 2016/679), as well as national data protection regulations of participating countries.(3-6) The tasks of this working group include the developing and using of data management protocols regarding the secure collection, transfer, storage, handle and share of radiographic images and the related sensitive information; Anonymizing datasets to protect patient privacy; Ensuring all data handling procedures comply with relevant legal and ethical standards. By ensuring all the above the WG5 will support the objectives of all the other WGs and especially WG3 and WG 5.

Summary of Activities in the Reporting Period

From the initiation of the Action until the end of July 2026 the WG leader (Anastasia Mitsea) and co-leader (Kety Karagianni) have participated in the Core Group and MC meetings coordinating with the leaders and co-leader of other WGs. In particular, after WG3 finalizes and clarifies the kind, quality, quantity and special characteristics of the radiographic images that are necessary to recruit for the Action, we will finalize the draft document that we have already prepared concerning the data management and privacy. This document is fundamental for the interaction of WG1 (imaging), WG2 (dataset/annotation), WG3 (AI development), and WG4 (clinical validation).

By now, a draft document has been prepared and will be finalized shortly after our recent collaboration with Dr. Noemia Bessa Vilela with scientific background of Law, Comparative Law, ethics to ensure that all EU legal and ethical issues will be addressed. Specifically, the document will include A) a Data Management Plan (DMP) for the Action and B) a collaboration agreement. Concerning the data management Plan/ Protocol, it will include instructions about the radiographic images that will be used. Specifically, we will use all formats (e.g. jpg., DICOM) of intraoral and extraoral radiographic images (e.g. panoramic and cephalometric x-rays , CT, CBCT, MRI), and hand and wrist x-rays. Apart from data specification, the document will be also referred to, derived data, data processing, and data transfer procedures. We will clarify the secure data-sharing procedures between WGs members and participating institutions and emphasize the for-data protection officers (DPO's). Each institution will have to provide the relevant ethical approval and informed consent documents for recruiting radiographic images. Since each image is associated with sensitive data like chronological age and sex, clinical and radiological findings, imaging parameters anonymization procedures will be followed.
Regarding the collaboration agreement, a clarified publication policy will be agreed by all parties and should be followed. All parties will have to agree on confidentiality of all information, data and materials. Finaly the document will be referred to intellectual property of the data, rights of the data subjects, as well as the publication policy. All the above will go into detail in the final document, taking into account all relevant parameters, ethical and legal issues.
All participants will have to follow the procedures and rules that will be presented in the final document regarding ethical and regulatory issues. We will account for all potential challenges and delays such as harmonization of consent and privacy rules of all participating countries, delays in ethical approvals etc. We plan to have finalize the document until our next MC meeting in order to have feedback from all MC members.

Conflicts of interest

The author declares no conflict of interests.

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WG6 – Dissemination and Communication

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Keywords: COST; AID-AgE; Communication; Dissemination.

Introduction

The Dissemination, Communication Strategy will ensure that the project's results are effectively shared, understood, and used by relevant audiences. Dissemination activities will target the scientific and professional communities through publications, conferences, workshops, and open-access outputs. Communication activities will raise awareness of the project among wider stakeholders, policymakers, and the general public through channels such as the project website, social media, newsletters, and outreach events. Exploitation activities will focus on maximizing the long-term value and practical use of the project results, including academic, political, societal, and, where relevant, commercial uptake. The strategy will define target audiences, key messages, responsibilities, timing, and measures of success to ensure broad visibility, impact, and sustainability beyond the project's lifetime.[(1-4)]

Discussion

In working group 6 (WG6), dissemination and communication is focused on COST action CA24147 - Artificial Intelligence Driven Dental AgEstimation Network (AID-AgE) is focused on spreading the philosophy of using classical methods and artificial intelligence in dental age estimation. In the past ten months, the representative of WG6 and his collaborators have organized the logo, website aidage.eu, which is available and provides all readers with the information that is carried out within this COST action. Then the dissemination of information was organized on social networks Linkedin and Instagram. We use social networks to spread information about our activities and regularly collect followers. The representative of WG6 actively participated in the Training School - Forensic and radiographic methods in AI-based age estimation, which was held in

Belgrade, Serbia on May 11 and 12, 2026. The last activity of WG6 was the preparation of the document Science Communication Plan of the COST Action Artificial Intelligence Driven Dental AgEstimation Network, which was accepted in August 2026.[5-10]

Conclusion

WG6 has taken important steps in the first ten months and will continue its activities through the Management Committee in September in Lisbon, Portugal.

Conflict of interest

The author declare no conflict of interests.

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WG7 – Training and Education Activities within COST Action CA24147: Achievements, Strategy and Future Perspectives

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Keywords: Artificial Intelligence; Education; Forensic Age Estimation; Standardization; Training.

Objective

COST Action CA24147 (AID-AgE) aims to identify the most effective integration between artificial intelligence and forensic age estimation, combining the potential of new technologies with validated scientific methodologies. Age estimation may directly affect people's lives, rights and legal status; therefore, technological innovation must always remain subject to rigorous scientific validation, critical evaluation and appropriate human oversight. AI should support expert decision-making, not replace the responsibility and critical judgement of the expert. Within this framework, Training and Education are conceived as a continuous process of scientific dissemination, capacity building and knowledge exchange. The strategy follows two complementary directions: participation in scientific meetings and congresses with specific expertise relevant to the research topics of the Action, and bringing the Action and its methodologies directly to geographical and professional contexts where forensic age-estimation expertise and reference data are most needed.

Discussion

Two activities represented particularly significant examples of this strategy. The Belgrade Training School provided a structured educational environment combining theoretical and practical training on dental and skeletal approaches to forensic age estimation. Dental age-estimation methods based on open apices represent an example of methodologies developed and subsequently applied and validated across different populations.[1]

Particular attention was devoted to methodological variability, interpretation of results, population differences and limitations of available reference data. The activities carried out in Nairobi represented the complementary dimension of this strategy: bringing AID-AgE directly to a context where further development of age-estimation research, training and population-specific reference data is particularly important. Researchers from Kenya and representatives from other African countries, particularly Namibia and Somalia, discussed the applicability of current methods to African populations. Previous research has demonstrated both the applicability of third-molar approaches in African populations and the importance of considering geographical and population variability when applying the third molar maturity index.[2,3]

Training was directly connected with research planning through harmonised protocols, local data collection and multicentre validation. Particular attention was also devoted to the future integration of these data into artificial-intelligence and machine-learning approaches, which are increasingly being investigated in dental age estimation.[4]

Conclusions

The Training and Education strategy of CA24147 will continue to combine participation in specialised international scientific events with activities directed towards countries, institutions and professional environments where the expertise developed within the Action can have the greatest impact. Future activities will expand this approach to additional geographical areas and scientific communities, promoting shared educational materials, practical protocols, data collection and multicentre collaboration.

A major commitment for the coming years will be to bring AID-AgE beyond its existing network, while maintaining a strong presence within international scientific communities directly related to the Action's research. This integrated model — training, standardisation, data collection, validation and artificial intelligence — will guide future Training and Education activities.

Conflicts of interest

The author declares no conflict of interests.

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TECHNICAL SEMINAR

Forensic Odontology and Artificial Intelligence

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Keywords: Artificial Intelligence; Biological Ontologies; Confidentiality; Datasets; Forensic Dentistry.

Abstract

Artificial intelligence (AI) in dentistry is moving from image classification toward clinical and medico-legal decision support. Yet a model cannot be evaluated, transferred or lawfully reused on the strength of an accuracy value alone. Reuse depends on knowing what the dataset represents, how information was collected and labelled, how privacy risks were controlled, and whether the meaning of each variable remains stable across institutions and countries. We argue that dataset documentation, privacy engineering and ontology-based semantics should form one governance architecture. Dental radiographs make the need particularly clear: they are clinically rich, potentially identifying, population-sensitive and capable of influencing legal thresholds. The AIdentifyAGE ontology offers a concrete case by linking judicial context, individual data, examinations, dental development methods, radiographic images, reference studies and AI outputs,

already publich in BioPortal. Under the EU Artificial Intelligence Act, systems used to assist judicial authorities may be high-risk depending on intended purpose; regulatory sandboxes offer supervised experimentation, not exemption or certification. The central proposal is practical: publish a reusable evidence package—not necessarily unrestricted personal data—containing a data statement, protocol, dictionary/ontology mapping, privacy and access plan, model documentation, validation results and audit trail. This is the minimum information required to transform an isolated performance result into evidence that can be reproduced, independently evaluated, and used responsibly.

Introduction

The next bottleneck in dental AI is not another architecture. It is evidence that can travel. Dentistry already uses AI for radiographic analysis, synthesis and prediction, treatment planning and population-level applications, as outlined by the FDI white paper and recent reviews.[1,2] However, strong performance within one database does not establish that a model will remain valid in another clinic, device, population or legal setting. Data shift may enter through image acquisition, referral pathways, age distribution, ancestry or geography, dental development patterns, disease prevalence, fillings, annotation practice and the exclusion of technically difficult cases. A model therefore travels only as far as the documentation of its data-generating process permits.

This matters acutely in forensic dental age assessment.[3-5] An estimated age may affect access to child protection, asylum procedures, healthcare and the applicable judicial pathway. The output is not merely a number; it is an inference produced from an image, a method, a reference population, assumptions and uncertainty. If these elements are not traceable, neither a clinician nor a court can determine whether the result is relevant to the individual case. The same principle extends to clinical decision support: a useful output must remain linked to the evidence and conditions that produced it, not detached as an apparently objective score.

Discussion

What information should be published to enable responsible application?

Open science does not imply that all medical or dental images should be made publicly available without restrictions. Dental radiographs constitute health data and may contain identifying information in image headers, embedded text or anatomical characteristics. Consequently, unrestricted data disclosure may be incompatible with data-protection requirements, the conditions of informed consent and the protection of the individuals represented in the dataset. Scientific transparency should therefore be understood as the availability of sufficient information to assess how the dataset was constructed, how the model was developed and whether the reported results can be independently examined.

The description of the dataset should begin with its provenance and intended purpose. Authors should report the institutions involved, the study period, the clinical or forensic setting, the recruitment or case-selection process and the inclusion and exclusion criteria. The unit of analysis—such as the individual, examination, radiograph, tooth or anatomical structure—should also be defined. Relevant characteristics of the study population, including age distribution, sex and geographical or population background, should be reported when legally and scientifically appropriate. This information establishes the population and circumstances to which the model's conclusions may reasonably apply. Without it, readers cannot determine whether performance estimates are relevant to another institution, population or decision-making context.

Image acquisition and preprocessing procedures also require detailed documentation. Studies should identify the imaging modality, equipment, software and relevant acquisition parameters. Authors should describe image-quality assessment, preprocessing, cropping, resizing, normalisation, enhancement and the criteria used to exclude images. These factors can alter the information available to an AI system and may explain differences in performance between datasets. A model developed using images from one device, institution or acquisition protocol should not be assumed to perform equally well under different technical conditions without external validation.

The reference standard assigned to each image must be clearly described. Authors should explain how the reference labels were defined, who performed the annotations, the expertise and number of annotators, whether they were blinded to relevant information and how disagreements were resolved. Inter-observer agreement, missing information and uncertain or borderline cases should also be reported. In forensic dental age assessment, for example, the developmental stage assigned to a tooth is an expert interpretation rather than an unquestionable fact. The resulting AI output therefore depends partly on the reliability and consistency of the annotation process.

Authors should provide a structured data dictionary defining each dataset variable. Each variable should have a clear definition, format, unit, permitted values and relationship to other variables. Where possible, dataset variables should be mapped to a publicly available and versioned ontology. This semantic layer is particularly important when information originates from different clinical, radiological, forensic and judicial systems. Ontology mapping can reduce ambiguity and enable researchers to establish whether variables bearing similar names represent the same observation, method or outcome.

Authors should also explain how the dataset was divided for model development and evaluation. Training, validation and test sets should normally be separated at the individual level rather than only at the image level. Images from the same person, repeated examinations or closely related records should not appear in both training and test sets unless this is explicitly required by the study design and appropriately justified. Duplicate detection and site separation should be reported. These precautions reduce data leakage, which can produce overly optimistic performance estimates by allowing the model to encounter information during training that is also present in the evaluation data.

Model reporting should include the model version, architecture, training procedure, hyperparameters, decision thresholds and performance measures. Results should not be limited to a single measure of accuracy. Depending on the task, authors should report discrimination, calibration, uncertainty, confidence intervals and performance across clinically or legally relevant subgroups. External validation using data from an independent institution or population is particularly important before the model is applied beyond the context in which it was developed. Failure analysis should identify cases in which the model performs poorly, including low-quality images, uncommon anatomical patterns and under-represented population groups.

Where legally and technically possible, the code and trained model parameters should be made available under an appropriate licence. When they cannot be released, the authors should explain the restriction and provide sufficient technical documentation to permit independent assessment. The dataset, code, ontology and model should have persistent identifiers and explicit version numbers. Changes to preprocessing, annotations, ontology definitions, model parameters or decision thresholds should be recorded, because modifications may affect the interpretation and reproducibility of the results.

The requirement for scientific openness does not mean that the complete raw dataset must always be publicly downloadable. Public disclosure may be inappropriate when images or associated metadata create a substantial risk of re-identification or when disclosure would conflict with consent, data-protection legislation, institutional agreements, licences or third-party rights. In such cases, the publication should describe the reason for restricting access and specify how qualified researchers may request access.

Possible mechanisms include a data-use agreement, review by a data-access committee, analysis within a secure research environment, federated analysis in which the data remain at the originating institution, or evaluation using a protected test dataset. The selected mechanism should be proportionate to the sensitivity of the information and the purpose of the proposed analysis. Access conditions should identify who evaluates requests, which researchers and purposes are eligible, what security requirements apply, how long access is granted and whether there is a procedure for reviewing refusals.

The expression "data are available from the authors upon reasonable request" is insufficient when the meaning of "reasonable" is not defined. Such statements may appear to support transparency while providing no predictable or equitable route to independent verification. A useful data-availability statement should specify the responsible institution or committee, the access criteria, the required documentation, the expected review process and the principal reasons why a request may be refused.

Synthetic data may reduce some privacy risks and can be useful for software development, teaching and preliminary methodological research. However, synthetic data should not automatically be regarded as anonymous or representative. The methods used to generate them, their similarity to the source data, the risk of reproducing identifiable records and their ability to preserve clinically relevant characteristics should be evaluated and reported. Moreover, model performance demonstrated only on synthetic data cannot replace evaluation using representative real-world data.

Privacy is a lifecycle property, not a one-time deletion

Medical images may retain identifiers in DICOM headers, burned-in text or pixel data; craniofacial anatomy may also enable recognition or linkage. A 2025 scoping review found heterogeneous approaches to medical-imaging privacy and emphasised the need to balance data utility with de-identification.(6) Removing names is therefore only the beginning. A defensible workflow includes data minimisation, separation of keys, role-based access, encryption, logging, retention limits, breach procedures and a documented assessment of residual re-identification risk. Pseudonymised data remain personal data when re-identification remains possible. In the European context, dental images and linked health information engage the GDPR, including the special-category regime and research safeguards.(7)

Privacy choices should be tied to the intended analysis. Cropping, masking or defacing may reduce risk but also remove relevant anatomy or introduce artefacts. The publication should report exactly which tags and pixels were transformed, who verified the result, and whether diagnostic or predictive utility changed. For multi-centre work, federated infrastructures may reduce central movement of data; the European Federation for Cancer Images (EUCAIM) illustrates how common data models, curation, annotation and privacy-preserving access can be combined in a distributed imaging ecosystem.(8) However, the use of a federated data infrastructure does not remove the obligations of each participating institution concerning the lawful basis for data processing, local data security, potential information leakage from AI models, and the governance of analysis results returned to researchers.

Ontologies provide meaning and traceability to data

A data dictionary can list fields; an ontology can represent what those fields mean, how entities relate and which inferences are permitted. Dental informatics has long recognised the cost of fragmented terminology and poorly documented electronic dental records.(9) The Oral Health and Disease Ontology (OHD) demonstrated that data from electronic dental records could be structured for secondary use, queried and analysed through a common framework.(10,11) Its continued extension to dental restorative materials also shows that an ontology is not a finished glossary: it requires domain experts, ontology engineers, reuse of established vocabularies, logical definitions, validation and versioning.(12) Knowledge-graph work in aerospace dentistry similarly illustrates how explicit process knowledge can support computable clinical decision support.(13)

Ontology does not anonymise a radiograph, establish a lawful basis or validate a model. Its contribution is different: it preserves meaning and provenance. For each prediction it can link the person-level observation, image, acquisition event, tooth or anatomical structure, staging method, reference study, algorithm and version, uncertainty estimate, report and decision context. This semantic chain makes it possible to ask not only "what did the model predict?" but "using which evidence, method and reference population, under which version and for what purpose?" That is a prerequisite for reproducibility and meaningful human review.

AIdentifyAGE Ontology

AIdentifyAGE is especially useful because it crosses a boundary that most dental datasets avoid: the path from biological observation to a medico-legal and potentially judicial use. The published ontology models judicial context, individual-level information, forensic examination, dental developmental assessment, radiographic imaging, statistical reference studies and AI methods.(14) The ontology is publicly listed in NCBO BioPortal and its development repository is available through the AIdentifyAGE GitHub organisation.(15,16) These are complementary forms of transparency: the portal supports discovery and reuse of the vocabulary; the repository can expose the artefact, documentation and version history.

The next step should be to use the ontology as a reporting contract for datasets and models. A dataset release or controlled-access application could require ontology-aligned metadata; a model card could identify the exact concepts and versions used; and each inference could produce a provenance record. Competency questions should be tested against real cases—for example: Which method and reference population supported an age interval? Was the image quality sufficient? Which model version generated the result? What uncertainty crosses a legal threshold? Which variables were unavailable? If the ontology cannot answer these questions, it is not yet adequate for accountable decision support.

AI Act, sandboxes and judicial support

The EU AI Act does not classify a system by academic field or by the word "forensic" alone. Classification depends on intended purpose and use. Annex III includes certain AI systems intended to assist a judicial authority, or acting on its behalf, in researching and interpreting facts and law and applying law to concrete facts; these uses may be high-risk, subject to the Regulation's conditions and exceptions.[17] A dental age-estimation system used as scientific support to an expert is therefore not automatically identical to a system used by a court. Nevertheless, where its output materially informs a judicial determination, the design should anticipate high-risk expectations: data governance, technical documentation, logging, transparency, human oversight, accuracy, robustness and cybersecurity. The final decision must remain genuinely human and contestable, not a ritual confirmation of an opaque score.

Regulatory sandboxes under the AI Act are supervised environments for developing, training, testing and validating innovative systems, potentially including real-world conditions.[17,18] They do not suspend the GDPR, waive professional duties or certify a model for deployment. For AIdentifyAGE-like systems, a valuable sandbox would bring together forensic odontologists, data-protection officers, AI developers, ontology engineers, judicial users, child-rights expertise and competent authorities. It should predefine the intended purpose, population, acceptable error and uncertainty, escalation rules, human-review protocol, security controls and exit criteria. Results—including failures and subgroup limitations—should be preserved as evidence for later conformity, procurement and oversight decisions.

Conclusions

AI models intended to support clinical, forensic or judicial decisions should only be considered for implementation when their development and evaluation can be independently examined. This requires a documented connection between data collection, image acquisition, annotation, model development, validation and the final output. The limitations associated with the study population, technical conditions and intended application must also be clearly identified.

The responsible development of dental AI depends on the combined use of appropriate dataset documentation, privacy safeguards, semantic definitions, independent validation and controlled access procedures. These components should not be treated separately. Dataset documentation without consistent semantic definitions can leave variables open to interpretation. An ontology can improve data organisation and traceability, but it does not replace data governance or model validation. Privacy measures protect individuals but do not, by themselves, address bias or limited model performance. Similarly, participation in a regulatory sandbox does not demonstrate that a system is suitable for clinical or judicial implementation.

Public access to identifiable dental images is not required in every case. However, restrictions on data access should be justified and accompanied by a defined procedure for legitimate scientific evaluation. Dataset provenance, variable definitions, annotation procedures, privacy measures, model and ontology versions, validation results and known limitations should be adequately documented and available for examination.

In medico-legal applications, these requirements are particularly important because an AI-generated estimate may affect decisions concerning age, legal status and access to protection. The purpose of documentation, ontologies and governance mechanisms is therefore not only to improve reproducibility. It is also to ensure that AI-supported conclusions can be understood, evaluated and challenged before they contribute to decisions affecting individual rights.

Conflicts of interest

The author declares no conflict of interests.

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Teaching Machines to Read Teeth: A Primer on Neural Networks for Dental Age Assessment

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Keywords: Deep Learning; Convolutional Neural Networks (CNNs); Dental Age Assessment; Panoramic Radiographs; Medical Image Segmentation & Detection.

Abstract

Dental age assessment has traditionally relied on expert visual scoring of tooth mineralization and root development, a process that is time-consuming and subject to inter and intra-observer variability. Deep learning offers a path towards automated, reproducible, and scalable analysis of dental radiographs, but effective adoption requires a shared understanding of the underlying model families and their appropriate use cases. This talk provides a foundational, non-mathematical-heavy overview of the deep learning building blocks most relevant to the task of AI-driven dental age assessment.

The talk begins with the basics of artificial neural networks (the perceptron, activation functions, backpropagation, and gradient descent) to establish common vocabulary across the dentistry, radiology, statisticians and AI communities. It then introduces convolutional neural networks (CNNs), explaining why convolution and pooling operations are naturally suited to radiographic image analysis, and briefly touring canonical architectures (VGG, ResNet, DenseNet, EfficientNet) that recur throughout the dental-age literature as backbones for feature extraction.

Building on this foundation, the talk maps CNN variants onto the four task types most relevant to this area:

- Classification: e.g., sex prediction, or binary staging tasks such as pre vs. post-third-molar mineralization, framed as supervised image classification problems;[(1)]
- Regression: direct assessment of chronological or dental age as a continuous output, discussing loss functions (MAE, MSE) and multi-task architectures that jointly predict age and sex;[(2)]
- Object detection: localizing and enumerating individual teeth or specific landmarks (e.g., third molars) in panoramic or CBCT images, using detector families such as Faster R-CNN and YOLO;[(1)]
- Segmentation: pixel-level delineation of tooth structures, root apices, or pulp chambers via encoder–decoder architectures such as U-Net.

Throughout, the talk emphasizes practical considerations directly relevant to the dental age assessment area: data annotation requirements and inter-rater reliability, transfer learning and pretraining strategies for limited medical datasets[(3)], interpretability tools (e.g., Grad-CAM) to build clinical and legal trust[(4)], generalizability across imaging modalities (panoramic, periapical, CBCT) and populations, and pitfalls such as dataset bias linked to genetic, environmental, and socio-economic factors.

The session closes with a brief look at emerging directions, including transformer-based vision models and multi-modal approaches combining radiographic and clinical/demographic data.[(5)] The goal is not to make every participant a deep learning engineer, but to give clinicians, radiologists, forensic scientists and statisticians enough conceptual grounding to critically use and evaluate and, why not, develop AI models, as well as contribute meaningfully to data collection and validation protocols, and communicate effectively with members of this community.

Conflicts of interest

The author declares no conflict of interests.

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Pilot Evaluation of Image Preprocessing and YOLO-Based Anatomical Cropping in Hand–Wrist Radiographs

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Keywords: Age Estimation, Hand; Wrist, Radiography; Machine Learning.

Introduction

Hand and wrist radiographs are two-dimensional greyscale medical images that contain complex spatial information on skeletal development. Their automated analysis presents important computational challenges because images may differ in resolution, orientation, field of view, exposure, contrast and background artefacts.(1-5) Image preprocessing—including intensity normalisation, contrast enhancement, resizing and anatomical region-of-interest extraction—may improve image standardisation and model training. However, excessive or inaccurate cropping may remove relevant anatomical structures, particularly the epiphyses and growth plates. Therefore, preprocessing and automated region detection must be evaluated carefully before being incorporated into an artificial intelligence pipeline.(1,6)

Convolutional neural networks can learn developmental patterns directly from radiographic images, while object-detection models such as YOLO can identify and extract potentially informative anatomical regions. Nevertheless, the performance of these approaches depends on image quality, dataset size, anatomical coverage and the preservation of clinically relevant information.(1-6) A preprocessing strategy that improves image uniformity does not necessarily improve model generalisability.(3,6-8)

In clinical and forensic applications, skeletal development constitutes a biological marker of age.(7, 9-17) Hand and wrist radiographs allow the assessment of the radius, ulna, carpal bones, metacarpals and phalanges and are used to evaluate skeletal maturity in children, adolescents and young adults, including individuals up to 21 years of age.(10-13,15,16,18,19) The Greulich and Pyle Atlas remains the most widely used reference method and is based on the comparison of a hand–wrist radiograph with sex-specific reference standards of skeletal development.(12,13)

A 2017 systematic review conducted by the Norwegian Institute of Public Health included 17 studies and found that the mean difference between Greulich–Pyle skeletal age and chronological age was rarely greater than one year within individual age groups. However, the review also identified methodological heterogeneity and a risk of age mimicry and concluded that the available evidence for estimating unknown chronological age was limited. The findings therefore support a general agreement between skeletal and chronological age, but not an unqualified claim of "excellent correlation". Norwegian Institute of Public Health systematic review.(14)

Objective

The objective of this pilot study was to evaluate the feasibility of adapting an existing dental-imaging artificial intelligence pipeline to two-dimensional hand and wrist radiographs. Specifically, it compared different image-processing strategies, including analysis without preprocessing, CLAHE-based contrast enhancement, anatomical cropping and YOLOv11-based region detection, using regression and binary classification tasks. The study also examined whether preprocessing preserved the anatomical information required for subsequent skeletal maturity and age-related analysis.

Material and Methods

This pilot study included 597 two-dimensional greyscale hand and wrist radiographs obtained from 493 individuals, comprising 301 female and 296 male radiographs. Ethical approval was granted by the Ethics Committee (approval no. 218/23), and authorisation was obtained from the Director of the Stomatology Department. Data confidentiality and processing complied with Article 89 of Regulation (EU) 2016/679—the General Data Protection Regulation. Demographic, clinical and radiographic data were recorded in two structured Microsoft Excel® databases.

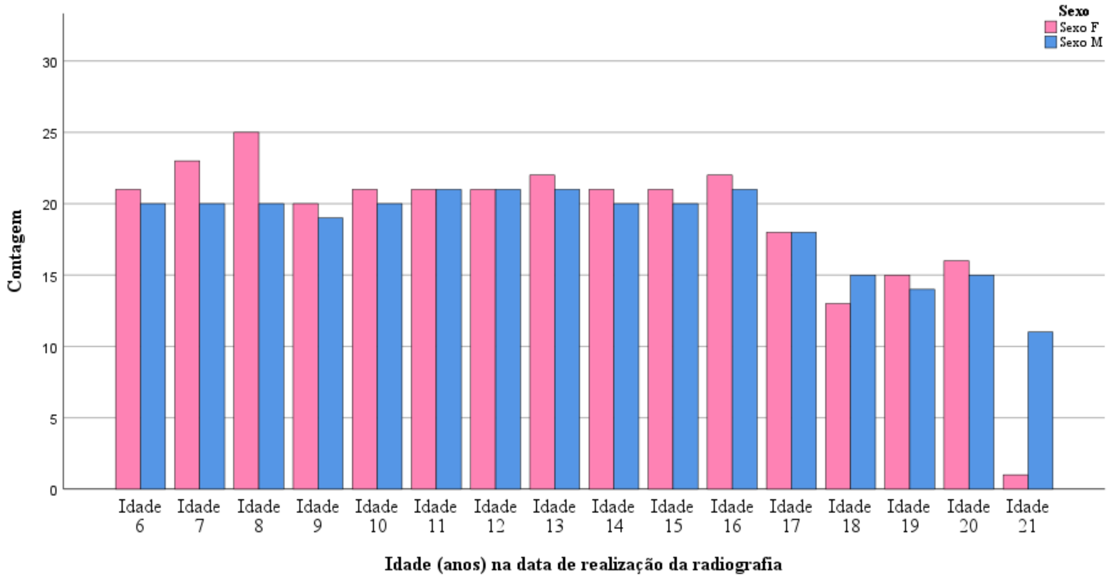

Figure 1. Sample distribution by sex and age

Following image-quality assessment, three image-processing pipelines were evaluated: analysis of the original whole-hand radiographs without preprocessing; intensity normalisation and contrast enhancement using Contrast-Limited Adaptive Histogram Equalisation (CLAHE), followed by anatomical cropping; and automated region-of-interest detection and cropping using YOLOv11. The YOLO-based approach was intended to identify anatomical regions associated with skeletal maturation while reducing irrelevant background information. Particular attention was paid to the preservation of the radius, ulna, carpal bones, metacarpals, phalanges, epiphyses and growth plates during automated cropping.

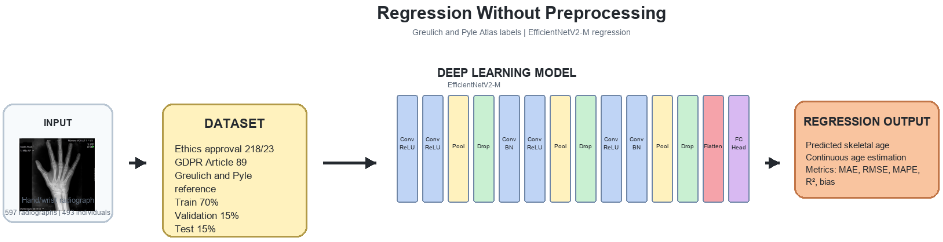

Figure 2. Workflow of the regression model without the image preprocessing

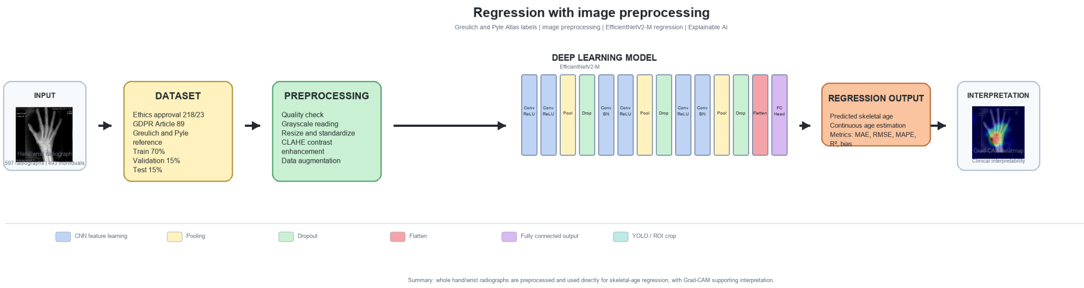

Figure 3. Workflow of the regression model with the image preprocessing

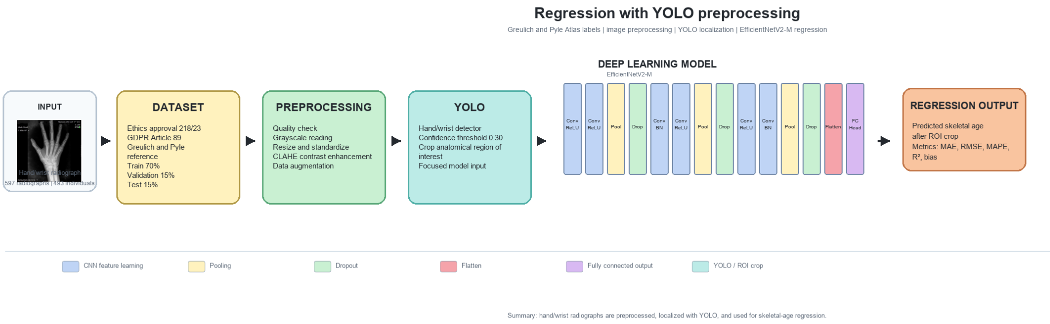

Figure 4. Workflow of the regression model without the image preprocessing and YOLO

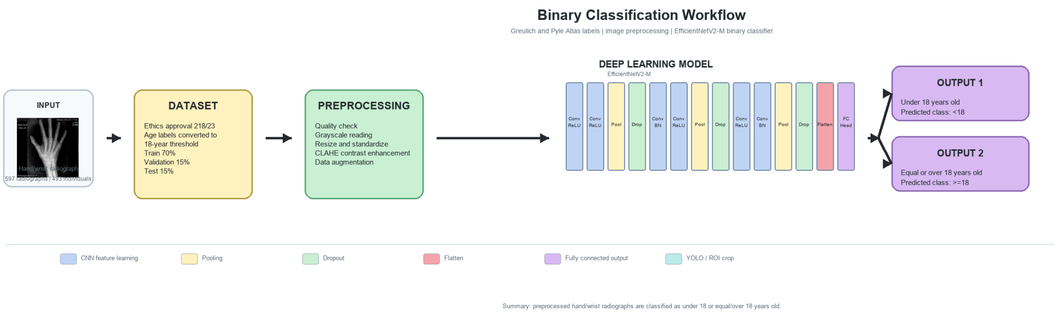

Figure 5. Workflow of the binary classification model with the image preprocessing

The dataset was divided into training, validation and test sets using a 70%, 15% and 15% allocation, corresponding to 417, 90 and 90 radiographs, respectively.

Chronological age was used as the reference label for continuous regression and for binary classification according to the 18-year legal threshold. The Greulich and Pyle Atlas was not used to generate the model labels; it was considered the established clinical reference method for the conventional assessment and interpretation of skeletal maturation in hand and wrist radiographs.

An EfficientNetV2-M convolutional neural network was adapted from a previously developed dental-imaging artificial intelligence pipeline and evaluated for two supervised learning tasks: continuous age regression and binary classification according to the 18-year legal threshold. The principal training configuration used a learning rate of 0.01, 100 epochs, a batch size of 4, a random seed of 42, a momentum of 0.9, a weight decay of 0.0001 and a model-saving interval of 25 epochs.

Regression performance was evaluated using mean absolute error (MAE), root mean squared error (RMSE), mean absolute percentage error (MAPE), coefficient of determination (R^2) and prediction bias. Binary classification performance was evaluated using accuracy, precision, recall, F-score, specificity, negative predictive value and the area under the receiver operating characteristic curve (ROC-AUC). Training and validation curves were examined to evaluate convergence and identify possible overfitting. Gradient-weighted Class Activation Mapping (Grad-CAM) was applied to visualise the image regions contributing to model predictions and to determine whether model attention corresponded to anatomically relevant skeletal structures.

Results

For continuous age regression, the model applied to the original whole-hand radiographs without image preprocessing achieved a test MAE of 1.099 years, RMSE of 1.371 years, MAPE of 0.090, R^2 of 0.895 and bias of −0.143 years.

CLAHE-based contrast enhancement combined with anatomical cropping produced the best regression performance, with a test MAE of 0.823 years, RMSE of 1.139 years, MAPE of 0.065 and R^2 of 0.927. However, the negative bias increased to −0.259 years, indicating a tendency towards age underestimation, particularly among older individuals.

In contrast, YOLOv11-based region detection and cropping did not improve model performance. This pipeline achieved a test MAE of 1.316 years, RMSE of 1.602 years, MAPE of 0.108, R^2 of 0.844 and bias of 0.134 years. These results were inferior to those obtained both without preprocessing and with CLAHE followed by anatomical cropping, suggesting that the YOLO-based procedure may have excluded relevant skeletal information.

Case-level analysis demonstrated considerable variability. The ten most accurate predictions presented absolute errors ranging from 0.10 to 0.74 months. Conversely, the ten largest errors ranged from 64.31 to 82.09 months and occurred predominantly in older individuals, although one substantial overestimation was observed in a younger individual.

For binary classification at the 18-year legal threshold, the test set confusion matrix included 72 correctly classified individuals aged <18 years, 12 correctly classified individuals aged ≥18 years and six misclassifications. The model therefore correctly classified 84 of the 90 test radiographs, corresponding to an overall accuracy of 93.3%. For individuals aged <18 years, precision, recall and F-score were 96.0%. For individuals aged ≥18 years, precision, recall and F-score were 80.0%. The overall F-score was 0.880, the negative predictive value was 0.960, specificity was 0.960 and ROC-AUC was 0.968.

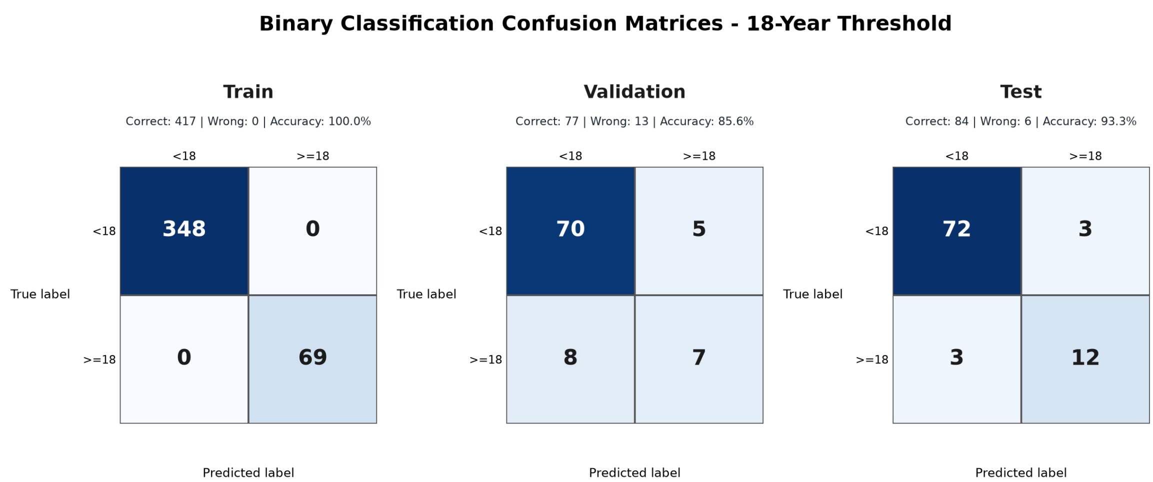

Figure 6. Confusion matrixes for the binary classification for the threshold 18 years old

Training accuracy reached 100%, whereas validation accuracy was 85.6%. The progressive reduction in training loss, accompanied by an increase and marked fluctuation in validation loss, demonstrated overfitting. Grad-CAM visualisations also showed activation in regions outside the principal skeletal structures in some radiographs, suggesting that the model may have partially relied on image artefacts or non-anatomical features.

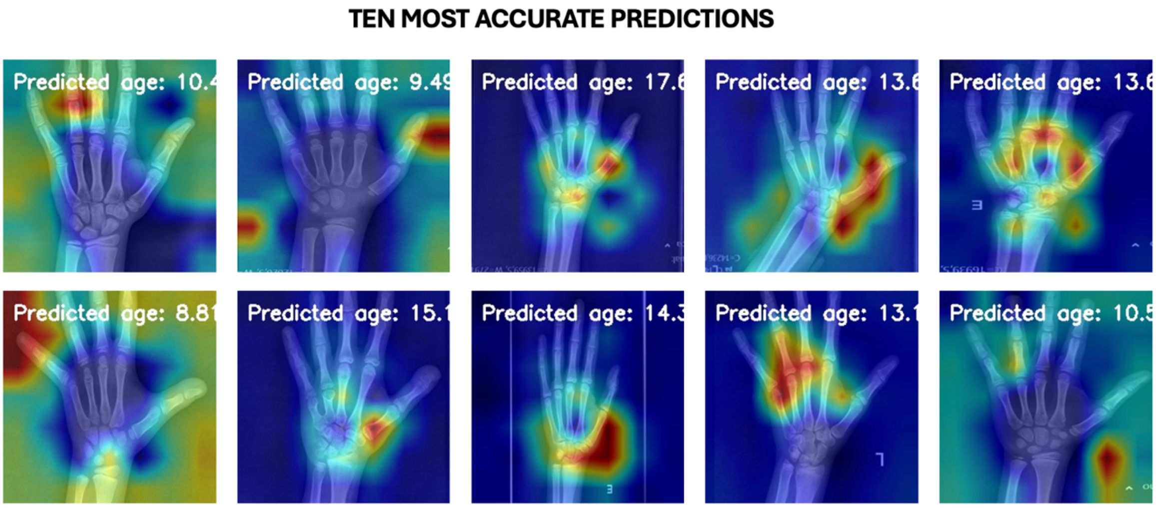

Figure 7. Heatmaps for predicting age, ten most accurcate predictions

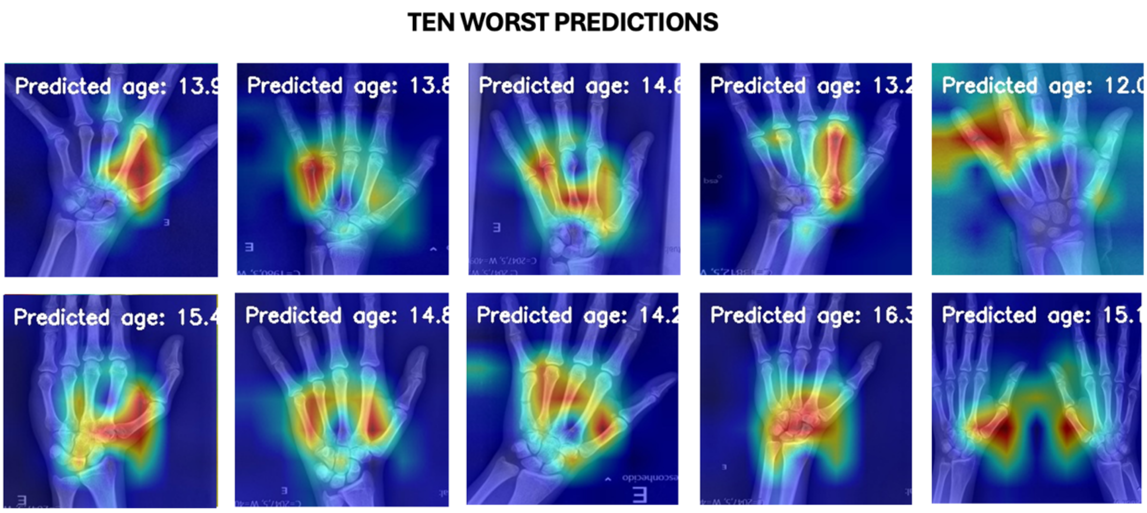

Figure 8. Heatmaps for predicting age, tem worst predictions

Discussion

The main methodological challenge identified in this pilot study concerned image preprocessing and the application of YOLOv11 to hand and wrist radiographs. Although automated cropping can reduce irrelevant background information and standardise image presentation, the YOLO-based pipeline produced poorer regression performance than both the unprocessed whole-image model and the CLAHE-based anatomical cropping approach. This suggests that the YOLO model did not yet detect the anatomical regions required for skeletal maturity assessment with sufficient precision. In particular, cropping may have excluded portions of the distal radius and ulna, carpal bones, epiphyses or growth plates, thereby removing biologically relevant information. The application of YOLO to hand and wrist analysis requires a dedicated training and annotation strategy. A model trained only to detect the general outline of the hand may generate an acceptable bounding box but may not preserve all the structures used in the Greulich and Pyle Atlas. Future YOLO development should therefore use expert-annotated radiographs in which the distal radius and ulna, carpal bones, metacarpals, phalanges, epiphyses and growth plates are explicitly identified. The model should also be trained to accommodate differences in image orientation, laterality, magnification, field of view, exposure and skeletal development. Particular care is required to prevent the exclusion of the wrist or distal forearm when the hand is automatically cropped.

The results also demonstrate that preprocessing should not be treated as a single intervention. CLAHE combined with anatomical cropping improved regression performance, whereas YOLO-based cropping reduced it. Consequently, the numerical improvement observed after CLAHE cannot be generalized to all preprocessing approaches. An ablation analysis is needed to evaluate separately the effects of intensity normalization, CLAHE, resizing, background removal, anatomical cropping and YOLO-based region extraction. Whole-image and region-based models should also be compared to determine whether local anatomical information provides additional value without losing the broader pattern of skeletal maturation.

For binary classification at the 18-year legal threshold, performance was better for individuals aged <18 years than for those aged ≥18 years. Precision, recall and F-score were 96.0% for the <18-year group and 80.0% for the ≥18-year group. Of the 75 minors in the test set, 72 were correctly classified and three were incorrectly classified as adults. Of the 15 adults, 12 were correctly classified and three were classified as minors. This difference is partly explained by the marked class imbalance, as the test set contained five times more individuals aged <18 years than individuals aged ≥18 years.

From a judicial perspective, the two types of classification error do not have equivalent consequences. Incorrectly classifying a minor as an adult may result in the loss of legal safeguards and child-protection measures. Conversely, classifying an adult as a minor may affect the application of age-dependent legal procedures. The model should therefore not be evaluated only through overall accuracy. Sensitivity for detecting minors, false-adult and false-minor rates, class-specific predictive values, calibration and uncertainty around the 18-year threshold must also be reported. In accordance with the principle of *in dubio pro minore*, uncertain or borderline cases should not be automatically classified as adults.

The perfect training performance, contrasted with a validation accuracy of 85.6% and increasing validation loss, indicates substantial overfitting. The apparent test accuracy of 93.3% must therefore be interpreted cautiously. The relatively small number of individuals aged ≥18 years limits the stability of the class-specific estimates, particularly the reported 80.0% recall, which was based on only 15 adult test cases.

Additional concerns include the relatively small dataset, the presence of more radiographs than individuals and the absence of external validation. The data split must be performed at the participant level; otherwise, radiographs from the same individual could occur in both training and test sets, leading to data leakage and artificially optimistic results.

Grad-CAM activation outside anatomically relevant regions suggests that the model may have learned associations with image borders, labels, positioning or acquisition artefacts instead of relying exclusively on skeletal structures. Before further model training, these potential confounders should be removed or standardized, followed by systematic examination of the resulting attention maps.

Overall, the findings support the feasibility of adapting an artificial intelligence pipeline to hand and wrist radiographs but do not yet support clinical or judicial implementation. The next stage should prioritize expert anatomical annotation, optimization of YOLO for hand–wrist structures, preservation of the complete anatomical field, calibration around the 18-year threshold and external validation.

Conclusions

The dental-imaging AI pipeline was successfully adapted to hand–wrist radiographs as a pilot workflow. CLAHE with anatomical cropping improved regression performance, whereas YOLO-based cropping requires further region-specific training to preserve relevant skeletal structures. The models remain research prototypes and require larger datasets, optimization of YOLO for hand–wrist structures, preservation of the complete anatomical field and calibration around 18 years threshold and external validation.

Conflicts of interest

The authors declare no conflict of interests.

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From Networking to Innovation: Lessons Learned from the MDVI COST Action

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Keywords: Migrant Disaster Victim Identification (MDVI); AI-based Innovations; Collaborative pipelines, CoPAS.

Background

The increasing number of missing migrants has become one of the most pressing humanitarian and forensic challenges of the past decade. The identification of deceased migrants requires coordinated collaboration among a wide range of stakeholders, including forensic practitioners, humanitarian organizations, law enforcement agencies, policymakers, and technology developers. To address these challenges, the MDVI (Migrant Disaster Victim Identification) COST Action was established to create a multidisciplinary European network dedicated to advancing the scientific, technological, and operational framework for migrant identification.(1) One of its primary objectives is to foster innovation in digital forensics, artificial intelligence, biometrics, and engineering, translating advances in these fields into practical solutions that address operational and casework needs.

Discussion

Over the past three years, the MDVI COST Action has demonstrated that an active international community of researchers and practitioners working on artificial intelligence and digital technologies for humanitarian forensic applications can thrive when driven by clearly defined operational challenges arising from real MDVI investigations and continuous feedback from end users. Within this framework, the network has fostered the development of innovative approaches in automated image and video analysis (including image-based personal identification, kinship analysis, and image annotation), drone-assisted search and detection, 3D facial imaging, social media analysis, and ante-mortem/post-mortem (AM/PM) reconciliation tools for personal identification. The presentation will highlight these success stories and discuss the key technical factors underlying their development, including data acquisition, annotation strategies, data processing pipelines, and rigorous validation.

At the same time, the activities of the MDVI COST Action highlighted several challenges that may limit the effectiveness of collaborative networking. These include difficulties in data availability and sharing arising from differences in legal, ethical, and operational frameworks across countries, barriers to interdisciplinary communication, and uneven technological readiness and digital literacy among both solution developers and end users. Collectively, these factors can become significant obstacles to rapid and effective technology and knowledge transfer and ultimately discourage the formation of new partnerships.

One of the key elements facilitating the transition from networking to innovation is the adoption of the CoPAS platform and its concept – a secure, modular environment designed to support the deployment, sharing, and integration of forensic software within a unified ecosystem.[2] CoPAS addresses several barriers that commonly hinder technology transfer in forensic science, including fragmented software development, incompatible operating systems, cybersecurity concerns associated with cloud-based solutions, and the technical complexity of deploying AI applications. Beyond its technical capabilities, CoPAS strengthens the scientific community by providing a standardized environment and an integrated marketplace for sharing, validating, and disseminating analytical tools.

Conclusions

The MDVI COST Action has demonstrated that the transition from networking to innovation can be both highly successful and inherently challenging. While the Action has effectively bridged research, technology, and operational practice, supporting humanitarian response and delivering meaningful societal impact, it has also demonstrated the limitations of multidisciplinary and international collaboration. The lessons learned throughout this process will be presented as a set of recommendations for AID-AgE COST Actions and other collaborative research networks seeking to translate scientific innovation into operational practice.

Conflicts of interest

The authors declare no conflict of interests.

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INTERNATIONAL WORKSHOP
AgEstimation at a Turning Point? The Role of AI and COST Action CA24147

Medico-Legal Age Assessment in Living Individuals: From Expert Examination to Artificial Intelligence-Assisted Decision Support

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Keywords: Age Estimation; Dental Age Assessment; Bone Age Assessment; Artificial Intelligence; Forensic Dentistry; Radiography; Undocumented Living Individuals.

Introduction

Medico-legal age assessment in a living individual may be requested when chronological age cannot be established from documentary evidence or when there are substantiated doubts concerning the authenticity or reliability of the documents presented.(1-3) This is particularly relevant for undocumented individuals and unaccompanied minors because the expert conclusion may influence access to child-protection services, immigration status, criminal responsibility and other age-dependent rights. The purpose is not to determine an exact age—no currently available method can do so—but to estimate an age range and assess, with known uncertainty, the probability that the individual has reached a relevant legal threshold.(4-6)

Before any examination is performed, the medico-legal question must be clearly defined. The competent authority should not simply ask, "How old is this person?" It should identify the specific legal threshold at issue. The question may be whether the person has reached the minimum age of criminal responsibility, remains under 18 years of age or has crossed another threshold established by the applicable legislation. Legal majority is not a biological marker; it is a legal category defined by each jurisdiction. The expert estimates the person's probable chronological age based on biological development and reports the associated uncertainty. Applying the relevant legal threshold to the individual case remains the responsibility of the administrative or judicial authority.(7-9)

When an individual states that they are a minor, the presumption of minority should apply while reasonable doubt remains. The procedure must respect the best interests of the child, human dignity, physical integrity, the right to information, informed consent and the right to challenge the result. The individual should receive comprehensible information, in a language they understand, about the purpose of the examination, the proposed methods, their limitations, any exposure to ionising radiation and the possible consequences of the assessment. Refusal to undergo an examination should not, by itself, be interpreted as evidence of adulthood. These safeguards are set out in the 2018 EASO Practical Guide, which also states that examinations involving nudity or the observation or measurement of genitalia and other intimate body parts should not be used for age-assessment purposes.(10-13)

Biological markers

Medico-legal age assessment should consider independent biological markers, principally dental development and skeletal maturation. These markers do not directly measure chronological time. They assess processes of growth and maturation that are related to age but subject to individual and population variability.(14-16)

Dental examination allows the assessment of tooth presence, eruption sequence and, most importantly, the stages of mineralisation and root development. Dental mineralisation is generally more informative than eruption because the latter can be influenced by local factors such as lack of space, impaction, tooth loss, pathology or treatment. In late adolescence, third molars become particularly relevant, although they show greater developmental variability than the other teeth.(17)

Skeletal maturation may be assessed using the hand and wrist by examining the development and fusion of the epiphyses. Hand radiographs are particularly informative during childhood and adolescence. Once hand maturation is complete, however, this examination no longer allows adequate differentiation between late adolescence and early adulthood. In such cases, the medial end of the clavicle becomes relevant because it is among the last regions of the skeleton to complete maturation. When the medico-legal question concerns a threshold in late adolescence or early adulthood, examination of the clavicle may be justified, preferably using computed tomography with an appropriate low-dose protocol and slice thickness suitable for the classification of ossification stages.(18-20)

The recommendations of the Study Group on Forensic Age Diagnostics—AGFAD—associated with the work of Andreas Schmeling, propose a combination of a general physical examination, dental examination with panoramic radiography, and radiographic examination of the hand. When hand maturation is complete and the legal question requires further assessment, examination of the clavicle may be added.(21-24)

Performing several examinations does not mean that separate “dental ages” and “bone ages” should be mechanically averaged. Each marker must be interpreted using an appropriate method and reference study. Agreement between independent markers may strengthen the conclusion, whereas discordant findings require consideration of factors such as disease, altered growth, medical treatment, image quality, classification error or an inappropriate reference study.(25,26)

Justification of radiological examinations

Radiological examinations can provide information that is not available through clinical observation alone. An assessment based on appropriately indicated radiographs is therefore likely to be more informative and reproducible than a conclusion based only on physical appearance. However, greater information does not mean absence of error, nor does it justify the automatic performance of every available examination(1,2)

Exposure to ionising radiation must be individually justified. The established ALARA principle—As Low As Reasonably Achievable—remains valid but has been complemented by ALADA—As Low As Diagnostically Acceptable—and, more recently, by ALADAIP: As Low As Diagnostically Acceptable, Indication-oriented and Patient-specific. ALADAIP adds two important requirements: the examination must respond to a specific indication, and the imaging protocol must be adapted to the individual. The objective is not to obtain the most visually perfect image, but an image of sufficient quality to answer the medico-legal question, using the lowest exposure compatible with that purpose.(3,4)

Previous clinical images should therefore be consulted whenever available. A radiograph should not be repeated solely to comply with a protocol. Computed tomography of the clavicle is not a first-line examination. It should only be considered when preceding methods cannot adequately address the relevant legal threshold and when the expected benefit justifies the exposure.(5,6)

Importance of reference studies

No dental or skeletal stage has an age-related meaning in isolation. Its interpretation depends on reference studies describing the distribution of known chronological ages associated with each developmental stage.(1-3)

An appropriate reference study should use a contemporary sample of individuals of known age, an adequate sample size and clearly defined inclusion criteria. It should describe the population, sex distribution, age distribution, geographical and socioeconomic context, classification method, observers' experience, and intra- and interobserver agreement. It should also report the distribution of chronological ages within each stage rather than only a mean age.(8-10)

Applying an inappropriate reference study may introduce systematic error. Differences between populations, health conditions, nutrition, socioeconomic factors and secular trends may affect biological development. The expert must explain why a particular reference study is applicable to the individual being assessed and acknowledge the absence of a perfect correspondence when an adequately representative reference population is unavailable.(16-18)

When addressing a legal threshold, the minimum ages observed for a particular stage may be especially relevant. However, the "minimum age" reported in a study is not a universal biological property. It is influenced by the size and composition of the sample and must be interpreted alongside the complete age distribution, confidence intervals and methodological quality of the study.(22,23,25,27)

The need to review the concept of "holistic" age assessment

The 2018 EASO Practical Guide made an important contribution by placing the best interests of the child, the benefit of the doubt, proportionality and the exclusion of intimate examinations at the centre of the process. Nevertheless, some components of the model described as "holistic" require scientific reconsideration.[1-3]

Psychological age, emotional maturity, behaviour, physical appearance and biographical narrative are not equivalent to chronological age. Psychological assessment may be essential for identifying trauma, vulnerability, capacity to understand the procedure and protection needs. However, it is not a validated biological marker capable of converting psychological maturity into years of chronological age. Cultural background, migration experiences, institutionalisation, violence, exploitation and trauma may profoundly affect how a child behaves or presents themselves.[4-6]

Similarly, height, weight, somatic development and secondary sexual characteristics display considerable variability. They cannot reliably distinguish a 17-year-old person from someone aged 18 or 19. Observation of genital or breast development is intrusive, insufficiently specific for chronological age and contrary to the recommendations contained in the EASO guide itsel.[13] Undressing a child or presumed minor for age-estimation purposes does not provide information proportionate to the potential harm and should not form part of a contemporary medico-legal protocol.

A "holistic" assessment should not therefore mean combining indicators of unequal scientific validity and producing a final average. A multidisciplinary approach remains necessary, but each discipline should address the questions within its own area of competence. Forensic medicine and forensic odontology assess biological markers. Psychology and social services evaluate functional maturity, vulnerability and protection needs. The judicial authority considers the evidence and applies the law. These contributions are complementary but are not interchangeable.

Artificial intelligence and decision support

Manual classification of dental and skeletal developmental stages is subject to intra- and interobserver variability. The same expert may classify an image differently on separate occasions, and two experts may assign different stages to the same anatomical structure.

Artificial intelligence may improve consistency, provided that it is used as a decision-support instrument and not as a replacement for the forensic expert.[1-3]

An appropriate AI system should identify the anatomical structure and the region of interest (ROI) used in the analysis—for example, a third molar, the hand and wrist, or the medial clavicular epiphysis. It should indicate whether the image is of sufficient quality, present the resulting classification or age estimate, quantify uncertainty and provide information that allows the user to understand which anatomical regions contributed to the output.[1-6]

Explainability should not be limited to a visually attractive heatmap. It should provide evidence that the model relied on the relevant anatomical structure rather than on irrelevant elements, such as equipment markers, embedded text, patient positioning or institution-specific image characteristics.

The criteria proposed by Palmela Pereira in 2026 for AI-assisted forensic dental age assessment include definition of the medico-legal intended purpose, internal and external validation, population representativeness, image-quality assessment, uncertainty management, performance around relevant legal thresholds, explainability, human oversight, data protection, documentation and auditability.[1] The model should be evaluated using independent data, and its results should be reported according to sex, age group and relevant population. High overall accuracy may conceal clinically and legally important errors in cases close to the 18-year threshold. The purpose is to support a reasoned expert opinion, not to automate a decision that may affect fundamental rights.

Conclusions

Medico-legal age assessment in a living individual should begin by defining the relevant legal threshold and establishing that a substantiated doubt exists to justify the procedure. When the person may be a minor, the presumption of minority, the best interests of the child, informed consent, use of the least intrusive method and the benefit of the doubt must prevail. Dental and skeletal examinations provide more objective information than physical appearance, behavior or secondary sexual characteristics. Nevertheless, they remain estimates subject to biological and methodological variability. Panoramic dental radiography, hand radiography and, in justified circumstances, computed tomography of the clavicle should be selected progressively and in accordance with the ALADAIP principle. Results must be based on appropriate reference studies, including the associated uncertainty and be interpreted jointly by qualified experts.

Artificial intelligence may reduce variability in manual classification and improve documentation of the assessment process. It is acceptable, however, only when it is validated, explainable, auditable and used under meaningful human oversight. The final conclusion must remain understandable and open to independent review and challenge. A biological estimate—whether produced manually or with AI assistance—must never be presented to a court as an exact chronological age.

Conflicts of interest

The authors declare no conflict of interests.

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Key Aspects of the Strategy COST Action AID-AgE

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Keywords: Forensic Odontology; Dental Age; Assessment; COST Action.

Introduction

The key of this COST action is to develop artificial intelligence (AI)-driven models that enhance accuracy and reliability in dental age estimation, by analyzing dental radiographs (panoramic, periapical, and cone-beam CT).

Discussion

Artificial Intelligence-based technologies used in forensic dentistry include deep neural networks, Artificial neural networks, machine learning, and computer technology. Accurate estimation of biological age is essential in clinical and forensic fields, particularly in legal medicine, pediatrics, and orthodontics. Dental age estimation involves several methods that rely on the analysis of teeth development, structure, and wear. To date, a large number of works have been published in which artificial intelligence is used to estimate dental age.[(1-3)] The results obtained contribute to the importance of artificial intelligence in comparison to classical methods for estimating dental age in children, subadults and adults.[(4,5)]

Conclusion

In addition to the advantages, the application of artificial intelligence also has some disadvantages, which may be related to discrimination, transparency, accountability, privacy, security, ethics and others. Artificial Intelligence systems should be used as a support tool, not as a replacement for forensic experts. COST Action AID-AgE will, during its five-year work, produce the best methods and protocols for the application of artificial intelligence in estimating dental age.

Conflicts of interest

The authors declare no conflict of interests.

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Artificial Intelligence in Forensic Age Estimation: From Quantitative Evidence to Responsible Decision Support

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Keywords: Artificial Intelligence; Forensic Age Estimation; Human Oversight; Probability; Quantitative Methods.

Objective

Artificial intelligence offers new opportunities for forensic age estimation, but its introduction into forensic decision-making also raises important scientific, methodological and ethical concerns. COST Action CA24147 (AID-AgE) aims to explore how AI can be integrated with validated age-estimation methodologies while maintaining transparency, scientific control and human responsibility. This is particularly important because age assessment may influence fundamental decisions concerning an individual's rights, legal status and future. The objective is therefore not to replace the expert or transfer responsibility to an algorithm, but to determine how AI can provide reliable, transparent and controlled support to forensic evaluation.(4)

Discussion

AI can support forensic age estimation at different levels, including image analysis, identification of anatomical structures, measurement, data integration and prediction. However, each of these steps may also introduce errors or biases. An algorithm may incorrectly identify a structure, produce inaccurate measurements, misinterpret data, or generate predictions influenced by the quality, composition and geographical representativeness of its training dataset. Moreover, an apparently precise numerical output may create a misleading perception of certainty. Ethical and scientifically responsible use of AI therefore requires validation, transparency, appropriate datasets and continuous expert oversight.[1-4]

In this context, quantitative age-estimation methods acquire particular importance. Measurements and numerical parameters provide information that can be verified, reproduced, compared and statistically evaluated.[1] This also allows the expert to identify and critically evaluate the different steps leading from biological evidence to the final estimate.

Age estimation is intrinsically associated with uncertainty. Rather than transforming biological information into an apparently certain categorical answer, forensic evaluation should therefore provide an estimate together with its associated probability and uncertainty, particularly when addressing legally relevant thresholds such as the probability that an individual is older than 18 years. Large multi-regional studies demonstrate the importance of geographical and population variability when interpreting quantitative indicators and defining appropriate reference values.[2]

Within AID-AgE, a digital platform is being developed as a practical decision-support tool. Its purpose is to integrate validated quantitative indicators, population-specific information and statistical models and to provide the expert with immediately interpretable probabilistic information. AI and machine-learning approaches may further improve this process by integrating multiple anatomical indicators, analysing complex relationships and exploiting increasingly large and geographically diverse datasets.[3] The progressive incorporation of new population data will also allow models and reference values to be continuously tested and externally validated.

The platform should therefore not be conceived as a "black box" producing an automatic forensic conclusion. The expert should remain able to understand which data were used, how they were processed, what probability is associated with the result and what limitations may affect its interpretation. Its purpose is to provide the best available quantitative evidence, not to make the final decision.

Conclusions

The principal challenge is not simply to make forensic age estimation more automated, but to make it more measurable, transparent, reproducible and scientifically controllable. Quantitative methods, appropriate reference datasets, probabilistic interpretation and AI can together provide more powerful decision-support tools. However, technological sophistication cannot replace scientific validation or professional responsibility. When an assessment may affect a person's life and rights, the expert must remain able to understand, verify and, when necessary, question the result. AI should strengthen forensic evidence and expert judgement, not replace them.

Conflicts of interest

The authors declare no conflict of interests.

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