

# Preinterventional Third-Molar Assessment Using Robust Machine Learning

J.S. Carvalho<sup>1,3\*</sup>, M. Lotz<sup>2\*</sup>, L. Rubi<sup>1</sup>, S. Unger<sup>2</sup>, T. Pfister<sup>2</sup>,  
J.M. Buhmann<sup>1,3°</sup>, and B. Stadlinger<sup>2,3°</sup> 

Journal of Dental Research  
2023, Vol. 102(13) 1452–1459  
© International Association for Dental, Oral,  
and Craniofacial Research and American  
Association for Dental, Oral, and Craniofacial  
Research 2023



Article reuse guidelines:  
sagepub.com/journals-permissions  
DOI: 10.1177/00220345231200786  
journals.sagepub.com/home/jdr

## Abstract

Machine learning (ML) models, especially deep neural networks, are increasingly being used for the analysis of medical images and as a supporting tool for clinical decision-making. In this study, we propose an artificial intelligence system to facilitate dental decision-making for the removal of mandibular third molars (M3M) based on 2-dimensional orthopantomograms and the risk assessment of such a procedure. A total of 4,516 panoramic radiographic images collected at the Center of Dental Medicine at the University of Zurich, Switzerland, were used for training the ML model. After image preparation and preprocessing, a spatially dependent U-Net was employed to detect and retrieve the region of the M3M and inferior alveolar nerve (IAN). Image patches identified to contain a M3M were automatically processed by a deep neural network for the classification of M3M superimposition over the IAN (task 1) and M3M root development (task 2). A control evaluation set of 120 images, collected from a different data source than the training data and labeled by 5 dental practitioners, was leveraged to reliably evaluate model performance. By 10-fold cross-validation, we achieved accuracy values of 0.94 and 0.93 for the M3M–IAN superimposition task and the M3M root development task, respectively, and accuracies of 0.9 and 0.87 when evaluated on the control data set, using a ResNet-101 trained in a semisupervised fashion. Matthew's correlation coefficient values of 0.82 and 0.75 for task 1 and task 2, evaluated on the control data set, indicate robust generalization of our model. Depending on the different label combinations of task 1 and task 2, we propose a diagnostic table that suggests whether additional imaging via 3-dimensional cone beam tomography is advisable. Ultimately, computer-aided decision-making tools benefit clinical practice by enabling efficient and risk-reduced decision-making and by supporting less experienced practitioners before the surgical removal of the M3M.

**Keywords:** deep learning, algorithms, radiography, panoramic, mandible / diagnostic imaging, humans

## Introduction

The use of machine learning (ML) to support decision-making and to automate routine tasks in the medical domain causes an increase in efficiency and more robust decision-making in the health care system (Shehab et al. 2022). Biologically inspired, deep multilayered neural networks (DNNs) have been introduced for various classification, regression, and segmentation tasks, including the analysis of medical images (Litjens et al. 2017; Shen et al. 2017). Particularly, the analysis of these medical images has benefited greatly from the introduction of convolutional and transformer neural networks, with the residual neural network (ResNet) (He et al. 2016) and the vision transformer (ViT) (Vaswani et al. 2017) being the most widely used model architectures. In dentistry, methodological research in this area has proved fruitful, with several variations of these models proposed for tooth structure segmentation, the classification of dental plaque, and the detection of caries (Schwendicke et al. 2020; Shan et al. 2021; Wang et al. 2021; Kuhnisch et al. 2022).

The removal of mandibular third molars (M3Ms) is the most common surgical procedure in oral surgery and can cause multiple complications, including damage to the inferior

alveolar nerve (IAN) (Leung and Cheung 2011; Sigron et al. 2014). It is known from the literature that direct contact of the M3M root with the IAN significantly increases the risk of an IAN damage occurring. In a study by Eyrych et al. (2011), it was documented that a narrowing of the IAN canal and the direct contact between M3M root and the IAN were the most prominent factors influencing the risk of IAN impairment. Furthermore, these authors demonstrated that in 95.7% of the cases, postsurgical IAN impairment occurred in M3Ms with fully developed roots. To minimize the operative risks, localization of the listed structures based on radiographs has to be

<sup>1</sup>ETH Zurich, Department of Computer Science, Zurich, Switzerland

<sup>2</sup>University of Zurich, Center for Dental Medicine, Zurich, Switzerland

<sup>3</sup>ETH AI Center, Zurich, Switzerland

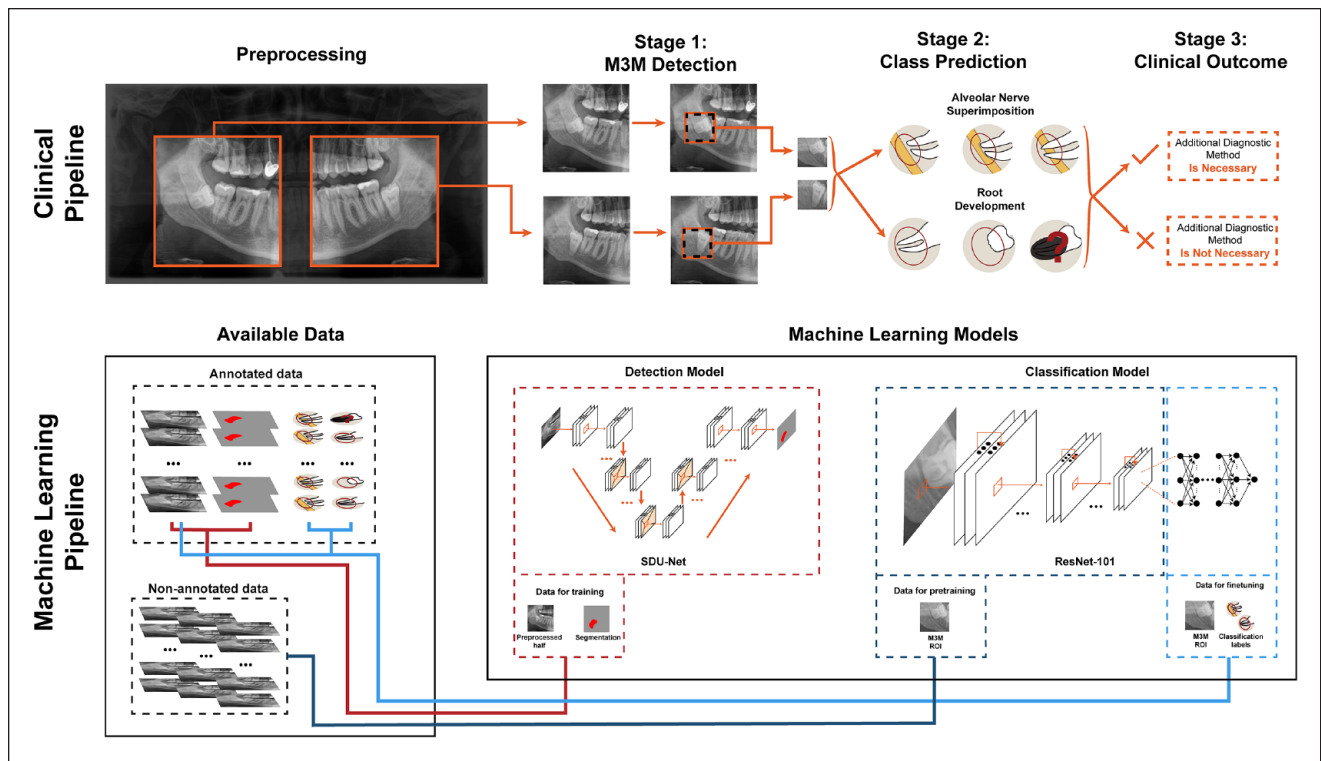
\*Equally submitting first authors.

°Equally submitting last authors.

A supplemental appendix to this article is available online.

## Corresponding Author:

B. Stadlinger, University of Zurich Center for Dental Medicine,  
Plattenstr. 11, Zurich, 8032, Switzerland.  
Email: bernd.stadlinger@zzm.uzh.ch



**Figure 1.** Summary of the end-to-end pipeline. Clinical pipeline: depiction of the 3 main stages that include detection of the mandibular third molar (M3M), its characterization with respect to superimposition with inferior alveolar nerve (IAN) and root development, and the final clinical outcome to require or not require an additional diagnostic method. Machine learning pipeline: depiction of the available annotated and nonannotated data and its usage to train the machine learning models that will provide the necessary outcomes for the clinical pipeline. More precisely, the spatially dependent U-Net (SDU-Net) relies on orthopantomogram (OPG) images and masks data (red connecting line) and outputs the location of the M3M; the ResNet-101 is first pretrained with nonannotated images (dark blue line) and then fine-tuned with OPG images and the class labels (light blue line).

preoperatively assessed as a mandatory surgery step. In critical cases, 3-dimensional imagery is required to evaluate the anatomical location of the IAN and M3M root superimposition and the root development as observed in the orthopantomogram (OPG). To automate the task of identifying critical cases, previous studies made steps toward automatically evaluating the risk of extraction difficulties and IAN damage after M3M surgery by using deep learning on radiographic or computed tomography (CT) images. The most popular approaches employ ResNet models to classify the positional relationship between the M3M and the IAN (Fukuda et al. 2020; Choi et al. 2022; Sukegawa et al. 2022).

In this study, we built an end-to-end pipeline to detect and to classify M3M and IAN in panoramic radiography (OPG images) by evaluating multiple recent methods from the machine learning field (Fig. 1). The OPG is a commonly applied screening image. In clinical practice, it is not appropriate to routinely perform a cone beam CT (CBCT) due to radiation exposure. The OPG needs to fulfill various criteria in order to indicate a CBCT. Semisupervised methods allow building artificial intelligence (AI) systems for less demanding tasks of clinical practitioners, making diagnostic procedures more scalable. In particular, even a nonchallenging labeling task can be highly time-consuming and costly. In our pipeline, a spatially dependent U-Net (SDU-Net) was used to detect and

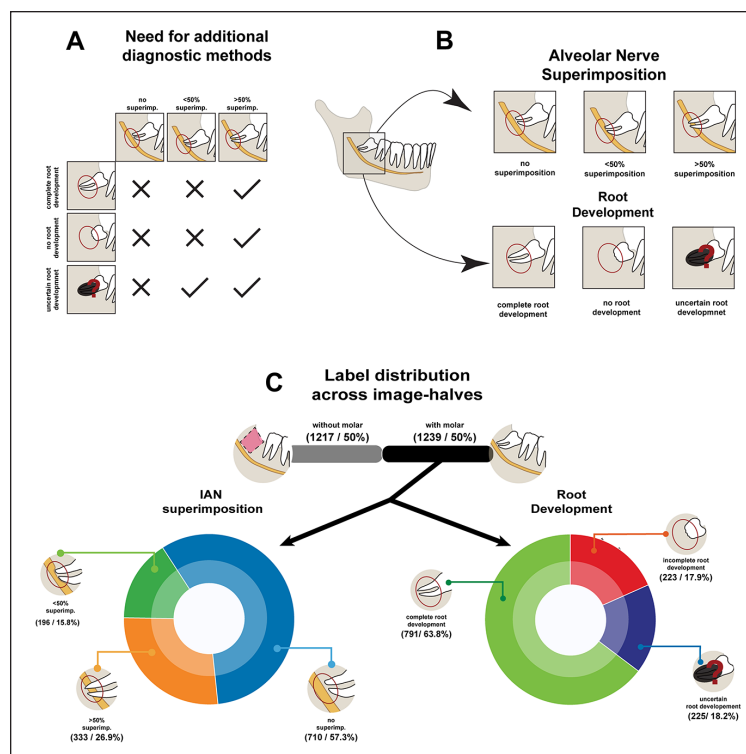
segment the region of the M3M and IAN, and a ResNet-101 architecture, trained through contrastive-based semisupervised learning, then classified M3M and IAN superimposition and M3M root development on the identified patches. The final output classification results were used to decide if an additional diagnostic method is required for therapy planning (Fig. 2A).

## Materials and Methods

As all data are completely anonymized, no ethics approval was required for this study. Nevertheless, an ethics waiver was obtained from the cantonal ethics committee Zurich (BASEC-Nr.: 2021-00057). For additional details concerning the description of materials and methods, refer to the Appendix.

### Training and Validation Data Set

A total of 4,516 panoramic radiographic images were collected from patients at the Center of Dental Medicine of the University of Zurich, Switzerland, acquired between 2017 and 2021. Patients had a mean age of  $37.3 \pm 22.2$  y with a sex distribution of 2,479/2,034 men/women. For 3 patients, no record of the sex could be found. In total, 2,940 images were acquired using Sirona Orthophos SL (Dentsply-Sirona) and 1,576 using



**Figure 2.** Therapy planning characterization and additional details on labelling procedure. **(A)** Matrix depicting the need for additional diagnostic intervention based on the combination of the potential outcomes from the 2 classification tasks. **(B)** Depiction of the class labels used in the annotation process of the mandibular third molar (M3M): the alveolar nerve superimposition task considers “no superimposition,” “superimposition <50%,” and “superimposition >50%,” whereas the root development task considers “complete root development,” “no root development,” and “uncertain root development.” **(C)** Distribution across label assignment for all tasks.

Soredex Cranex-D (Dexis) with pixel numbers of 1,404 to 1,536 vertically and 2,612 to 3,296 horizontally. Pixel sizes were 0.096 mm and 0.1 mm for Cranex and Sirona, respectively.

In total, 1,228 of the Sirona data were labeled by a last-year dental student who was trained on the task according to the annotation scheme illustrated in Figure 2B. Both halves of every image were annotated with a polygon, circumscribing the region of interest (ROI) of the M3M and the IAN, and each identified M3M was classified according to its spatial relation to the IAN (no superimposition, superimposition <50%, and superimposition >50%) and its root development (undeveloped, fully developed, and uncertain development). The distribution of label frequency within the data set of 1,228 labeled images is depicted in Figure 2C. The remaining 3,288 images (1,712 Sirona and 1,576 Cranex) had annotations provided.

### Control Evaluation Data Set

A total of 120 panoramic radiographic images were collected from a new cohort of patients at the Center of Dental Medicine of the University of Zurich, Switzerland, acquired in 2022 with

a panoramic x-ray (Axeos; Dentsply-Sirona). Patients had a mean age of  $31 \pm 21.6$  y with a sex distribution of 56/64 men/women. All images were acquired using Sirona Axeos with 1,404 vertical and 2,612 to 2,988 horizontal pixels. The data set was labeled following the same guidelines described for the training and validation data sets and as illustrated in Figure 2B. From the 120 OPGs, there were 144 identified M3Ms, which will be used in evaluating the classification tasks. No ROI segmentation masks were provided for the external evaluation data set. A total of 5 dental practitioners annotated each image independently. Inconsistent annotations were resolved by committee consensus. The overall agreement between the 5 annotators for the 3 annotation tasks before discussion can be seen in the Table, as calculated using Fleiss’s  $\kappa$  for the assessment of reliability of agreement between several annotators classifying items, with 1 meaning perfect agreement and 0 meaning no agreement. We used the interannotator agreement to identify and judge border cases preemptively.

### Image Preprocessing

All OPGs were split into 2 halves across the vertical axis, and each half was cropped such that the region from the mandibular jaw angle to the second incisor was preserved. The left half was horizontally flipped to match the positioning of the right half of the jaw. Final OPG patches were normalized to the pixel range of [0,1] and downsampled to  $224 \times 224$  pixels.

### Mandibular Third Molar Detection

To detect the ROI around the M3M and IAN, 3 different DNNs were evaluated: the YOLOv5 (Jocher 2020), which is a regression-based architecture developed specifically for object detection in images, and 2 different architectures developed for medical image segmentation, the U-Net and the SDU-Net (Ronneberger et al. 2015; Carvalho et al. 2022). Models with segmentation-based architectures were trained through supervised learning with the polygonal mask as a target and the YOLOv5 through the centroid of the mask.

### Mandibular Third Molar and Alveolar Nerve Classification

For the classification task, 2 widely used and high-performing DNNs were extensively evaluated: the ResNet-101 and the ViT-B. Both networks share a 2-stage construction principle: they can be separated into 1) a feature extractor, which learns how to extract features through a series of complex transformations of the original input image, and 2) a compact classifier

**Table.** Agreement between the Annotators for the External Evaluation Data Set.

	Molar-L	Molar-R	Superimposition-L	Superimposition-R	Development-L	Development-R
Fleiss's $\kappa$ agreement	0.91	0.93	0.83	0.78	0.86	0.87

component, which predicts the labels of the classification task from extracted features.

In this work, we explored a novel approach in which the feature extractor was pretrained through contrastive-based self-supervised learning. For this method, both models were pretrained using large amounts of nonannotated OPG data, relying only on properties from the image itself for learning, and ultimately leading to models that were more robust to the inherent biases of the labeling process.

For the pretraining of the feature extractors, all images, both labeled and unlabeled, were used for self-supervised training through SimCLR (Chen et al. 2020). After selecting the ROI, each image patch was augmented by composing a series of transformations: rotations, translations, additive gaussian noise, and gaussian smoothing. Maximizing the agreement between features from augmented versions of the same image, while minimizing the agreement between features from augmented versions from different images, empowered the model to learn highly descriptive features for each image.

**Final classification models.** After the self-supervised pretraining, the models were trained by supervised learning for both subtasks using the corresponding annotations. The models were fine-tuned by temporarily fixing the weights of the feature extractor and by adjusting the learning rate. To compare our semisupervised approach to a baseline model, we additionally trained each model by purely supervised learning (see Fig. 4).

### Model Performance Evaluation

For the evaluation of model performance, accuracy, precision, recall, Matthew's correlation coefficient (MCC) (Chicco and Jurman 2020), and the F1-score were used, with the last 2 metrics being known to robustly mitigate imbalances in the label distribution (Boughorbel et al. 2017). The in-distribution evaluation was performed through 10-fold cross-validation, where the models were trained in 8 of the subsets, validated on 1, and evaluated on the last subset. All data splits were performed in a patient-wise way. The main goal of the cross-validation was to disperse the inherent intraclass variation of the images. To statistically and scientifically validate the performance of our models, we used the external evaluation data set described earlier. A control evaluation set with a different cohort of patients and a different panoramic x-ray machine is considered an out-of-distribution data set.

To visualize model performance, we used the receiver operator characteristics (ROC) curve to depict the performance of the model prior to fixing its threshold and the confusion matrix to show all truly and falsely predicted classes of the models.

## Results

### Third Molar Detection

Figure 3 shows a direct comparison of the performances of the 3 detection models used, evaluated in both the training data set (in-distribution evaluation; see "Training and Validation Data Set") and the external evaluation data set (out-of-distribution evaluation; see "Control Evaluation Data Set").

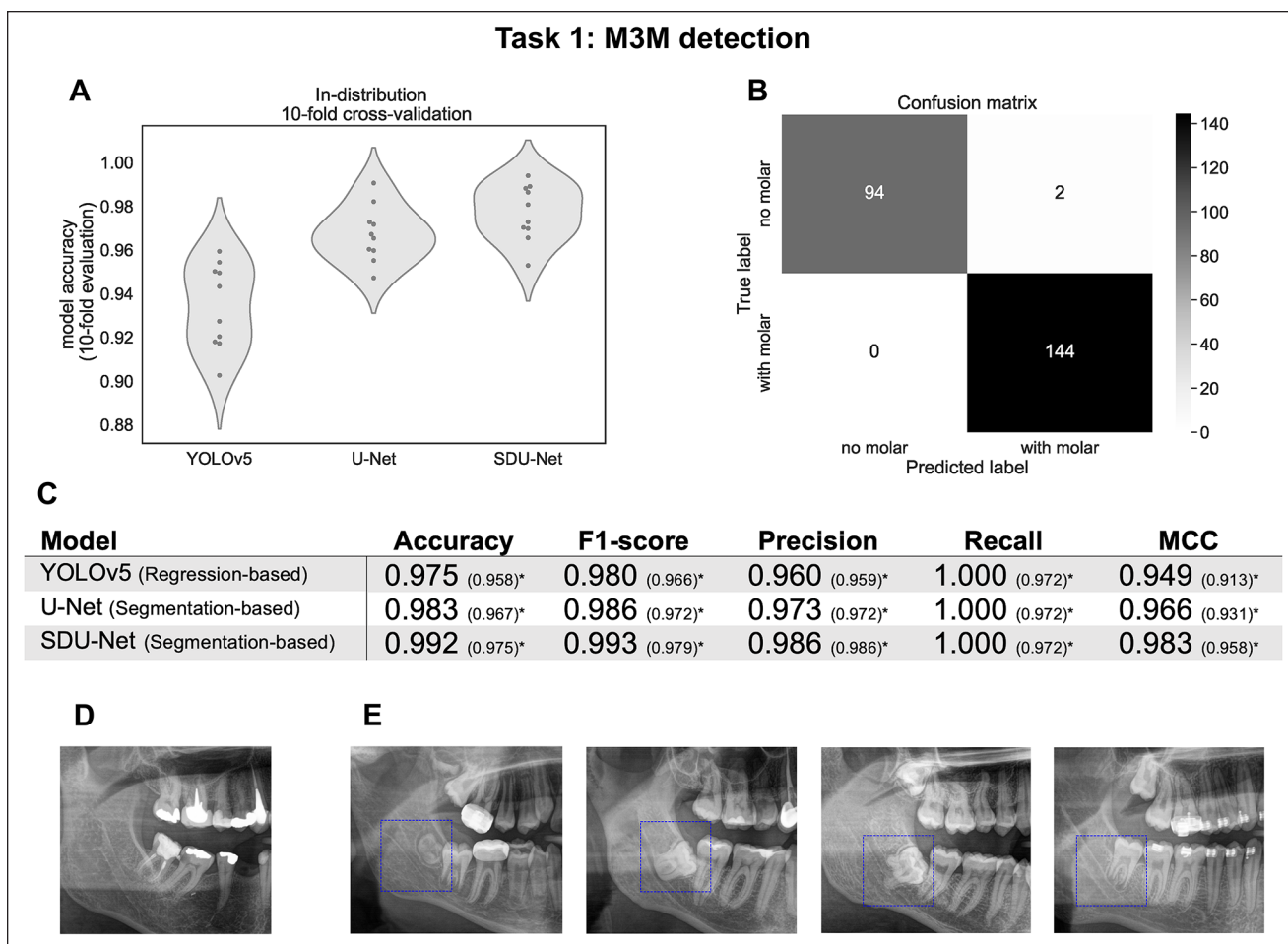
In the in-distribution evaluation, as depicted in Figure 3A, YOLOv5 has both an overall lower performance, as well as a higher standard deviation across cross-validation folds when compared to segmentation-based methods, with the U-Net being slightly outperformed by the SDU-Net. The accuracies for the YOLOv5, the U-Net, and the SDU-Net were  $0.934 \pm 0.019$ ,  $0.967 \pm 0.013$ , and  $0.977 \pm 0.013$ , respectively. The accuracy, F1-score, precision, recall, and MCC values evaluated on the out-of-distribution data can be seen in Figure 3C. The values inside the brackets represent results including 4 samples that had shifted M3Ms and were therefore wrongly classified. An example of a shifted M3M can be seen in Figure 3D. Excluding these cases, all 3 architectures were able to correctly identify all M3M, achieving a recall of 1.00. In all settings, the segmentation-based architectures, U-Net and SDU-Net, showed a better performance than the regression-based method, YOLOv5, with the SDU-Net being the best-performing model across all metrics tested. This model achieved accuracy values and an F1-score above 0.99, having misidentified only 2 images. Figure 3E shows 4 examples of correctly identified M3Ms.

### Classification

For both the IAN superimposition and the root development prediction tasks, the performances of the cross-validations are depicted in the violin plots in Figure 4A and F, respectively. Note that in these 2 tasks, from the total of 240 image-halves, only the 144 labeled as having a M3M were used to evaluate the models. The supervised ResNet-101, which was the best-performing model in the in-distribution setting, achieved an accuracy of  $0.94 \pm 0.01$  and  $0.93 \pm 0.02$ ; the supervised ViT-B achieved  $0.92 \pm 0.03$  and  $0.90 \pm 0.02$ ; the semisupervised ResNet-101 achieved  $0.93 \pm 0.01$  and  $0.90 \pm 0.02$ ; and the semisupervised ViT-B achieved  $0.90 \pm 0.02$  and  $0.87 \pm 0.02$ , all respectively for the IAN superimposition and the root development prediction tasks.

Interestingly, the trend of supervised models overperforming semisupervised ones was inverted when evaluating these models on the external evaluation data set, as can be seen on the ROC curves in Figure 4B and G and on the accuracy in the tables in Figure 4D and I. Evaluated on the external evaluation set, the





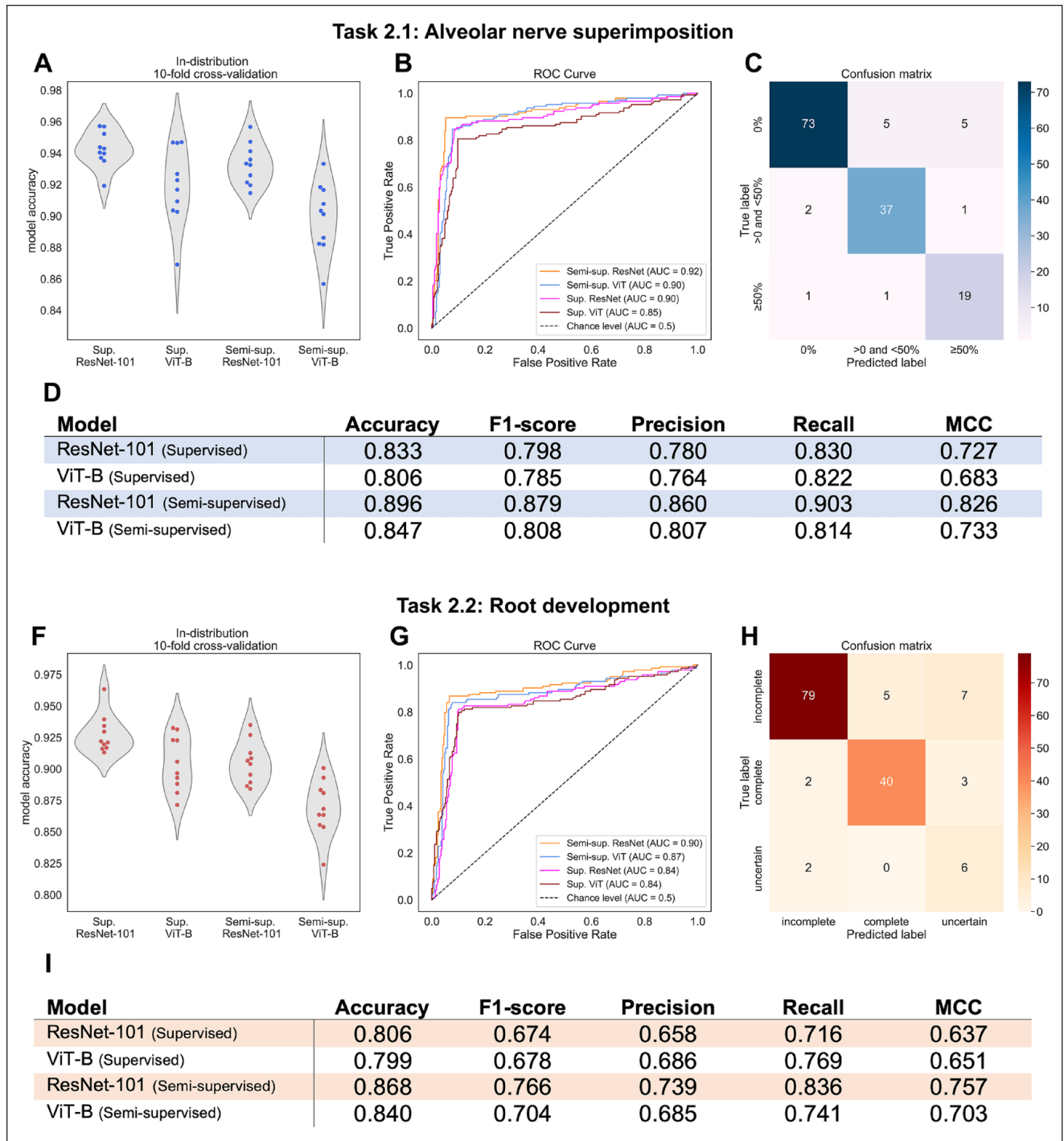
**Figure 3.** Overall results of model performance for the mandibular third molar (M3M) detection task. **(A)** Violin plot of the 10-fold cross-validation results for all architectures on the training data set. Each point represents 1 iteration of the cross-validation for each model. **(B)** Confusion matrix of the best-performing model, the spatially dependent U-Net (SDU-Net) architecture evaluated on the external evaluation data set (out-of-distribution evaluation). **(C)** Table of all performance metrics (accuracy, F1-score, precision, recall, and Matthew's correlation coefficient [MCC]) for all models evaluated on the out-of-distribution data. \*Performances computed taking into consideration the samples where the M3M is shifted to mesial. **(D)** Example of a shifted M3M where the model did not recognize the existence of a M3M. **(E)** Examples of 4 successfully detected M3Ms using the SDU-Net.

best model was the semisupervised ResNet-101. For the IAN and M3M superimposition, the semisupervised ResNet-101 and the semisupervised ViT-B yielded area under the receiver operating characteristic AUROC scores equal to or greater than 0.90 (Fig. 4B). For the root development task, these models achieved AUROC scores of 0.90 and 0.87, respectively (Fig. 4G).

Figure 4C and H show the confusion matrices of the semisupervised ResNet-101, which was the best-performing model, making it easier to visualize single failure points. For the IAN superimposition task, 10 images out of 83 were misclassified for 0% superimposition, 3 images out of 40 for <50% superimposition, and 2 images out of 21 for >50% superimposition, giving a total failure rate of 10%. For the root development, the total failure rate was 13% with 12 out of 91, 5 out of 45, and 2 out of 8 misclassifications for incomplete, complete, and uncertain root development, respectively.

## Discussion

Following the recent trend to develop DNN-based models for the detection and diagnosis of the M3M, this work bridges several gaps in previous research. First, it demonstrates the potential of semisupervised learning (Shehab et al. 2022), being, to the best of our knowledge, the first of its kind in the field of dental imaging to use large quantities of original data without expert annotations as a catalyst for highly robust ML models. Second, it also demonstrates the full potential of an integrated end-to-end pipeline that, starting from an original OPG image, detects and classifies the M3M into the relevant categories for further clinical diagnostic. With the final classification of both the M3M root development and its superimposition with the IAN, the clinical practitioner effectively receives the most relevant diagnostic information to further decide on the best next



**Figure 4.** Overall results for the superimposition of the mandibular third molar (M3M) with the inferior alveolar nerve (IAN) and the M3M root development classification tasks. **(A, F)** Violin plots of the 10-fold cross-validation results for ResNet-101 and ViT-B, trained with supervised and semisupervised learning, and evaluated on the training and validation data sets. Each point represents 1 iteration of the cross-validation for the respective model. **(B, G)** Receiver operator characteristics (ROC) curves of the models evaluated on the external evaluation data set. **(C, H)** Confusion matrices for the ResNet-101 trained with semisupervision and evaluated on the external evaluation data set. **(D, I)** Table of all performance metrics (accuracy, F1-score, precision, recall, and Matthew's correlation coefficient [MCC]) for all models evaluated in the external evaluation data set.

steps in the diagnostic radiological assessment pipeline for the patient.

Our proposed evaluation strategy was developed to identify and correct overly optimistic model performance both through

robust evaluation metrics that are resilient to unbalanced label distribution and through an external validation data set that could potentially detect assimilated shortcut features. As highlighted in the medical imaging domain (Shehab et al. 2022),

and in particular in the field of dentistry (Schwendicke et al. 2020; Ma et al. 2022), such benchmarking proved essential for trustworthy machine learning. As expected, we observed an overall drop in all model performances when models were evaluated by in-distribution cross-validation in comparison to the out-of-distribution control data set. However, these drops in performance were relatively minor in all models trained through semisupervised learning, indicating strong robustness of our models to distribution shifts. Such a robustness to distribution shifts was also confirmed recently by Navarro et al. (2021) in a work tackling pneumonia detection in x-rays. As Hendrycks et al. (2019) advanced, one explanation to the inherent robustness of semisupervised learning is its nonreliance on labels for training and thus effectively being able to avoid any nonrelevant potential correlation between the labeling process and image features.

There have been several studies trying to evaluate the risk of extraction complications during M3M. Although some studies have reported good prediction accuracy, none of the studies challenged their performance results by external validation, rendering it difficult to reliably assess the robustness of their models. First, in the M3M detection, our work compares favorably to Lee et al. (2022) and Zhu et al. (2021), which report a recall of 0.83 and 0.85, respectively. In screening pipelines, high precision should be prioritized to avoid excessive manual labor. However, as Hicks et al. (2022) point out, optimal recall may be necessary in settings where identifying all positive samples is crucial. In fact, in this clinical pipeline, any missed M3M leads to a complete break in the system, and to this extent, we see our detection model effectively fulfilling its goal. It is still important to highlight that all detection models have failed to detect the shifted M3M, and this may point out a systematic annotation error in the original training data. In the classification task, Choi et al. (2022) showed an accuracy of 0.63, Sukegawa et al. (2022) reached an accuracy of 0.86, and Zhu et al. (2021) reported an average precision of 0.85 when evaluating the spatial relation of the M3M and the IAN on OPGs. Liu et al. (2022) have used the more advanced visualizing technique of CBCTs to evaluate the M3M–IAN relation, achieving the highest accuracy of 0.93. These results demonstrate that we could outperform recent studies on the spatial relation of M3M and IAN using OPG images, reaching an accuracy of 0.9. We could not find any other studies mastering the task of automated root development prediction, making our study the first to address this question. Finally, MCC values of 0.82 for the M3M–IAN relation task and 0.75 for the M3M root development task, performed on the control evaluation test, suggest that our models were able to strongly generalize.

From a clinical point of view, a limitation of OPTs is that IAN branches may be undetected, indicating a CBCT. The indication of CBCTs, however, has to be weighted against the radiation exposure. For this reason, the Swiss guidelines suggest that the indication of a CBCT prior to third molar removal is based on defined 2-dimensional characteristics in OPTs (Dula et al. 2015). A ML-based system supports dentists in radiological diagnosis possibly avoiding misdiagnosis. An advantage is the opportunity to integrate, for example, a

guideline into a decision support system that would equally be available for more or less radiologically experienced practitioners. A further aspect is that incidental findings could be automatically detected, avoiding a time-consuming consultation of radiological experts.

Therefore, we see future efforts advancing beyond the methodological limitations of this work by establishing consistent benchmarks and widely accepted systematic annotation schemes, as already suggested in Ma et al. (2022). In addition, with the recent development of generative modeling in computer vision (Pang et al. 2021), we like to highlight the potential of infusing OPG images with 3-dimensional information, enabling a highly robust and fine-grained estimation of the relationship between the M3M and the IAN. In a consecutive project, it would be of interest to develop an algorithm that automatically detects the relation between the tooth roots and the mandibular canal for CBCTs.

## Conclusion

Even though AI is in the center of many research projects and will most likely play a major role in aided medical and dental decision-making, its application has hardly found its way into dental routine. In this study, we have developed a robust end-to-end ML pipeline that enables preoperative M3M assessment from OPGs to support the practitioner in everyday clinical practice as a decision-making aid and potentially supports the time management of clinical staff with significantly increased efficiency. Our pipeline helps to classify the risk of nerve injury during the removal of the M3M by preemptively evaluating M3M root growth and the positional relationship of the M3M root and the IAN. Based on the classification outcome, the practitioner can decide whether further radiological examination is required or not and thus considerably improve patient care.

## Author Contributions

J.S. Carvalho, contributed to conception and design, data analysis and interpretation, drafted and critically revised the manuscript; M. Lotz, S. Unger, contributed to conception and design, data acquisition and interpretation, drafted and critically revised the manuscript; L. Rubi, contributed to data analysis and interpretation, drafted and critically revised the manuscript; T. Pfister, contributed to data acquisition, drafted and critically revised the manuscript; J.M. Buhmann, contributed to data conception and design, critically revised the manuscript; B. Stadlinger, contributed to conception and design, data interpretation, critically revised the manuscript. All authors gave final approval and agree to be accountable for all aspects of the work.

## Acknowledgments

We thank Valérie Schmidt-Ziltener for supporting the data extraction and Yara Jäkel for supporting the figure design.

## Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

## Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

## ORCID iD

B. Stadlinger  <https://orcid.org/0000-0001-5044-7052>

## References

- Boughorbel S, Jarray F, El-Anbari M. 2017. Optimal classifier for imbalanced data using Matthews correlation coefficient metric. *PLoS One*. 12(6):e0177678.
- Carvalho JBS, Santinha J, Miladinović Đ, Cotrini C, Buhmann JM. 2022. Holistic modeling in medical image segmentation using spatial recurrence. Paper presented at: MIDL 2022. Proceedings of the 5th International Conference on Medical Imaging with Deep Learning. PLMR. 172:199–218; Zürich, Switzerland. [accessed 2023 July 12]; <https://proceedings.mlr.press/v172/carvalho22a.html>.
- Chen T, Kornblith S, Norouzi M, Hinton G. 2020. A simple framework for contrastive learning of visual representations. Paper presented at: PMLR 2020. Proceedings of the 37th International Conference on Machine Learning; Vienna, Austria. [accessed 2023 July 12]; <http://proceedings.mlr.press/v119/chen20j/chen20j.pdf>.
- Chicco D, Jurman G. 2020. The advantages of the Matthews correlation coefficient (mcc) over f1 score and accuracy in binary classification evaluation. *BMC Genomics*. 21(1):6.
- Choi E, Lee S, Jeong E, Shin S, Park H, Youm S, Son Y, Pang K. 2022. Artificial intelligence in positioning between mandibular third molar and inferior alveolar nerve on panoramic radiography. *Sci Rep*. 12(1):2456.
- Dula K, Benic GI, Bornstein M, Dagassan-Berndt D, Filippi A, Hicklin S, Kissling-Jeger F, Luebbert HT, Sculean A, Sequeira-Byron P, et al. 2015. SADMFR guidelines for the use of cone-beam computed tomography/digital volume tomography. *Swiss Dent J*. 125(9):945–953.
- Eyrich G, Seifert B, Matthews F, Matthiessen U, Heusser CK, Kruse AL, Obwegeser JA, Lubbers HT. 2011. 3-dimensional imaging for lower third molars: is there an implication for surgical removal? *J Oral Maxillofac Surg*. 69(7):1867–1872.
- Fukuda M, Arijji Y, Kise Y, Nozawa M, Kuwada C, Funakoshi T, Muramatsu C, Fujita H, Katsumata A, Arijji E. 2020. Comparison of 3 deep learning neural networks for classifying the relationship between the mandibular third molar and the mandibular canal on panoramic radiographs. *Oral Surg Oral Med Oral Pathol Oral Radiol*. 130(3):336–343.
- He K, Zhang X, Ren S, Sun J. 2016. Deep residual learning for image recognition. Paper presented at: CVPR 2016. Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition; Las Vegas, NV, USA. [accessed 2023 July 12]; [https://www.cv-foundation.org/openaccess/content\\_cvpr\\_2016/papers/He\\_Deep\\_Residual\\_Learning\\_CVPR\\_2016\\_paper.pdf](https://www.cv-foundation.org/openaccess/content_cvpr_2016/papers/He_Deep_Residual_Learning_CVPR_2016_paper.pdf).
- Hendrycks D, Mazeika M, Kadavath S, Song D. 2019. Using self-supervised learning can improve model robustness and uncertainty. *Adv Neural Inf Process Syst*. 32. 33rd Conference on Neural Information Processing Systems (NeurIPS 2019), Vancouver, Canada. [accessed 2023 July 12]; <https://arxiv.org/pdf/1906.12340.pdf>.
- Hicks SA, Strumke I, Thambawita V, Hammou M, Riegler MA, Halvorsen P, Parasa S. 2022. On evaluation metrics for medical applications of artificial intelligence. *Sci Rep*. 12(1):5979.
- Jocher G. 2020. YOLOv5 by ultralytics. In: software C, editor. 7.0 ed. [accessed 2022 Sep 7]. <https://github.com/ultralytics/yolov5>.
- Kuhnisch J, Meyer O, Hesenius M, Hickel R, Gruhn V. 2022. Caries detection on intraoral images using artificial intelligence. *J Dent Res*. 101(2):158–165.
- Lee J, Park J, Moon SY, Lee K. 2022. Automated prediction of extraction difficulty and inferior alveolar nerve injury for mandibular third molar using a deep neural network. *Appl Sci*. 12(1):475.
- Leung YY, Cheung LK. 2011. Risk factors of neurosensory deficits in lower third molar surgery: a literature review of prospective studies. *Int J Oral Maxillofac Surg*. 40(1):1–10.
- Litjens G, Kooi T, Bejnordi BE, Setio AAA, Ciompi F, Ghafoorian M, van der Laak J, van Ginneken B, Sanchez CI. 2017. A survey on deep learning in medical image analysis. *Med Image Anal*. 42:60–88.
- Liu MQ, Xu ZN, Mao WY, Li Y, Zhang XH, Bai HL, Ding P, Fu KY. 2022. Deep learning-based evaluation of the relationship between mandibular third molar and mandibular canal on CBCT. *Clin Oral Investig*. 26(1):981–991.
- Ma J, Schneider L, Lapuschkin S, Achibat R, Duchrau M, Krois J, Schwendicke F, Samek W. 2022. Towards trustworthy AI in dentistry. *J Dent Res*. 101(11):1263–1268.
- Navarro F, Watanabe C, Shit S, Sekuboyina A, Peeken J, Combs SE, Menze BH. 2021. Evaluating the robustness of self-supervised learning in medical imaging. *arXiv preprint arXiv:2105.06986*. [accessed 2023 July 12]; <https://arxiv.org/abs/2105.06986>.
- Pang Y, Lin J, Qin T, Chen Z. 2021. Image-to-image translation: methods and applications. *IEEE Trans Multimedia*. 24:3859–3881. doi:10.1109/tmm.2021.3109419.
- Ronneberger O, Fischer P, Brox T. 2015. U-net: convolutional networks for biomedical image segmentation. Paper presented at: Medical Image Computing and Computer-Assisted Intervention–MICCAI 2015: 18th International Conference, Munich, Germany, October 5–9, 2015, Proceedings, Part III 18 (pp. 234–241). Springer International Publishing.
- Schwendicke F, Samek W, Krois J. 2020. Artificial intelligence in dentistry: chances and challenges. *J Dent Res*. 99(7):769–774.
- Shan T, Tay FR, Gu L. 2021. Application of artificial intelligence in dentistry. *J Dent Res*. 100(3):232–244.
- Shehab M, Abualigah L, Shambour Q, Abu-Hashem MA, Shambour MKY, Alsalibi AI, Gandomi AH. 2022. Machine learning in medical applications: a review of state-of-the-art methods. *Comput Biol Med*. 145:105458.
- Shen D, Wu G, Suk HI. 2017. Deep learning in medical image analysis. *Annu Rev Biomed Eng*. 19:221–248.
- Sigron GR, Pourmand PP, Mache B, Stadlinger B, Locher MC. 2014. The most common complications after wisdom-tooth removal: part 1: a retrospective study of 1,199 cases in the mandible. *Swiss Dent J*. 124(10):1042–1046.
- Sukegawa S, Tanaka F, Hara T, Yoshii K, Yamashita K, Nakano K, Takabatake K, Kawai H, Nagatsuka H, Furuki Y. 2022. Deep learning model for analyzing the relationship between mandibular third molar and inferior alveolar nerve in panoramic radiography. *Sci Rep*. 12(1):16925.
- Vaswani A, Shazeer N, Parmar N, Uszkoreit J, Jones L, Gomez A, Kaiser Ł. 2017. Attention is all you need. *Adv Neural Inf Process Syst*. 30. [accessed 2023 July 12]; [https://proceedings.neurips.cc/paper\\_files/paper/2017/file/3f5ee243547dee91fbd053c1c4a845aa-Paper.pdf](https://proceedings.neurips.cc/paper_files/paper/2017/file/3f5ee243547dee91fbd053c1c4a845aa-Paper.pdf).
- Wang H, Minnema J, Batenburg KJ, Forouzanfar T, Hu FJ, Wu G. 2021. Multiclass CBCT image segmentation for orthodontics with deep learning. *J Dent Res*. 100(9):943–949.
- Zhu T, Chen D, Wu F, Zhu F, Zhu H. 2021. Artificial intelligence model to detect real contact relationship between mandibular third molars and inferior alveolar nerve based on panoramic radiographs. *Diagnostics (Basel)*. 11(9):1664.