·数智口腔专栏·综述·

# 人工智能图像处理技术在口腔医学中的应用

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【摘要】 近年来,人工智能(AI)图像处理技术已逐渐成熟并应用于口腔医学领域,有力地推动了口腔医学的发展。本文系统综述了AI图像处理技术在口腔医学中的研究与应用进展,涵盖基础理论、关键技术及临床实践等多个方面。在阐释深度学习、机器学习等核心技术的基础上,重点分析了该技术在各类口腔医学图像中的具体应用,并进一步展望了其未来发展方向、潜在应用价值,以及伴随而来的伦理与法律挑战,为实现更广泛、更可靠的临床应用,仍有诸多关键问题亟待解决。

【关键词】 人工智能; 口腔医学; 图像处理; 深度学习; 机器学习

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**Application of artificial intelligence image processing technology in stomatology**

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**【Abstract】** In recent years, artificial intelligence (AI) image processing technology has matured and been widely applied in stomatology, significantly advancing the field. This article systematically reviews its research and application progress, covering fundamental theories, key technologies, and clinical practices. Based on explanations of technologies including deep learning and machine learning, it focuses on analyzing specific applications across various dental images and discusses future directions, potential value, and associated ethical and legal challenges. To achieve more extensive and reliable clinical applications, key issues remain to be addressed.

**【Key words】** Artificial intelligence; Oral medicine; Image processing technology; Deep learning; Machine learning

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随着人工智能(artificial intelligence,AI)技术的发展,其在医学图像处理领域的应用正不断深化与拓展。在口腔医学中,疾病的精准判断与治疗方案的制定建立于对各类图像的准确解读之上。然而,传统的人工判读高度依赖医师经验与主观判断,处理海量数据时存在效率瓶颈,且难以保证结果的一致性与可重复性。加之口腔颌面部结构精细、解剖变异大、病损表现多样且早期征象隐匿,进一步增加了精准诊

断的难度。在此背景下,AI图像处理技术大幅提升了图像识别、分割和定量分析的精度与效率,其不仅能够辅助医师快速并精准地定位病灶,更能量化分析病变特征,为诊断与治疗提供更可靠的支撑[1]。

一、口腔医学中的人工智能图像处理技术研究进展

口腔医学图像处理经历了从传统技术到AI的演进。传统方法虽能提取部分结构信息,但依赖人工设计特征,难以适应口腔复杂的解剖与病变变异。随着机器学习及深度学习等技术的发展,模型实现了对病变特征的自动识别,推动该领域迈入数据驱动的智能分析新阶段[2]。

1. 传统图像处理技术:传统图像处理技术以像素操作和数学变换为核心,通过对图像进行灰度调整、滤波增强、边缘检测及形态学处理等方法,实现信息提取与视觉优化。在口腔医学中,图像增强与分割技术是提高图像质量、准确识别组织结构的有力帮手[3]。例如,直方图均衡化可通过调整灰度分布,提升根尖片图像的对比度和细节清晰度[4]。在面对锥形束CT(cone-beam computed tomography,CBCT)图像因对比度低、噪声高而难以实现精准分割的挑战时,研究人员应用分水岭变换,结合逐步阈值分割与标记点技术,有效实现了颌骨三维重建及牙列的逐颗分割,为口腔外科手术规划与模拟种植体植入提供了高精度三维模型支撑[5]。然而,此类方法依赖于人工设定特征与复杂参数调整,其泛化能力仍显不足。

2. AI驱动的图像处理技术:为克服传统方法的局限,以机器学习及深度学习为代表的AI图像处理技术,在口腔医学图像分析中展现出巨大的应用潜力。作为AI的关键构成,机器学习涵盖数据收集、预处理、特征提取与筛选,随后借助分类或回归算法构建预测模型,并通过系统评估指标完成模型的验证与优化[6]。从简单线性回归到复杂深度学习模型的演进中,机器学习不仅推动了计算能力的提升,更大幅拓展了其在口腔医学中的应用边界[7]。

深度学习是机器学习的重要分支,凭借深层神经网络结构,能自动从图像中学习特征[8]。其中,卷积神经网络(convolutional neural networks,CNN)是最具代表性的架构之一,其通过卷积层提取局部特征,经池化层降维后,由全连接层整合信息并完成分类或回归任务,在图像分析中表现突出[9]。YOLO(You Only Look Once)系列模型作为目标检测CNN,以单次推理即可实现目标定位与分类的特性,在牙齿目标的快速检测与区域定位中应用广泛[10]。U型卷积神经网络(U-shaped convolutional network,U-Net)作为基于CNN的经典分割模型,在牙齿分割与识别中取得了优异性能[11]。此外,生成对抗网络等模型也在图像去噪、伪影校正等重建与增强任务中发挥重要作用,为后续诊断提供更高质量的图像基础[12]。

二、人工智能图像处理技术在口腔医学图像中的应用

口腔医学图像在疾病的诊断及辅助治疗中已得到广泛应用,通过对海量影像数据的学习,AI模型能够有效检测出人眼难以察觉的病变特征,显著提升诊断的准确性与客观性。

1. 口腔X线平片图像的智能处理及应用:AI在牙体病变检测领域发展迅速,基于神经网络的模型在X线影像分析中展现出较高的诊断效能。在龋齿识别任务中,多项研究显示其准确率普遍超过80%[13-14]。在根尖周病变的检测中,Diagnocat系统[15]与YOLO系列模型[16]均可有效实现病变的精准定位。与此同时,AI在牙根纵裂识别[17]、牙髓暴露风险预测[18]及牙根形态评估[19]等方面也展现出多样化分析能力。

牙周炎的诊断需结合临床检查和放射学检查,牙槽骨高度是问题核心。深度学习中的U-Net[20]、YOLOv8[21]及集成模型[22]在口腔全景曲面体层片的牙槽骨吸收检测与牙周炎分期诊断中表现出较高准确性。系统评价显示,AI模型检测牙槽骨吸收的灵敏度为92.3%,特异度为91.7%,曲线下面积(area under curve,AUC)为0.97,具有临床应用的潜力[23]。

下颌第三磨牙常因位置特殊而引起系列问题,AI模型有望成为其临床评估的高效检测工具,并覆盖术前诊断到操作指导的全流程[24-27]。颌面部囊肿和肿瘤早期症状易被忽视,直至它们生长开始影响到周围的解剖结构时才会被发现,AI有助于实现颌骨病变的早期检测[28-29]。YOLOv8、RT-DETR-L分别在透射线与不透射线病变检测任务中表现突出[30]。即使上颌存在含气结构的干扰,DetectNet网络对上颌囊肿的检测精确率也可达90%[31]。此外,AI在区分根尖囊肿与肉芽肿[32]、成釉细胞瘤和角化囊性牙源性肿瘤[33]、Stafne骨腔与牙源性病变[34]等方面,也展现出精准的鉴别能力。

头影测量分析是正畸医师进行诊断和制定治疗计划的基石。2009年,Leonardi等[35]验证了CNN在头影测量自动识别方面的可靠性。基于CNN的算法可实现精确迅速的定位标志点识别,其在2 mm误差范围内检测准确率为97.30%,37点定位耗时3 s[36];对于Gonion等关键易错点,其定位误差可降低至半数[37]。目前,AI模型与医师的判断差异已基本处于医师间自身差异水平[38],以Uceph为代表的临床数字化软件已逐步整合相关算法并投入实际应用,极大提高了医师的诊疗效率。

Song等[39]将CNN模型应用于口腔全景曲面体层片,以辅助钙化疾病(颈动脉钙化、淋巴结钙化和唾液腺结石)的检测,该算法使全科医师的诊断准确率显著提升(从11.4增至39.8)。与此同时,AI图像处理技术的应用已进一步拓展至上颌窦、颞下颌关节及颌骨疾病等的辅助诊断与影像学分析[40-42]。综合而言,AI在口腔疾病的细分领域已取得重要进展,但要实现真正稳定、可复现的临床应用,还需重视多中心外部验证,并建立多样性数据集以支撑模型泛化。

2. 口腔CBCT图像的智能处理及应用:CBCT扫描耗时短、辐射剂量低,可实现颌面结构三维高分辨率可视化,近年来在临床中得到广泛的应用。但其图像仍普遍存在散射噪声及灰度不均匀等固有缺点,影响诊断准确性与后续分析。深度学习方法已经被用于增强CBCT图像分割性能[43]和降低伪影指数,改善图片质量[44]。其不仅分割下颌神经管的精度高,速度也比人工快近100倍[45]。研究表明,AI模型识别

上颌窦与磨牙解剖关系的准确率达89%[46]，并在牙体与髓腔分割中展现出优于传统方法的性能[47]。

在疾病检测方面，AI与CBCT图像的结合，不仅可有效检测牙周炎、龋齿和根尖周炎等常见疾病[48-49]，例如Kirnbauer等[50]研究开发的全自动算法，在CBCT图像中检测根尖周病变的灵敏度与特异性为97.1%和88.0%，能有效辅助临床诊断。更重要的是，二者的结合可大幅提升隐匿性病变的诊断敏感性。ResNet-50模型在牙根纵裂的检测中展现出优异的诊断性能[51]，特征选择技术与深度学习模型的结合则能提升牙根外吸收识别性能[52]。Talaat等[53]研究开发的模型在颞下颌关节骨关节炎的诊断中表现出色，其诊断结果与金标准的一致性显著高于口腔放射专家，有望消除诊断主观性。InceptionV3模型在术前鉴别成釉细胞瘤和牙源性角化囊肿的准确率优于口腔颌面外科医师，展现出强大的辅助诊断潜力[54]。进一步而言，AI模型不仅可针对单一病种实现高精度检测，还可向覆盖全口疾病诊断的系统化方向发展[55]。

在临床决策支持中，AI在种植及正畸临床场景中已实现对CBCT影像的辅助分析与规划应用。在种植学领域，AI可用于自动骨密度分类，为口腔种植术前规划和术中备洞提供更详尽的指导方案[56]；最新研究还提示，基于CNN的模型具备预测种植体成功率的潜能[57]。在正畸领域，基于CBCT图像数据，AI已实现矫治效果模拟，从而辅助制定治疗方案。此外，通过结合口内扫描与CBCT数据，AI还可自动分割牙根并完成冠部配准，从而无创监控牙根位置，为正畸治疗中的牙根位置监控提供了新方法[58]；CNN模型对腭中缝成熟度的自动分期将有助于扩弓治疗方案的选择[59]。值得关注的是，在颌骨肿瘤等复杂疾病的诊疗领域，相关技术仍需持续探索与验证。

3. 口腔磁共振(magnetic resonance, MR)及超声图像的智能处理及应用：MR成像是软组织检查的常用手段，在口腔疾病诊断中具有重要价值。AI图像处理技术已广泛应用于MR图像数据分析，显著提升了相关疾病的诊断效能。对于腮腺疾病，Zheng等[60]提出的模型在训练集与验证集中鉴别良恶性肿瘤的AUC分别达0.952和0.938，增强了传统影像方法的鉴别诊断能力；U-Net、ResNet等模型在腮腺肿瘤分类与分期中也表现出较高的准确率[61-62]。对于颞下颌关节疾病，深度学习模型(如VGG16、InceptionV3等)可准确检测关节盘移位及积液，其诊断能力与颞下颌关节疾病专家相当[63-64]。在口腔鳞状细胞癌(oral squamous cell carcinoma, OSCC)淋巴结转移的预测与诊断方面，基于深度学习技术构建的模型，不仅能实现高精度的淋巴结转移预测，还能显著降低隐匿性转移的漏诊率[65]。

口腔超声图像能实时显示软硬组织信息，针对唾液腺超声在诊断原发性干燥综合征时评分者间一致性不佳的问题，研究人员创新性地引入了放射组学与AI算法，该模型可靠性达到了临床医师水平[66]。多模态分析模型在腮腺肿瘤的良恶性鉴别中也具有较高的诊断准确率[67]。在形态学分析方面，基于YOLOv8的深度学习模型能够自动分割下颌骨髁突，具备成为高效临床辅助工具的潜力[68]。实时成像是超声技术的核心优势，推动AI与实时超声工作流深度融合，以实现对动态影像的全过程分析，是进一步提升其诊断效能的重要途径。

4. 口腔病理图像的智能处理及应用：口腔病理图像的智能处理对准确诊断疾病、合理制定治疗方案具有关键意义。深度学习模型对OSCC组织病理学图像的智能分析已取得显著进展[69-70]，例如EfficientNetB3模型的识别准确率可达99%[71]。另有基于VGG16与SAM优化器构建的模型，在OSCC病理分类任务中AUC值达0.960，且其辅助能有效提升病理医师的诊断能力[72]。在研究人员的不懈求索下，基于组织病理图像的AI模型不仅实现了口腔上皮异常增生的分类与癌变风险预测[73]，还可直接从原发灶切片中预测淋巴结转移情况[74]。这些高度准确且稳定的工具体现出卓越的临床转化价值，有望成为辅助制定个性化治疗决策的可靠手段。

5. 口腔摄影照及视频的智能处理及应用：得益于获取的便捷性，通过相机或手机拍摄的口腔内照片已成为重要的数据源。在健康自查与疾病早期筛查场景中，用户仅需拍摄口腔照片，AI模型即可协助识别异常。研究证实，深度学习模型借助口腔照片在筛查口腔潜在恶性疾病[75]及检测OSCC[76]等任务中表现优异，具备良好的早期筛查应用潜力。对于龋病、牙龈炎等问题，通过CNN进行牙面分割预处理，能有效提升模型对龋病的分类与定位能力[77-78]。Oral-Mamba深度学习模型对牙龈炎、龋齿和牙结石分割准确率达83%[79]。Chau等[80]开发的AI系统，更是能够在像素级别上精准识别牙龈炎。对于黏膜病变，AI在识别复发性阿弗他溃疡[81]、口腔扁平苔藓[82]等方面也取得了进展，进一步扩展了其应用范围。

在提升诊疗效率与支持远程医疗方面，AI驱动的智能分析正突破传统界限。早期，为实现基于照片的牙齿三维重建，研究主要依赖从明暗恢复形状(shape from shading, SFS)等方法[83-84]。在此基础上，Chen等[85]通过结合参数化模型与深度学习，仅利用有限角度的口内照片即可重建出牙齿的三维形态与咬合关系，为远程正畸评估提供了新技术方案。此外，较图片而言，视频可提供更为丰富的信息。一项临床评估显示，基于智能手机和即时通讯应用的同步远程会诊模式极具潜力：远程专家诊断与现场专家诊断结果具有高度一致性，为口腔病变的远程可靠诊断提供了技术支持[86]。

## 三、人工智能图像处理技术在口腔医学中的未来展望

1. 口腔医学图像处理技术的问题与挑战：AI在口腔医学图像分析的性能上限，主要受三大关键因素制约。一是数据与标注瓶颈，标准化高质量标注数据集稀缺，且存在数据异构、标注成本高和主观性强等问题，隐私保护形成的共享壁垒更加剧了优质训练数据的构建难度；二是成像技术固有局限，CBCT金属伪影、根尖片结构重叠等不同模态的技术短板，会引入噪声与信息缺失，成为算法设计的核心难题；三是模型解释性不足，跨设备验证性能显著衰减，制约其在临床的普及。

同时，该技术发展应用还面临多重伦理与法律挑战：（1）隐私保护层面，口腔图像采集与面部识别结合加剧信息泄露风险，需建立严格的数据管控保护机制[87]；（2）责任界定层面，AI辅助诊断偏差的责任认定复杂，需明确各方权责、完善法律规范以实现合理追责[88]；（3）技术应用层面，目前尚缺乏统一标准导致诊断结果差异大，需构建统一技术标准与质控体系，保障诊断精准可重复，维护患者权益。

2. 口腔医学图像处理技术的发展趋势：尽管面临诸多挑战，口腔医学图像处理技术朝着精准化、智能化和便捷化方向发展的趋势仍毋庸置疑[89]。在疾病诊断方面，AI可进一步整合多种数据来源，提高诊断准确性。例如，结合口腔影像数据和患者病史等，构建更全面的诊断模型。在治疗规划方面，AI图像处理技术有助于实现个性化治疗方案的制定。通过对患者口腔结构的三维建模，结合AI算法，为患者提供最佳治疗策略。

综上所述，AI图像处理技术在口腔医学中展现出广泛的应用前景与卓越性能（图1），部分技术如牙周评估、头影测量等已逐步进入临床辅助应用阶段。然而，现有研究多处于探索阶段，尚需通过大样本、多中心研究进一步验证技术有效性，同时系统性应对伦理规范与数据隐私等核心问题。随着相关数据积累与技术体系的持续完善，AI不仅能提升基层口腔诊疗的可及性，辅助临床医师实现高效精准诊断，更将推动口腔医疗迈入精准、高效和普惠的智能新时代。

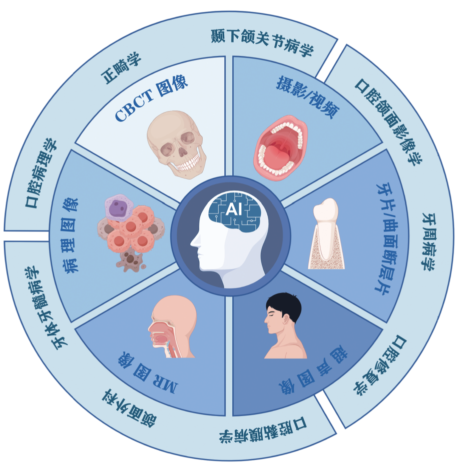


**图1**　人工智能图像处理技术在口腔医学中的应用架构　CBCT：锥形束CT；MR：磁共振。

**利益冲突**　所有作者均声明不存在利益冲突

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