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·综述·

# 数字化技术在口腔正畸监控中的应用进展

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**【摘要】** 在正畸治疗中，对患者的临床监控有利于及时发现并妥善处置问题，确保矫治计划的顺利实施，是决定正畸治疗成功与否的关键要素之一。本文对近年来数字化技术在正畸牙移动、正畸相关并发症以及矫治器戴用依从性监控中的应用进行综述，旨在为相关研究人员及临床医师提供洞见，推动数字化技术在正畸临床实践中的广泛应用，以期提高治疗效果并优化患者体验。数字化技术在正畸临床诊疗中逐渐得到广泛应用，不仅能够辅助临床决策和方案设计，也可在临床监控方面发挥重要作用。检查资料的数字化以及口腔模型的可视化使椅旁复诊监控更加便捷、精准、高效，远程监控技术帮助正畸医生及时发现患者口腔问题、采取相应措施。此外，多模态数据的融合可为根骨关系的监控提供指导，人工智能技术已初步实现正畸牙移动、相关并发症及患者戴用情况的自动识别，传感装置则可用于监测患者戴用情况，为临床决策提供数据支撑。数字化技术在口腔正畸监控中的应用前景广阔，然而仍需应对技术瓶颈、伦理考量及患者接受度等多重挑战。

**【关键词】** 口腔正畸；临床监控；数字化技术；远程监控技术；正畸牙移动；隐形矫治；口腔卫生；患者依从性；医学伦理

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**Advances in the application of digital technology in orthodontic monitoring**

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**【Abstract】** During orthodontic treatment, clinical monitoring of patients is a crucial factor in determining treatment success. It aids in timely problem detection and resolution, ensuring adherence to the intended treatment plan. In recent years, digital technology has increasingly permeated orthodontic clinical diagnosis and treatment, facilitating clinical decision-making, treatment planning, and follow-up monitoring. This review summarizes recent advancements in digital technology for monitoring orthodontic tooth movement, related complications, and appliance-wearing compliance. It aims

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to provide insights for researchers and clinicians to enhance the application of digital technology in orthodontics, improve treatment outcomes, and optimize patient experience. The digitization of diagnostic data and the visualization of dental models make chair-side follow-up monitoring more convenient, accurate, and efficient. At the same time, the emergence of remote monitoring technology allows orthodontists to promptly identify oral health issues in patients and take corresponding measures. Furthermore, the multimodal data fusion method offers valuable insights into the monitoring of the root-alveolar relationship. Artificial intelligence technology has made initial strides in automating the identification of orthodontic tooth movement, associated complications, and patient compliance evaluation. Sensors are effective tools for monitoring patient adherence and providing data-driven support for clinical decision-making. The application of digital technology in orthodontic monitoring holds great promise. However, challenges like technical bottlenecks, ethical considerations, and patient acceptance remain.

**【Key words】** orthodontics; clinical monitoring; digital technology; remote monitoring technology; orthodontic tooth movement; clear aligner therapy; oral hygiene; patient compliance; medical ethics

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在正畸治疗过程中，对矫治进程的密切监控是确保矫治效率和效果的关键。在实施固定矫治时，正畸医师需要对患者的矫治器完整性、口腔健康状况等保持关注，以便评估治疗进度及效果，做好正畸相关并发症的预防和处置，并为患者提供反馈和指导。此外，特别是无托槽隐形矫治还需要医生密切关注矫治器与患者牙列的贴合度及患者的依从性[1-2]。

在传统正畸治疗中，对患者的临床监控主要在椅旁进行。数字化技术在椅旁监控中的应用主要体现在检查资料的数字化[3]，通过获取相关数据，生成数字化三维模型，医生能够更精准地捕捉和分析患者口腔状况，及时与患者沟通并了解其反馈和需求，制定更符合个体特征及需求的矫治方案[4]。随着数字化技术在医学领域的不断发展，远程监控作为一种新型监控方式逐渐得到广泛应用。患者可以通过视频通讯以及智能设备完成口腔资料的采集和上传，实现口腔状况的及时反馈[5]。远程监控技术能够突破时空的限制，弥补常规椅旁监控的不足之处，同时提高医患之间的沟通效率[6-7]。因此，远程监控有望促进治疗效果的提升，在正畸领域具有广阔前景和重要的临床价值[8-9]。本文旨在对相关数字化技术在正畸牙移动、并发症以及患者依从性监控中应用的研究进行综述，为正畸医生在临床工作中应用数字化技术提供参考。

## 1　数字化技术与正畸牙移动监控

正畸牙移动（orthodontic tooth movement，OTM）是牙槽骨在外力作用下，压力侧骨吸收、张力侧骨沉积的过程。其速度通常取决于施力的大小和频率、牙根的数量和形状、骨小梁的质量以及个体的组织反应[10]。在治疗过程中，合适的加力方式和力值使牙齿按计划持续、稳定地移动，而通过患者的定期复诊，医生则能够评估治疗进展情况，并且根据实际情况及时调整治疗策略[11]。

在临床诊疗中，基于石膏模型的牙移动量测量被认为是评估牙移动进程的“金标准”。然而，石膏模型测量存在测量精度有限、时间成本高、模型易损坏丢失、制取过程可能引起患者不适等局限性[12]。因此，基于数字化模型的测量方法近年逐渐受到重视，多项研究证实其准确性已达到临床应用标准[13]。数字化印模技术利用口内扫描仪采集的口内图像或视频资料，迅速构建出患者的三维牙列模型。凭借其精度更高、失真更少的优势，采用共聚焦显微成像技术的一系列口内扫描仪产品在临床上应用最为广泛[14-15]。口内扫描仪的使用不仅显著缩短椅旁时间并降低材料成本，在与椅旁计算机辅助设计与制造（computer aided design / computer aided manufacturing，CAD/CAM）结合后还能够进一步提高诊疗效率[16]。此外，有研究显示，固定矫治中弓丝和托槽的存在对于口内扫描的精确度影响不大[12, 17]，这也有效避免了印模制作过程中托槽和弓丝的牵拉作用产

生的材料拉伸问题。

以Dental Monitoring（DM）为代表的人工智能（artificial intelligence，AI）驱动远程监控系统实现了正畸患者口内模型的远程生成和自动分析[18]。一项研究分别使用DM系统与口内扫描仪扫描错𬌗患者的牙列模型，得到三维数字化模型并进行比较，发现两者无显著统计学差异[19]。尽管临床应用时的扫描准确性可能受到患者口腔条件等多种因素的影响，但有研究显示，无论是用于固定矫治还是隐形矫治，远程监控系统扫的准确度均满足临床使用要求[20-21]。此外，有关患者对远程监控系统接受度的调查显示，绝大多数患者认为DM系统易于使用，并且大部分患者更倾向于使用该系统而非临床就诊[22]。

在隐形矫治过程中，实际的牙移动相比于预设的位移量会体现出轻微的“滞后性”[2]。因此正畸医生需要对患者牙移动情况进行监控，在发生“脱套”的情况时及时处置，必要时重启治疗方案。对此，利用三维模型重叠分析软件将术中扫描获得的数字化模型与预期方案模型进行叠加分析，即可判断牙齿是否按照预期方向移动[11,23]。但有研究发现，重叠标志点的选择、口内条件均可能对上述分析结果造成一定影响[11,23]。此外，部分远程监控系统基于深度学习（deep learning，DL）技术推出了矫治进展评估功能。以DM的GoLive系统为例，其能够根据患者上传的相片，自动判断矫治器与牙面之间的间隙大小，生成是否更换矫治器的建议，一定程度上提高了隐形矫治的效率。当诊断为不能更换矫治器时，该系统还能够标示出未按预期移动的个别牙齿、不良口腔健康状况以及脱落的附件等[24]。但也有研究显示，该功能得出的决策可重复性低，甚至同一样本在不同账号下得到的诊断结果可能不同[25]。由此可见，虽然多样化的远程数字化监控系统在正畸牙移动评估方面起到了一定辅助作用，其仍不能完全代替椅旁监控。

为确保隐形矫治的安全和有效性，在正畸过程中医生需要关注牙根与牙槽骨的位置关系[26]，但口内扫描仪及远程监控系统均重点关注牙冠而非牙根[11]。对根骨关系的监控通常借助CBCT实现，但由于CBCT具有较大的辐射量，其监控频率受到一定限制。为解决这一问题，有学者创新性地基于CBCT中的牙齿形态与口内扫描得到的牙列信息进行牙冠的配准叠加，继而借助CBCT中的牙根信息得到包含根骨关系的完整模型[27-29]。这种多模态数据融合技术可以实现根骨关系的可视化，预测并展示牙齿移动时的牙根位置信息，帮助正畸医生在矫治过程中对根骨关系进行监控[30-31]。

## 2　数字化技术与正畸相关并发症监控

正畸治疗中，固定矫治器部件（如托槽、弓丝、带环等）或隐形矫治器和树脂附件等，都会影响唾液、唇、舌、颊部的自洁作用，增加口腔卫生维护难度，导致食物残渣和菌斑滞留，造成口腔微环境改变[32-33]。研究显示，正畸矫治患者口内致龋菌和牙周致病菌水平上升，且固定矫治患者比隐形矫治患者情况更为严重[34-35]。

釉质脱矿是固定矫治最常见的不良反应之一，早期诊断牙菌斑或白垩斑并采取相应预防性措施，能够有效降低龋病进展的可能性[36]。Klukowska等[37]研发出的针对正畸患者的数字化菌斑图像分析（digital plaque image analysis，DPIA）技术，能够定量评估固定矫治患者的牙菌斑形成情况，便捷地反映患者口腔卫生状况。该技术可用于监控患者在治疗期间口腔卫生维护措施的有效性，并为患者提供预防牙菌斑的视觉辅助手段。一类数字化评估工具基于口内照也能实现对正畸患者龋损严重程度的准确评估[38-39]。此外，利用定量光诱导荧光数字化设备（quantitative light-induced fluorescence-digital，QLF）拍摄患者牙齿表面的荧光图像，还能够实现釉质脱矿的早期检测和菌斑的定量评估[40]。

正畸治疗可能影响牙周健康，尤其固定矫治更易增加牙周炎症的发生率[41]。然而，患者通常难以自行识别牙龈炎症，而需要通过医生用口腔探针等工具进行微创检查得以诊断[42]。当前，基于图片的牙龈炎早期诊断的应用愈发广泛[43]，这种方法帮助医生更及时地发现牙龈炎的早期症状，为及时干预和治疗提供了可能。Kim等[42]采用新型图像分析方法，证实了正畸患者口内相片中牙龈的红/绿（R/G）值与牙龈炎的相关性，能够作为利用图像诊断牙龈炎的重要指标。而一种基于目标检测的正畸患者牙龈炎检测模型，能够自动检测和诊断牙龈炎，其全类平均精度（mean average precision，mAP）为68.2%，为正畸患者提供了一种无创检测牙龈炎的方法[44]。牙周组织所有解剖学和形态学变量，统称为牙周生物型，其与正畸治疗显著相关[41]。研究显示，相比于基于口内相片及石膏模型的目测评估，利用正畸三维数字化模

型评估牙周生物型改变更为精确和全面[45]。

部分远程监控系统已经能够基于正畸患者术中口内相片或视频，实现对牙菌斑、牙结石、脱矿、牙龈萎缩或炎症等多种口腔病损的诊断[46]。且有研究表明，在正畸治疗期间应用远程监控系统能够有效改善菌斑控制且降低龋病发病率[47-48]。然而，该类系统需要患者购买配套的拍摄工具，不可避免地增加了治疗成本[49-50]。目前，一款智能手机软件（application，APP）已能通过分析手机拍摄的口内照片，初步实现对5种常见口腔问题（软垢、牙结石、龋病、牙周疾病和牙变色）的自动诊断[51]。虽然该研究开发的人工智能诊断模型的内部数据集未包含正畸患者术中相片样本，但这进一步体现了当前医疗数字化设备轻量化、便捷化的趋势。

## 3　数字化技术与正畸患者的依从性监控

活动矫治器（removable appliances）具有安全、美观及易于清洁等优点，但其治疗效果高度依赖患者配合。研究表明，患者活动矫治器戴用时长不足容易导致治疗周期延长、矫治效果及稳定性不佳[52-53]。

智能手机APP作为远程数字化监控和管理工具，通过引导患者定期自我评估，记录戴用情况，并将相关数据传输至医生端，一定程度提升了监控效率[46,53]。为了实现对患者更为智能化的监控，有团队在专业正畸监控APP中引入了名为“决策树（decision tree，DT）”的监督学习（supervised learning，SL）算法。该算法利用APP收集的大量用户数据，结合患者自身报告的矫治器戴用时长，分析其行为模式。当识别出患者依从性欠佳时，系统能自动发送提醒信息；对于依从性持续低下的患者，系统则及时将其反馈给医生，提示医生加强患者教育，关注矫治效果及潜在并发症，必要时对矫治方案进行相应调整[54]。

然而，多项研究表明，患者实际戴用活动矫治器的时长普遍较复诊时自我报告的戴用时间短，且均低于建议戴用时长[55-56]。近年来，正畸领域已经有多种成熟的技术手段用于客观监控活动矫治器戴用情况。其中一种常见方法是在矫治器中嵌入各类传感器，例如温敏、压敏和声敏传感器。这些传感器能通过感应装置所处环境的变化，监测患者的戴用时间，并将收集的数据以图表等形式直观呈现，从而降低医患沟通难度[53,57]。

一款温度传感器能够每15 min记录一次环境温度，当检测到温度超过35 ℃时记录的时间即为患者戴用活动矫治器的时间[58]。将该传感器嵌入双𬌗垫矫治器（twin-block appliance，TB）、口外弓-肌激动器（headgear-activator，HGA）等活动矫治器，在多项探究患者依从性影响因素的临床研究中作为客观监测患者戴用时间的可靠工具[58-60]，为医生对患者的临床监控及决策提供数据支撑。

下颌前导装置（mandibular advancement device，MAD）作为在阻塞性睡眠呼吸暂停（obstructive sleep apnea，OSA）等睡眠呼吸障碍治疗中的应用最多的正畸矫治器，其治疗效果同样依赖患者的配合[61-62]。Kwon等[63]将微型传感器嵌入MAD，以监控患者的实际戴用时间，并配合手机应用程序定期提醒患者提供主观戴用时间等信息，实现了对于患者依从性的远程监控。

## 4　结语与展望

对患者进行严密的临床监控是确保正畸治疗顺利进行的重要工作，其中多个环节可通过应用数字化技术得到有效提升。口内扫描技术使椅旁监控可视化，在提升监控精准度的同时使医患沟通更为便捷；远程监控系统的应用能够在减少诊疗时间与成本的同时持续改善患者体验。此外，多模态数据融合可为根骨关系提供指导，人工智能技术已初步实现正畸牙移动、相关并发症以及患者戴用情况的自动识别，而传感装置可用于监测患者的戴用情况，为临床决策提供数据支撑（图1）。

然而，当前数字化技术在正畸监控中的应用还面临着诸多挑战。尽管部分数字化技术已基本取得广泛应用，但在技术的准确性和稳定性、患者的接受度和舒适度等方面仍有进一步提升的空间，数字化技术的普及也面临着研发和设备成本较高、培训和操作有一定难度等实际问题。此外，远程监控系统的运作涉及对大量个人信息的采集、储存、传输与处理，在该过程中一旦出现数据泄露，患者的隐私安全将面临严峻威胁[8]。因此，在推进数字化技术在口腔正畸领域应用与发展的进程中，医师们必须审慎权衡其带来的益处与潜在风险，在符合伦理及相关政策的前提下，合理应用数字化技术，从而优化就医体验，不断提升正畸治疗的高效性和安全性。

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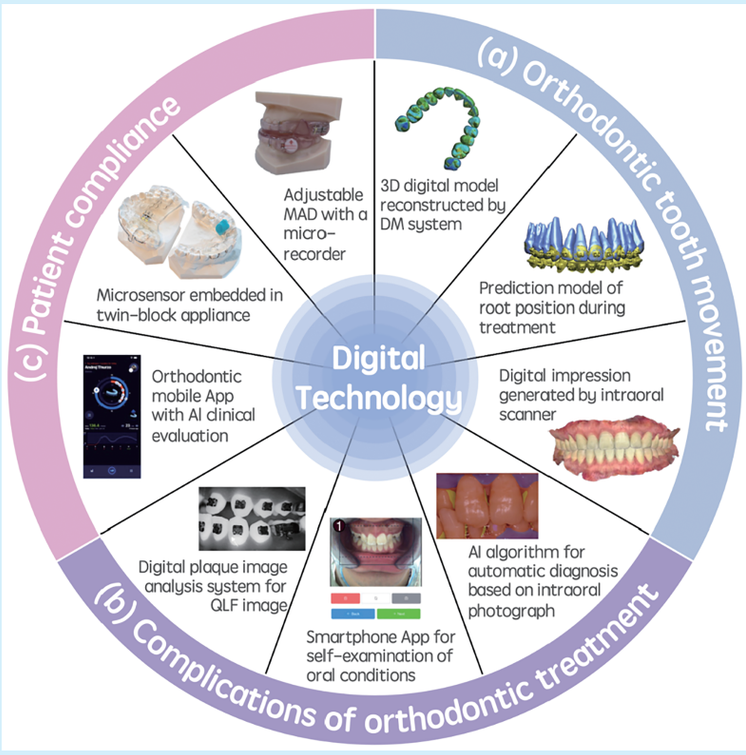


a: orthodontic tooth movement monitoring: this includes digital impressions generated by intraoral scanners, 3D digital models reconstructed by the DM system[21], and root position prediction models[28]. b: monitoring of orthodontic-related complications: this encompasses digital plaque image analysis system[40], AI diagnostic algorithms based on intraoral photographs, and smartphone apps for oral health self-examination[51]. c: patient compliance monitoring: this involves MAD[63] and twin-block appliances[60] embedded with microsensors and patient monitoring apps incorporating AI algorithms[54]. DM: dental monitoring; QLF: quantitative light-induced fluorescence-digital; MAD: mandibular advancement device

Figure 1　Application of digital technology in orthodontic monitoring

**图1**　数字化技术在口腔正畸监控中的应用

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