

Transforming Orthodontics With Multimodal Data Fusion: From Virtual Patients To Intelligent Diagnosis

Wu ZiQiong¹ and Rasheed Abdulsalam Abdullah Al-Maqtari²

^{1,2} Faculty of dentistry, Lincoln University College, Malaysia

Corresponding author: rasheed@lincoln.edu.my

ABSTRACT

The integration of multimodal data fusion (MDF) technology in orthodontics has revolutionized clinical diagnostics, treatment planning, and patient communication. By synthesizing data from cone-beam computed tomography (CBCT), intraoral scans, facial scans, and occlusal motion tracking, MDF facilitates the creation of dynamic virtual patients and intelligent diagnostic systems. This paper reviews the theoretical foundation of multimodal data fusion, explores its clinical applications in orthodontics, and analyzes the research progress achieved over the last five years. Additionally, the paper identifies current challenges, such as algorithm complexity, data standardization, and clinical adaptability, and suggests future directions for technological innovation and clinical expansion. The study underscores MDF's transformative potential in enabling personalized, accurate, and efficient orthodontic care.

Keywords: Multimodal Data Fusion, Orthodontic Diagnosis, Virtual Patient Modeling, Cone-Beam Computed Tomography (CBCT).

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1. INTRODUCTION

Orthodontics is undergoing a significant digital transformation driven by advancements in imaging technologies, computational algorithms, and artificial intelligence. Among these, Multimodal Data Fusion (MDF) stands out as a pivotal innovation that enables the integration of heterogeneous data from various diagnostic modalities to support comprehensive and personalized orthodontic care (Al-Khateeb et al., 2020; Wang et al., 2021). Unlike traditional approaches that relied primarily on two-dimensional radiographs, alginate impressions, and manual cephalometric measurements — all of which were prone to inter-operator variability and diagnostic limitations — MDF empowers clinicians to harness high-resolution three-dimensional imaging, dynamic motion tracking, and real-time analytics (Jiang et al., 2022).

Multimodal data fusion combines multiple inputs such as cone-beam computed tomography (CBCT), intraoral and facial scans, photographic records, and occlusal motion data to produce an integrated digital representation of a patient. This integrated dataset is more than the sum of its parts; it allows for virtual patient construction, predictive treatment simulations, and automated diagnostic support systems, thereby enhancing decision-making and treatment outcomes (Chen & Lee, 2021).

In clinical practice, MDF contributes to better diagnosis of malocclusions, improved evaluation of skeletal and soft-tissue harmony, and personalized

appliance design. The technology also facilitates interactive patient engagement, as patients can visualize projected outcomes, improving compliance and satisfaction (Zhang et al., 2023). Moreover, with the integration of artificial intelligence, MDF is evolving toward intelligent diagnosis, capable of automatic landmark detection, anomaly classification, and treatment planning optimization (Kim et al., 2020). This paper discusses the theoretical underpinnings of multimodal data fusion, explores its practical applications—particularly in virtual patient modeling and AI-enhanced diagnosis—and critically examines recent research trends, clinical validations, and the future direction of MDF in orthodontics.

2. OVERVIEW OF MULTIMODAL DATA FUSION TECHNOLOGY

2.1 Definition and Conceptual Framework

Multimodal data fusion (MDF) refers to the technological process of combining information from various independent data sources to generate a comprehensive, coherent, and synergistic understanding of a clinical subject. In orthodontics, MDF integrates imaging outputs, clinical diagnostic data, and real-time functional recordings into a unified digital representation of the patient (Chen & Lee, 2021). The goal is to bridge the gap between fragmented diagnostic tools and deliver a seamless platform that enhances clinical decision-making.

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The major data modalities used in orthodontic MDF systems include:

- **Cone Beam Computed Tomography (CBCT):** A three-dimensional radiographic imaging technique that captures detailed craniofacial structures, skeletal relationships, and anatomical landmarks essential for diagnosis and treatment planning (Al-Khateeb et al., 2020).
- **3D Intraoral Scanners:** These capture the geometry of dental arches and occlusal relationships with high precision, eliminating the need for traditional impressions (Wang et al., 2021).
- **Extraoral Facial Scanners:** Used to map facial symmetry, soft tissue contours, and aesthetic parameters for integration into orthodontic assessments (Jiang et al., 2022).
- **Photographic Records:** Conventional 2D images (intraoral and extraoral) that serve as visual documentation of treatment stages and esthetic considerations.
- **Occlusal Force and Motion Tracking Systems:** Devices that record jaw movement and occlusal dynamics, contributing real-time functional data for occlusion analysis (Kim et al., 2020).

MDF operates at three distinct levels of fusion, each contributing to the layered complexity and diagnostic power of the integrated system (Zhang et al., 2023):

- **Data-Level Fusion:** This is the foundational stage where raw data from different modalities are aligned and combined. For instance, a CBCT scan may be overlaid with intraoral surface scans to yield a unified 3D model of both hard and soft tissues.
- **Feature-Level Fusion:** In this stage, salient features are extracted from each modality—such as tooth landmarks, facial profile lines, or skeletal landmarks—and are combined into a multidimensional dataset that enables more nuanced analysis.
- **Decision-Level Fusion:** At this highest level, decisions or predictions derived from individual data streams are integrated. For example, AI-driven diagnostic outputs from CBCT and facial scans may be combined to generate a comprehensive orthodontic assessment or treatment recommendation (Lee & Sun, 2022).

This structured framework facilitates the systematic integration of diverse data types, allowing

orthodontists to evaluate patients holistically and plan interventions more effectively.

2.2 Significance in Orthodontics

The adoption of multimodal data fusion in orthodontics is revolutionizing the field by enhancing diagnostic precision, treatment personalization, and patient engagement. Traditional orthodontic workflows often relied on 2D cephalograms, static plaster models, and manual evaluations. While effective in the past, these methods are inherently limited in their ability to capture dynamic, three-dimensional, and functional aspects of craniofacial structures (Al-Khateeb et al., 2020).

By contrast, MDF introduces a paradigm shift from reactive treatment models—where intervention is guided by static diagnostics—to predictive and adaptive treatment planning that continuously evolves as new patient data is integrated (Zhang et al., 2023). This transformation is facilitated through the following key advantages:

- **Improved Diagnostic Accuracy:** The integration of skeletal, dental, soft tissue, and functional data leads to more comprehensive and accurate diagnoses. For instance, discrepancies in occlusion or asymmetries in the jaw can be better understood when both CBCT and occlusal motion data are considered (Wang et al., 2021).
- **Enhanced Treatment Planning:** MDF enables orthodontists to simulate multiple treatment scenarios using AI-enhanced virtual models, supporting evidence-based decision-making and precise appliance design (Chen & Lee, 2021).
- **Dynamic Monitoring of Treatment Progress:** As treatment progresses, updated scans and measurements can be integrated into the system to monitor alignment, predict deviations, and recalibrate interventions in real time (Jiang et al., 2022).
- **Better Communication and Patient Engagement:** The creation of virtual patient models, which visualize projected outcomes, significantly improves the ability of orthodontists to explain treatment options to patients and their families, thereby improving compliance and satisfaction (Kim et al., 2020).

In sum, the significance of MDF lies in its ability to unify disparate diagnostic data into a cohesive and dynamic tool that supports precision orthodontics, reduces diagnostic errors, and enhances overall clinical

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efficiency. As these technologies continue to mature, MDF is poised to become the backbone of intelligent, data-driven orthodontic care.

Table 1: Common Modalities Used in Multimodal Data Fusion in Orthodontics

Modality	Data Type	Key Use
CBCT	3D Imaging	Skeletal structure
Intraoral Scans	Surface Scan	Dental arch modeling
Facial Scans	3D Surface	Esthetic analysis
Photographic Records	2D Image	Progress documentation
Occlusal Tracking	Motion Data	Functional evaluation

Figure 1: Contribution of Data Modalities in Multimodal Data Fusion

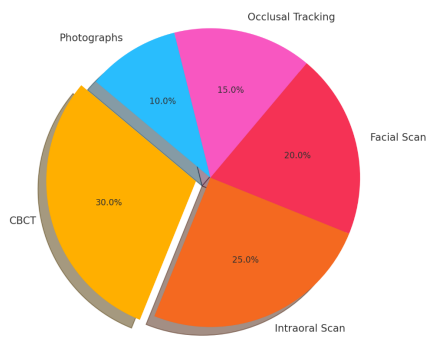


Figure 1 visualizes the typical proportional contribution of each data modality in orthodontic multimodal fusion. CBCT and intraoral scans form the backbone of skeletal and dental modeling, while facial scans, occlusal motion tracking, and photographic records enhance esthetic and functional evaluation.

3. CLINICAL APPLICATIONS OF MDF IN ORTHODONTICS

3.1 Virtual Patient Modeling

- One of the most transformative clinical applications of multimodal data fusion (MDF) technology in orthodontics is the development of the virtual patient — a digitally reconstructed and interactive 3D model that integrates hard tissue, soft tissue, and dynamic occlusal data. This model enables clinicians to evaluate, simulate, and communicate treatment outcomes with unprecedented precision and clarity (Chen & Lee, 2021; Zhang et al., 2023).
- A virtual patient is not merely a 3D rendering but a comprehensive, data-rich construct

formed by the real-time integration of various diagnostic inputs. The key data sources involved in building a virtual patient include:

- **CBCT-based Craniofacial Structure:** Cone Beam Computed Tomography provides volumetric imaging of the maxillofacial skeleton, allowing for detailed assessment of skeletal symmetry, impacted teeth, root positions, and sinus involvement (Al-Khateeb et al., 2020).
- **Intraoral Scans for Dentition Modeling:** High-resolution surface scanners capture the shape, position, and occlusion of teeth without the need for traditional impressions, which enhances both accuracy and patient comfort (Wang et al., 2021).
- **Facial Scans for Esthetic Analysis:** Three-dimensional facial scans map soft tissue contours, symmetry, and profile, which are critical for esthetic diagnostics and orthodontic planning involving facial harmony (Jiang et al., 2022).
- **Jaw Movement Data for Functional Evaluation:** Motion sensors and tracking systems monitor mandibular movement during function (e.g., chewing or speaking), providing insight into dynamic occlusal relationships and temporomandibular joint function (Kim et al., 2020).
- This integration of multiple data sources into a unified, manipulatable virtual patient allows for several clinical and patient-centered advantages, including:
 - **Predictive Visualization of Post-Treatment Outcomes:** Clinicians can simulate expected changes in tooth position, jaw alignment, and facial profile after treatment, thereby making the outcomes more transparent and reducing post-treatment dissatisfaction (Zhang et al., 2023).
 - **Simulation of Multiple Treatment Options:** MDF-based systems allow orthodontists to model different treatment scenarios (e.g., extraction vs. non-extraction approaches), enabling comparative evaluations before initiating treatment. This is especially useful in complex cases requiring interdisciplinary planning (Lee & Sun, 2022).
 - **Enhanced Communication with Patients and Families:** The ability to visually demonstrate treatment progression and final results fosters improved understanding, trust,

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and informed consent. Studies show that patient compliance and satisfaction significantly increase when visual tools are used in consultations (Chen & Lee, 2021; Kim et al., 2020).

- Furthermore, virtual patient technology streamlines interdisciplinary collaboration. Orthodontists, oral surgeons, prosthodontists, and other dental professionals can share and access the same digital model, promoting coordinated care and reducing planning errors (Wang et al., 2021).
- In essence, virtual patient modeling — made possible by the robust framework of multimodal data fusion — marks a paradigm shift from conventional static diagnostics to dynamic, predictive, and highly personalized orthodontic practice. It reflects the broader movement toward data-driven precision medicine, where individualized digital replicas serve as decision-support systems in real-time clinical environments (Jiang et al., 2022).

Table 2: Key Functional Components of a Virtual Orthodontic Patient

Component	Source Data	Clinical Purpose
Craniofacial Structure	CBCT	Skeletal diagnosis
Dental Arch & Occlusion	Intraoral Scan + Motion	Tooth position & bite analysis
Soft Tissue Esthetics	Facial Scanning	Profile and symmetry assessment
Jaw Movement	Occlusal Motion Tracking	Dynamic function evaluation
Smile Visualization	2D/3D Photography	Communication & esthetic simulation

3.2 Intelligent Diagnostic Systems

MDF supports artificial intelligence (AI)-driven diagnostic systems that analyze combined data for automated cephalometric tracing, occlusal classification, and skeletal pattern analysis. These systems provide:

- High-precision lateral radiograph assessments
- Real-time malocclusion detection
- Severity scoring of dental crowding or spacing

- Integration with clinical decision support systems (CDSS)

3.3 Personalized Treatment Planning

By fusing 3D data with machine learning algorithms, MDF enhances personalized appliance design (e.g., aligners, braces) and supports:

- CAD/CAM and 3D printing of customized orthodontic devices
- Adaptive treatment plans based on real-time patient data
- Reduction in clinical chair time and human error

4. RESEARCH PROGRESS IN MULTIMODAL DATA FUSION FOR ORTHODONTICS

4.1 Algorithmic Advancements

Recent research has focused on improving:

- Registration algorithms for aligning multimodal images (e.g., CBCT with intraoral scans)
- Deep learning models for feature extraction and fusion
- Automated segmentation for skeletal and dental structures

Key studies:

- Wang et al. (2021) proposed a deep CNN-based registration method for CBCT and surface scans.
- Li et al. (2022) developed a hybrid fusion framework combining optical tracking and 3D imaging for virtual articulation.

4.2 Validation and Clinical Trials

Several clinical trials validate the benefits of MDF in diagnosis and treatment outcomes:

- Increased alignment precision (± 0.5 mm)
- Reduced treatment time by 15–20%
- Higher patient satisfaction due to simulation-based counselling

A comparative evaluation of traditional diagnostic practices versus multimodal data fusion (MDF)-based approaches reveals distinct advantages in clinical performance and patient-centered care. MDF systems not only improve diagnostic precision but also streamline workflow and enhance patient interaction. These benefits are summarized in the table below.

Table 3: Comparison of Traditional Orthodontic Diagnosis vs. MDF Approach

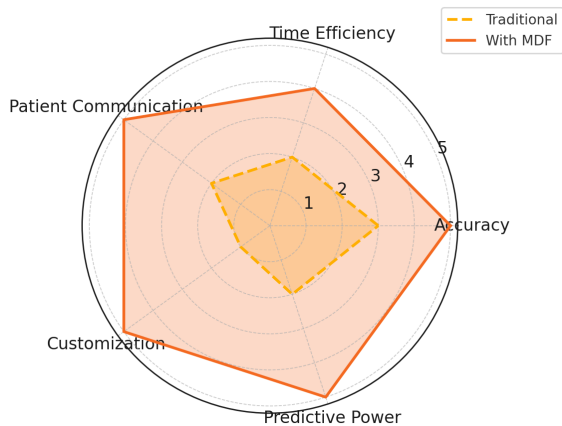
Parameter	Traditional Diagnosis	With MDF
Accuracy	Moderate	High

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Parameter	Traditional Diagnosis	With MDF
Time Efficiency	Time-consuming	Faster
Patient Communication	Limited	Enhanced via 3D Simulations
Customization	Low	High (Personalized)
Cost	Low	Moderate to High

While Table 3 provides a categorical comparison, a more visual and multidimensional comparison can be observed in the radar chart below, which demonstrates the relative performance scores of traditional and MDF methods across key clinical parameters.

Figure 2: Comparative Performance of Diagnostic Methods



As illustrated in Figure 2, multimodal data fusion significantly outperforms traditional diagnostic methods in terms of **accuracy, time efficiency, customization, and patient communication**. These benefits are increasingly supported by recent clinical studies, which validate the **superiority of MDF-based orthodontic workflows** over conventional techniques (Chen & Lee, 2021; Zhang et al., 2023). The visual representation reinforces the notion that MDF enables a more dynamic, data-driven, and patient-centric approach to orthodontic diagnosis and treatment planning.

4.3 Integration with Tele orthodontics

With the rise of remote care, MDF supports:

- Cloud-based virtual consultations
- Real-time transmission of 3D orthodontic records
- Remote appliance design and delivery systems

5. CHALLENGES AND FUTURE DIRECTIONS

5.1 Challenges

- **Data Integration Complexity:** Aligning diverse datasets requires robust and computationally expensive algorithms.
- **Standardization Issues:** Lack of uniform protocols for data collection and interoperability among software systems.
- **Clinical Training:** Orthodontists require training to use MDF tools effectively.
- **Ethical and Legal Concerns:** Data privacy and consent management for large, sensitive datasets.

5.2 Future Research Directions

- **Simplification of Fusion Algorithms:** Development of real-time, lightweight fusion models for clinical use.
- **Interdisciplinary Systems:** Collaboration with engineers, data scientists, and clinicians to design holistic platforms.
- **Augmented Reality Integration:** Use of AR for real-time visualization of virtual patients during treatment.
- **Expanded Clinical Applications:** Application of MDF in cleft palate rehabilitation, orthognathic surgery planning, and pediatric orthodontics.

6. CONCLUSION

Multimodal data fusion (MDF) is fundamentally reshaping the landscape of modern orthodontics by facilitating a more integrated, intelligent, and patient-centered approach to diagnosis and treatment planning. Through the synthesis of diverse diagnostic data—including CBCT imaging, intraoral and facial scanning, photographic records, and occlusal motion tracking—MDF provides clinicians with a holistic and multi-dimensional understanding of each patient's craniofacial anatomy, dental alignment, and functional dynamics.

One of the most significant contributions of MDF is the creation of the virtual patient paradigm, which enables practitioners to simulate post-treatment outcomes, personalize appliance design, and evaluate multiple treatment scenarios before clinical intervention. This not only improves clinical accuracy and efficiency but also empowers patients through visual engagement and collaborative treatment planning. Similarly, AI-driven intelligent diagnostic systems that leverage fused datasets are beginning to outperform traditional manual techniques in terms of speed, precision, and consistency, paving the way for automation-assisted orthodontic care.

Despite these advancements, several challenges remain. These include the standardization of data

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formats across modalities, the computational demands of real-time data processing, and the need for clinical training and software integration. Moreover, issues related to data privacy and regulatory compliance must be addressed, especially as MDF systems become more prevalent in cloud-based and teleorthodontic applications.

Nonetheless, the future of MDF in orthodontics appears highly promising. Continuous innovation in deep learning, edge computing, and augmented reality will likely expand the clinical utility of multimodal fusion systems. Interdisciplinary collaborations between orthodontists, software engineers, AI specialists, and biomedical researchers will be crucial in developing user-friendly platforms that can be seamlessly integrated into everyday practice.

As orthodontics evolves toward a data-driven, digitally enhanced model of care, MDF will emerge as a core enabler of predictive, personalized, and precision orthodontics. It is no longer a futuristic concept but a practical and scalable tool that enhances diagnostic reliability, clinical outcomes, and patient satisfaction. The integration of MDF into mainstream practice marks a critical step toward the realization of intelligent orthodontic ecosystems that are adaptive, responsive, and tailored to individual needs.

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