Review Article

Digital Surgical Planning

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Abstract

Digital Surgical Planning (DSP) has revolutionized the field of orthodontics by integrating advanced imaging, simulation technologies, and computer-aided design/computer-aided manufacturing systems. This comprehensive review explores the evolution, application, and impact of DSP within orthodontic practice, highlighting the shift from traditional manual techniques to highly precise digital methodologies. DSP offers numerous advantages, including enhanced accuracy, improved efficiency, shorter treatment times, and better patient outcomes. The discussion delves into key technologies such as cone-beam computed tomography, intraoral scanning, and 3D printing, as well as the role of virtual surgical planning (VSP) in pre-operative simulations. Despite its transformative potential, DSP faces challenges related to cost, learning curves, and the need for advanced surgical expertise. This article provides an in-depth analysis of DSP's role in modern orthodontics, offering insights into future trends and potential advancements in digital treatment planning and execution.

Keywords: 3D imaging, 3D printing, Computer-aided design/computer-aided manufacturing, Cone-beam computed tomography, Digital surgical planning, Orthodontics, Virtual surgical planning

Introduction

Orthodontics, a specialized branch of dentistry, focuses on diagnosing, preventing, and treating dental and facial irregularities.[1] Historically, orthodontic treatments relied heavily on manual techniques, including plaster models, two-dimensional (2D) radiographs, and physical measurements. While effective, these traditional methods had limitations such as time consumption, increased potential for human error, and less precision in treatment planning and execution.[2]

The advent of digital technologies has brought a paradigm shift to orthodontics, particularly with the introduction of Digital Surgical Planning (DSP).[3] DSP leverages advanced imaging modalities, virtual simulation tools, and computer-aided design/computer-aided manufacturing (CAD/CAM) technology to enhance treatment precision and efficiency. This approach integrates 3D imaging, such as cone-beam computed tomography (CBCT), with digital modeling and 3D printing, allowing for highly accurate surgical planning and customized treatment solutions.[4]

This article explores the development and application of DSP in orthodontics, discussing its benefits, challenges, and future potential. Through a detailed analysis of key technologies and methodologies, this review aims to highlight how DSP is transforming orthodontic practice and improving patient care.

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Discussion

Historical context and evolution of DSP

DSP in orthodontics has its roots in the broader advancements of medical imaging and modeling technologies. The development of 3D modeling techniques began in the 1970s, initially in the automotive and aerospace industries, and gradually transitioned into medical applications.[5] The introduction of computed tomography (CT) by Godfrey Hounsfield in the 1970s revolutionized medical imaging, allowing for 3D visualization of anatomical structures.

By the 1980s, 3D modeling techniques were adapted for orthognathic surgery, utilizing anatomical models derived from CT scans.[6] These early models were primarily used to visualize bone structures and plan complex surgeries. The 1990s and early 2000s saw the advent of more sophisticated technologies, such as CBCT and CAD/CAM systems, which enabled orthodontists to create detailed digital models and design custom appliances with high precision.[7]

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In recent years, DSP has evolved to incorporate virtual surgical planning (VSP), 3D printing, and artificial intelligence (AI). These technologies allow for enhanced pre-operative simulations, better patient communication, and the production of customized surgical tools and implants.[8] The integration of these innovations has marked a significant shift from manual techniques to a fully digital workflow in orthodontics.

Technologies in DSP

CBCT

CBCT is a cornerstone of DSP, offering detailed 3D imaging of craniofacial structures. Unlike traditional 2D radiographs, CBCT captures comprehensive data in a single scan, allowing clinicians to analyze bone and soft tissue structures simultaneously.[9] CBCT images are particularly useful in diagnosing complex cases, assessing jaw relationships, and planning surgical interventions, as shown in Figure 1.

One of the key advantages of CBCT is its ability to produce isotropic voxels, which maintain uniform resolution in all directions. This feature is crucial for creating accurate 3D models and performing precise measurements, which are essential for surgical planning and outcome prediction.[10] In addition, CBCT's lower radiation exposure compared to conventional CT makes it a safer option for repeated use in orthodontic assessments.

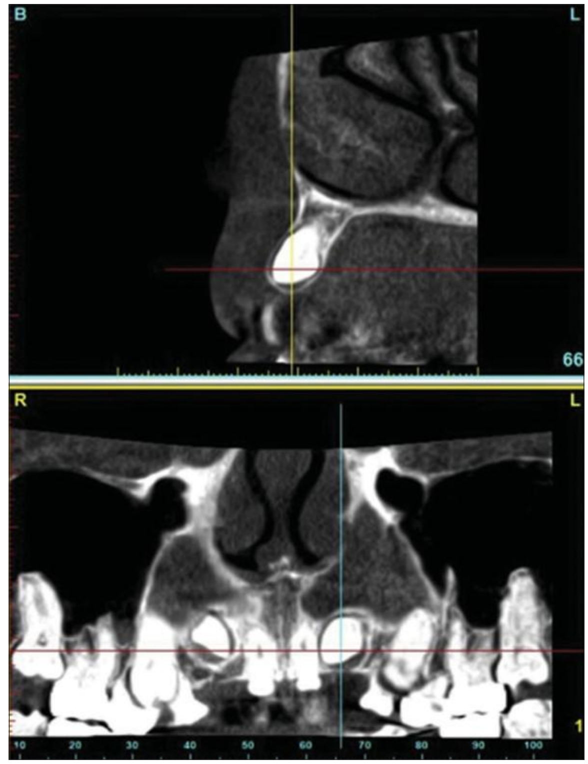

Figure 1: Depicting cross-sectional and panoramic views of cone-beam computed tomography of impacted canines

Intraoral scanning and 3D imaging

Intraoral scanners are portable devices that capture detailed digital impressions of the oral cavity.[11] These scanners use optical technologies, such as confocal microscopy and light triangulation, to create accurate 3D models of dental structures.

The digital models generated by intraoral scanners can be used for treatment planning, appliance fabrication, and monitoring treatment progress. 3D imaging technologies enable orthodontists to visualize and manipulate digital models in a virtual environment. This capability is particularly beneficial for assessing occlusal relationships, simulating surgical movements, and designing custom orthodontic appliances, as depicted in Figure 2. The integration of 3D imaging with CAD/CAM systems facilitates a seamless workflow from diagnosis to treatment execution.

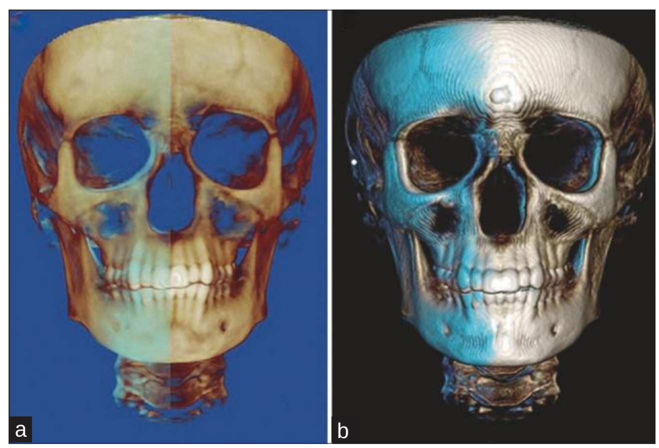

Figure 2: Asymmetry assessment uses mirroring and superimposition methods. (a) Dolphin 3D imaging software. (b) *In vivo* 3D imaging software

VSP

VSP involves using specialized software to simulate surgical procedures on digital models of the patient's anatomy. VSP allows clinicians to experiment with different surgical scenarios, visualize potential outcomes, and refine treatment strategies before the actual surgery.[12] This pre-operative simulation helps reduce surgical time, improve accuracy, and enhance patient outcomes.

During the VSP process, 3D models are used to simulate osteotomies, visualize jaw movements, and assess the impact of these movements on surrounding tissues. The software also aids in designing custom surgical guides, splints, and implants, which can be produced using 3D printing technology, as shown in Figure 3.

3D printing and CAD/CAM technology

3D printing has become an integral part of DSP, enabling the production of custom surgical tools and models. This technology allows for the creation of highly accurate and patient-specific guides, splints, and orthodontic appliances. CAD/CAM systems support the design and fabrication of these tools, providing a streamlined workflow from digital planning to physical implementation, as outlined in Figure 4.

The use of 3D-printed models in orthodontics enhances precision during surgery by providing tangible references for surgical procedures. These models are particularly useful for complex cases that require intricate planning and customized solutions. In addition, 3D printing reduces production time and costs, making custom appliances more accessible to a broader range of patients.

Advantages of DSP

- Enhanced Precision: DSP improves the accuracy of surgical procedures using 3D models and simulations to guide each step of the surgery
- Improved Efficiency: Virtual simulations streamline treatment planning, reducing the time needed for preparation and surgery
- Customization: The use of CAD/CAM technology allows for the creation of patient-specific surgical tools and orthodontic appliances
- Predictable Outcomes: VSP enables clinicians to anticipate surgical results, leading to higher treatment success rates
- Minimized Surgical Errors: By following a digital roadmap, clinicians can avoid potential mistakes during surgery
- Better Patient Communication: 3D models and simulations help patients understand their treatment plans, improving consent and satisfaction
- Interdisciplinary Collaboration: DSP facilitates better communication between orthodontists, surgeons, and other specialists, enhancing overall treatment coordination.

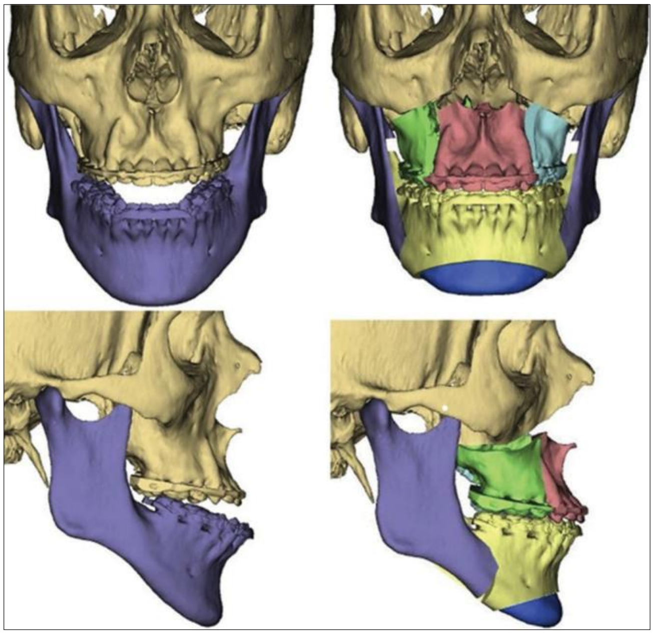

Figure 3: (Left) 3D reconstruction of pre-operative occlusion from cone-beam computed tomography. (Right) 3D rendering of the virtual surgical plan of 3-piece Le Fort, mandibular bilateral sagittal split osteotomy, and genioplasty

Challenges and limitations

- High Initial Costs: The equipment, software, and training required for DSP are expensive
- Learning Curve: Clinicians need specialized training to effectively use digital tools and interpret 3D models
- Technical Challenges: Software updates, hardware compatibility, and the risk of digital errors require ongoing management
- Time-Consuming Data Processing: Generating and analyzing digital models can be time-intensive
- Potential for Over-Reliance on Technology: There is a risk of reduced clinical judgment if clinicians rely solely on digital tools
- Accessibility Issues: Smaller practices may struggle to adopt DSP due to financial and technical constraints.

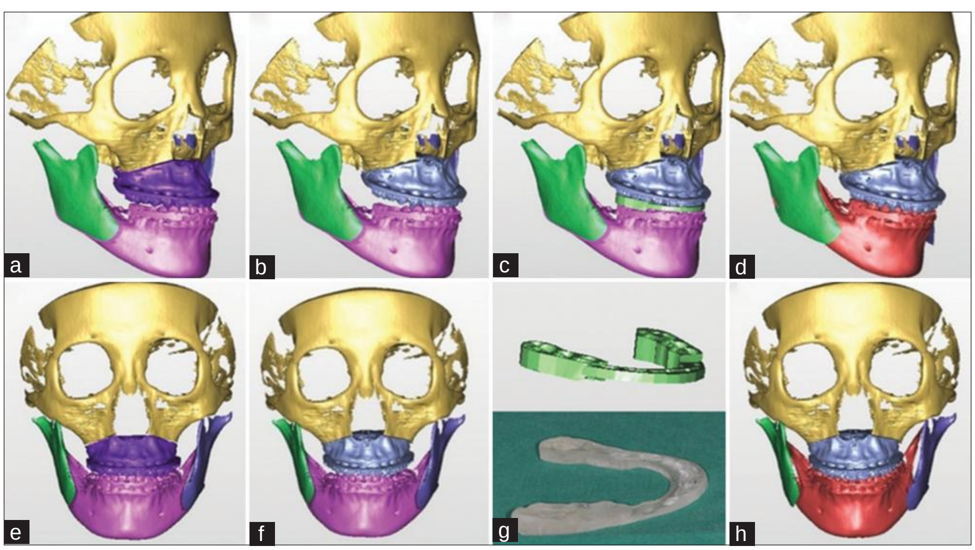

Figure 4: Fabrication of a computer-aided design/computer-aided manufacturing intermediate splint for two jaw surgery. (a) Laser-scanned dental cast data and cone-beam computed tomography data were superimposed in virtual space. (b) Maxillary repositioning was performed according to the surgical plan. (c) Virtual fabrication of an intermediate splint and 3D printed splint. (d) Simulated position of mobilized maxillomandibular structures. (e): Frontal view showing the relationship between the reconstructed segments and the native mandible. (f): Further adjustment and alignment to ensure occlusion and proper bone contact. (g): Fabrication of cutting guides for mandible and fibula.(h): Final simulated reconstruction with the fibula pieces integrated into the mandible.

Conclusion

DSP has redefined orthodontic practice by introducing advanced tools that enhance diagnostic accuracy, treatment planning, and surgical execution. DSP has become an indispensable tool in orthognathic surgery and orthodontics. By leveraging the power of advanced imaging, simulation, and computational technologies, clinicians can achieve outcomes that were once considered unattainable. The integration of CBCT, intraoral scanning, VSP, and 3D printing supports a comprehensive digital workflow that improves precision, efficiency, and patient outcomes.

As technology advances, future innovations like AI and machine learning may further enhance DSP, leading to fully digital orthodontic workflows.

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