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ORIGINAL RESEARCH

Digitally driven surgical guide planning

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Abstract

To investigate the role of a fully digital process in the surgical treatment of mandibular fractures in children. We analyzed a complete dataset from 22 children with mandibular fractures treated with digital surgical assistance. The patient's treatment process included preoperative thin layer CT (Computed Tomography) scanning, computer-aided design (3D reconstruction, virtual reduction, and internal fixation device determination and shaping), and 3D printing (jaw model, bite plate). We used occlusal and shaping plates during surgery to assist in fracture reduction and fixation. During the follow-up, we observed the occurrence of fracture healing, occlusal relationships, opening degrees, and complications in pediatric patients after surgery. Next, we used the 3D overlay function of MIMICS software to compare the preoperative surgical design with postoperative jaw imaging data to evaluate the overall surgical effect. The postoperative imaging data showed good fracture healing, normal occlusion during follow-up, and significant improvement in opening degrees. The mean preoperative opening degree was 23.59 $\pm$ 2.89 mm, and the mean postoperative opening degree was 29.82 $\pm$ 1.79 mm; there was a significant difference between these two parameters ($p < 0.05$). There were no complications such as tooth germ injury, nerve injury or fracture block displacement. The postoperative mandibular imaging data was imported into MIMICS software for 3D overlay visualization, and the postoperative mandibular morphology recovery was well-matched with the preoperative design. We measured the average upper deviation (0.65 $\pm$ 0.09) mm and the average lower deviation (-0.57 ± 0.14) mm. The fully digital process has a precise, minimally invasive, and safe effect in the surgical treatment of mandibular fractures in children, and the clinical effect is satisfactory.

Keywords

Digital surgery; Children; Mandibular fracture; Surgical treatment

1. Introduction

Children experience a dual period of physical and intellectual growth and development. Due to a lack of risk awareness and experience in dealing with risks, the risk prevention ability of children is poor and accidental injuries often occur. These injuries often include maxillofacial fractures, the most common form being lower jaw fractures [1]. Mandibular fractures in children are treated differently than in adults. Conservative treatment is often recommended for patients with mild jaw fractures and less obvious fracture displacement. However, precise and minimally invasive surgery is required to reduce the impact on the growth and development of the jaw and permanent teeth in children with obvious displacement; these cases are more complex due to the anatomical and physiological characteristics of the thin and elastic jawbone [2, 3].

Currently, digital technology is widely used in maxillofacial surgery, in areas such as surgical navigation, titanium plate preforming technology, and 3D digital guide plate technology; it has significant advantages in restoring function, improving the safety of surgery, and reducing the operation time [4, 5]. However, few reports relate to the digitally driven surgical guide planning for treating pediatric mandibular fractures. Here, we analyzed patient data relating to the full process of digitally-assisted surgery for pediatric mandibular fractures. We aimed to investigate the advantages of the full digital process when applied to the surgical treatment of pediatric mandibular fractures.

2. Materials and methods

2.1 General data collection

We recruited twenty-two pediatric patients with mandibular fractures admitted to the Oral and Maxillofacial Surgery Department of the First Affiliated Hospital of Bengbu Medical College during 2016–2022.

The inclusion criteria were as follows: (1) age $\leq$12 years; (2) confirmed as a mandible fracture with significant displacement; (3) surgery involving digital surgical technology. Patients were excluded if they had (1) old fractures or (2) incomplete medical records and imaging data. All patients underwent thin layer computed tomography (CT) scanning, computer virtual reduction, the design of internal fixation devices, 3D printed jaw models, and bite plates as auxiliary devices prior to surgery, and guided and assisted fracture reduction and fixation during surgery. Finally, software was used to compare and analyze the preoperative planning and postoperative reduction effects. The surgeries were all performed by experienced surgeons from the same professional group. Data was collected on the patient's age, gender, etiology, fracture site and type, opening degree, postoperative outcomes, complications and follow-up.

2.2 Preoperative data collection, virtual computer design and 3D printing

For patients, we used three-dimensional CT scanning of the maxillofacial region (thin layer 0.625 mm, 64-row spiral CT) to determine the location and type of fracture, degree of displacement, development of tooth germ, and degree of injury. Then we imported the CT imaging data into Mimics 20.0 software (Materialise, Levin, Belgium) in DICOM (Digital Imaging and Communications in Medicine) format and used the "selected threshold", "region growth" and "3D editing" tools to generate digital 3D images. Firstly, we determined the threshold range of bone tissue and separated soft tissue from bone tissue. Then, we manually edited the mask in the cross-section, coronal plane, and sagittal plane and divided this into independent fracture blocks. Finally, the regional growth function was used to assign different fracture blocks to independent masks, and different colors were used to represent the three-dimensional models of mandibular fractures in both teeth and tooth germs. After establishing a virtual fracture model, the displacement of the fracture was observed by rotating the model at different angles. The mirrored healthy half of the mandible was used as a template for reduction; then, movement and rotation functions were applied in three planes to reduce the bone blocks. The degree of rotation displacement and adjacent relationships between each fracture block was then determined, important anatomical markers were identified, and the optimal reduction strategy was designed. Finally, the normal anatomical form of the mandible was reconstructed.

After resetting the fracture model, a series of simulation designs were performed on the internal fixation device using simulation function options. The three-dimensional spatial position of the tooth germ was measured, and the design was based on the tooth germ and fracture line, including the length and model of the titanium plate, the number of titanium screws, implantation position, direction, length, and the shape of the titanium plate after bending. The titanium plate was virtually performed using a computer. Then, we measured and marked the position with a line in the software (in a 1:1 ratio) to the titanium plate. Then, we simulated a cylindrical design with the same diameter as the surgical titanium nail to avoid intraoperative damage to the permanent tooth germ (see Fig. 1). After the precise positioning of the internal fixation device, we selected a reference point to assist in positioning the titanium plates and screws. Next, we used the occlusal relationship between the upper and lower jaws after restoration to create an occlusal plate (see Fig. 2) with a thickness of 3 mm. The occlusal plate covered the cutting edge and occlusal surface of the mandibular dentition; this covered one-third of the labial and buccal sides; the lingual side was covered with free gingiva. We marked the surface projection position of the gingival papilla on the lingual side to accurately locate and punch holes. We formed an almost conical positioning hole (outside diameter: 1 mm, inside diameter: 0.5 mm) so that the intraoperative ligation wire could accurately pass through the dental gap to fix the bite plate. Finally, the mandible and bite plate were saved in STL format (both before and after restoration). Before printing the model, the model was checked and repaired, the placement direction was confirmed, support was added, and layered slices were imported into a 3D printer. Then, specific parameters were applied; for example, support materials, resolution, and temperature. We also created a 1:1 personalized and accurate 3D solid model to protect teeth and dental germ. This aimed to reduce surgical trauma and preserve growth and development potential.

2.3 Surgical methods

First, based on the patient's fracture site, we determined the range of exposure required and designed a surgical incision to expose the fracture line. Based on the virtual surgical plan, we then simulated the fracture reduction process on the fracture model, determined the required internal fixation device, and pre-formed the titanium plate on the molding template in advance. After cutting a suitable length of ligature wire, thread both ends into the lingual foramen, pass through the lingual adjacent space, and then exit from the adjacent buccal space. Finally, ligate and fix the bite plate on the mandibular dentition sequentially on the labial and buccal sides. We used a bite plate to restore the continuity of the fractured end. Preformed titanium plates were implanted into corresponding positions according to the preoperative design. If the tooth germ blocked the bone block for precise reduction, then the titanium plate was adjusted slightly according to the actual situation to reduce damage to the permanent tooth germ. After the pre-formed titanium plate had been tightly attached to the bone surface, a predetermined length of titanium nail was implanted and fixed at a set angle. Then the wound was rinsed and sutured in place (see Fig. 3).

2.4 Postoperative follow-up

Patients were instructed to maintain oral hygiene and a liquid diet. The patients also wore craniomandibular bandages for 1–2 weeks. We removed the occlusal plate once the occlusal relationship had recovered well (usually 3 weeks). All patients were surveyed for satisfaction, with a total score of 10 points. A score of 9–10 points indicates complete satisfaction, 6–8 points indicate basic satisfaction, and <6 points indicate dissatisfaction. After one month of surgery, open mouth training was conducted, and CBCT (Cone Beam Computed Tomography) scanning was performed during follow-up. Virtual 3D model reconstruction of the jaw morphology was performed using Mimics software, and the degree of restoration of the generated 3D jaw morphology was compared with the preoperative preset morphology. After four months of fracture

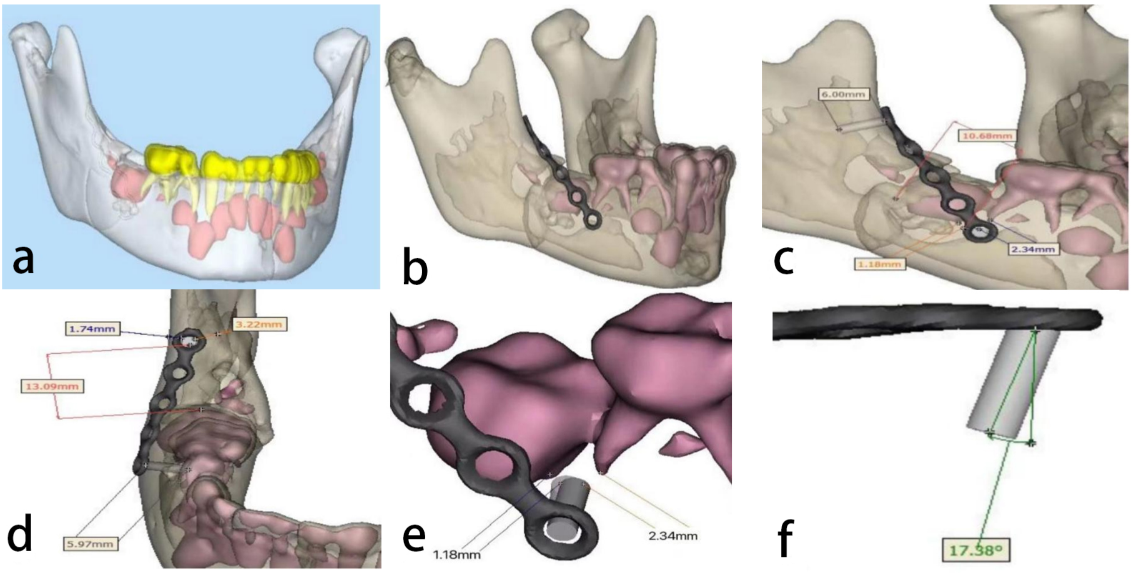

FIGURE 1. Design the internal fixation operation scheme for mandibular fractures in Mimics software. (a) Model after reduction; (b–d) Virtual design of the titanium plate and the position of the titanium nail; (e,f) Implantation angle and position of the titanium nail near the tooth germ.

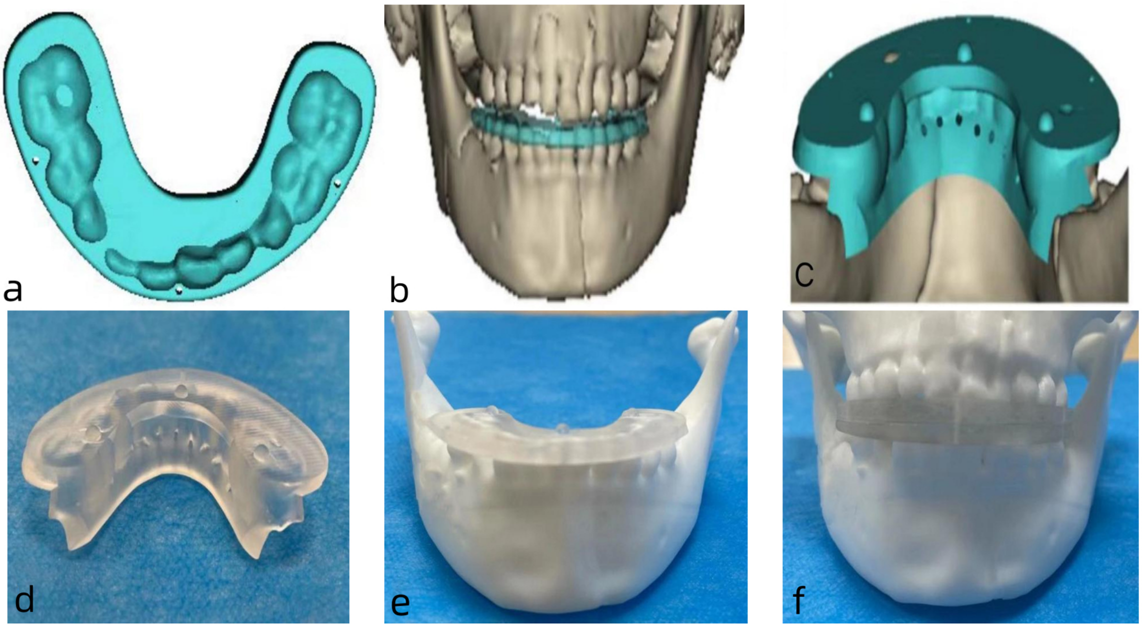

FIGURE 2. Occlusal guide plate. (a–c) Design of the occlusal guide plate in Mimics software. (d–f) Shows the 3D printed occlusal guide plate, (d) 3D printed mandibular occlusal guide plate, (e) Occlusal guide plate located in the mandibular dentition, and (f) Upper and lower occlusal guide plate located in the dentition.

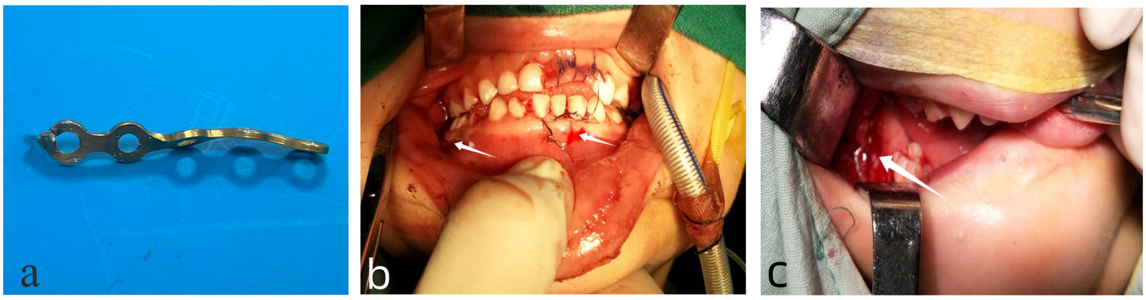

FIGURE 3. Surgical process. (a) Preformed titanium plates. (b,c) Implanted the internal fixation devices.

healing, we removed the internal fixation device. Patients were followed-up at 1, 3, 6 and 12 months after surgery to assess mouth opening, the occlusal relationship, tooth eruption, and the occurrence of complications. We acquired panoramic films or CBCT based on each patient's clinical situation to understand fracture healing, tooth germ development, and other conditions. Telephone follow-up was conducted 12 to 24 months after surgery to understand the development of each child's maxillofacial development and whether there had been any serious complications.

2.5 Efficacy evaluation indicators

2.5.1

Fracture healing evaluation criteria were as follows: excellent (fracture healing with complete restoration of maxillofacial function and appearance); good (fracture healing, poor alignment of the fracture end, improved maxillofacial function and appearance), and poor (misalignment and healing of fractures, loss of facial function). We recorded the occurrence of complications (tooth germ injury, poor occlusion, infection and nerve injury).

2.5.2

We followed up with each patient for one year after surgery to measure the patient's maximum opening degree and opening type.

2.5.3

We used the 3D overlay function of Mimics software to compare the preoperative virtual surgical design with the actual postoperative surgical application effect.

2.6 Statistical methods

The data were analyzed by SPSS 25.0 software (IBM company, SPSS, Chicago, IL, USA). The Shapiro-Wilk test was used to determine data distribution. For variables that conformed to a normal distribution, means $\pm$ standard deviations (SD) were used, and comparisons were made using t-tests. p values $<$ 0.05 were considered to be statistically significant.

3. Results

3.1 Patient characteristics

A total of 22 patients met our specific inclusion criteria, including 12 males and 10 females, with a mean age of 8.59 ± 2.44 years. Causes of injury were as follows: 12 cases of accidental falls, eight cases of traffic accidents, and two cases of high-altitude falls. The fracture site was as follows: one case of symphysis, six cases of chin foramen, one case of angle, three cases of symphysis with chin foramen, six cases of symphysis with condyle, two cases of symphysis with angle, two cases of chin foramen with angle, one case of condyle with chin foramen (see Table 1). Preoperative average opening degree 23.59 ± 2.89 mm. All patients had varying degrees of occlusal disorder, limited mouth opening, varying degrees of swelling, and pain in the maxillofacial region.

TABLE 1. Patient characteristics.

	Case (n)
Fracture site	
Symphysis	1
Chin foramen	6
Angle	1
Symphysis + chin foramen	3
Symphysis + condyle	6
Symphysis + angle	2
Chin foramen + angle	2
Condyle + chin foramen	1
Causes of injury	
Accidental falls	12
Traffic accidents	8
High-altitude falls	2

3.2 Fracture healing and complications

In total, 22 patients were followed up for 1–5 years. Postoperative panoramic or CBCT examinations showed that 21 patients had excellent fracture healing (see Fig. 4), while one patient had good fracture healing. Nineteen cases were completely satisfied, and three cases were satisfied (see Table 2, Fig. 5). There were no complications during postoperative follow-ups, such as tooth germ injury or nerve damage. Of these, one patient had a poor occlusal relationship. This patient had multiple mandibular fractures and could not wear an occlusal plate throughout the process. However, after three years of follow-up, the occlusal relationship gradually returned to normal. Another case of postoperative infection occurred in a patient who did not pay attention to maintaining oral hygiene, thus resulting in wound infection. Following anti-infection treatment, the fracture healed well.

TABLE 2. Evaluation of clinical effects.

	Age ($\leq$6)	Age (7–12)
Patients' satisfaction		
Very satisfied	6	13
Satisfied	1	2
Dissatisfied	0	0
Dysfunction		
Limited mouth opening	0	0
Malocclusion	1	0
Complication		
Tooth germ injury	0	
Infection	0	1
Nerve injury	0	0
Reoperation rate (%)	0	0

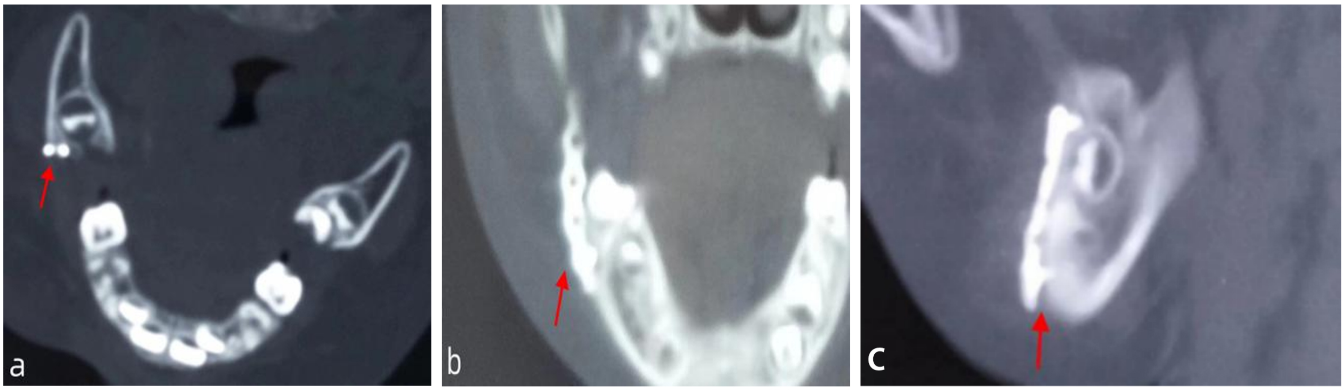

FIGURE 4. Postoperative radiographic data. (a) Cross-section. (b,c) Sagittal plane.

FIGURE 5. Occlusal relationship. (After two years of surgery).

3.3 Opening degree and opening type

The mean postoperative diameter of 29.82 ± 1.79 mm was significantly larger than the preoperative diameter of 23.59 ± 2.89 mm ($p < 0.001$). In the postoperative follow-up of 22 children, the opening type was normal ("↓"), thus indicating that the surgical treatment of mandibular fractures in children led to a significant improvement in the opening degree and opening type see Figs. 6,7.

3.4 Comparison of preoperative virtual surgery design and postoperative effects (Fig. 8)

Mean upper deviation (0.65 ± 0.09) mm, mean lower deviation (−0.57 ± 0.14) mm.

The patient in this example shows multiple mandibular fractures, with conservative treatment of the right condyle process and implantation of an internal fixation device at the right mandibular angle.

4. Discussion

Children are in a period of growth and development. With the eruption of permanent teeth and the development of the jaw, the shape of the jaw in children changes, and the occlusal relationship can gradually be reconstructed. Therefore, the treatment methods and goals for children are different from adults. The fracture line does not require anatomical reduction at both ends, and the occlusal relationship does not require precise recovery. As long as the continuity of the jaw is restored to achieve stable fixation. The ultimate goal of treatment is to help children's dental and maxillofacial systems achieve normal growth and development, such as tooth germ development, tooth eruption, mandibular development, and overall craniofacial development, and to minimize adverse reactions after injury [6, 7].

According to Sobrero *et al.* [8] conducted a retrospective study on the effectiveness of surgical treatment of mandibular fractures in 91 children and adolescents, discovering that internal fixation schemes were similar to those used for adults, although it was necessary to adapt hardware size and position

FIGURE 6. Opening degree. (After two years of surgery).

FIGURE 7. Facial photos. (a) Frontal view. (b,c) Side view.

according to teeth and the patient's age. Kao *et al.* [9] conducted a retrospective study of 150 cases of mandibular fractures in children founding that conservative treatment was the first choice and surgical treatment also achieved satisfactory results. Bansa *et al.* [10] compared 77 cases of conservative treatment with 23 cases of surgical treatment, drawing a conclusion that operative management provides an exceptional functional advantage. Nonsurgical management should be considered as the mainstay option for pediatric mandible fractures. Our study suggested that for mandibular fractures with significant displacement, Open Reduction and Internal Fixation (ORIF) are necessary. Surgical treatment has a stabilizing effect on the fracture end, which is beneficial for patients to undergo active physical therapy, which is consistent with Bae *et al.* [11]'s conclusion. For mandibular fractures in children, we should select personalized treatment methods according to the comprehensive consideration of fracture type, fracture site and fracture degree. Children are in the primary or mixed dentition stage, with the presence of many permanent tooth embryos in the jawbone and the small anatomical structure of the jawbone, leading to internal fixation devices are prone to damage the permanent tooth embryo. Extensive dissection during surgery can also affect fracture healing and jawbone development. These factors constrain the precise implementation of surgical design and scheme, making precise reduction and fixation after fractures more challenging. Therefore, it is necessary to reduce the impact of treatment on the development and function of children's maxillofacial fractures

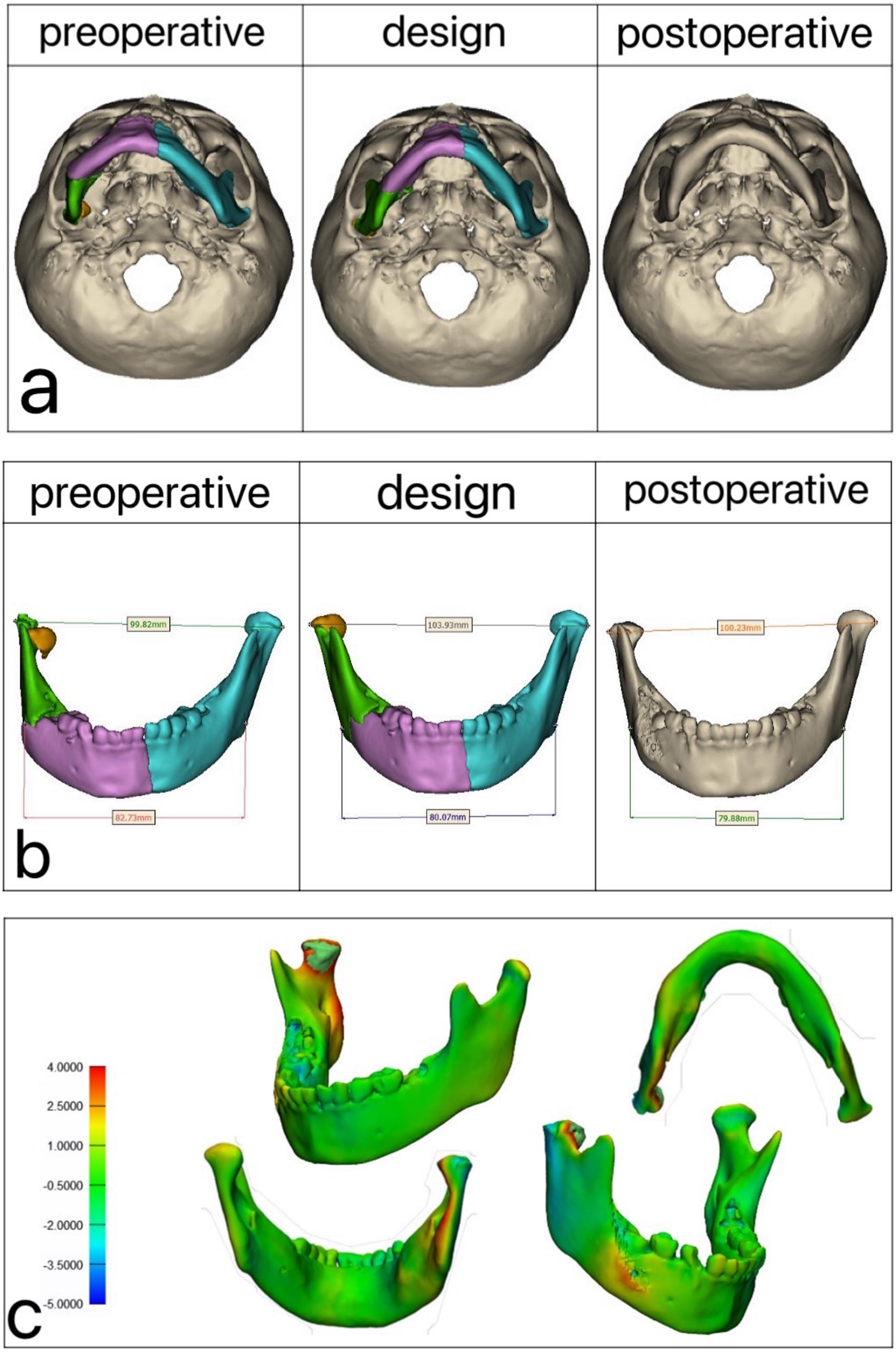

FIGURE 8. Comparison before and after surgery. (a) Compared with the bottom view, (b) Measurements of the distance between the condyle and the mandibular angle, and (c) The virtual design before surgery had a high degree of fitting with the mandibular shape effect after surgery.

[12].

The traditional surgical method involves the surgeon reducing the fracture based on preoperative CT imaging data acquired from the patient and determining the placement of internal fixation devices, thus making the surgeon's experience an important determinant of surgical efficacy. Consequently, there are certain limitations to traditional surgery [10]. Digital surgical technology is an interdisciplinary technology that combines computer imaging, graphic processing, precision manufacturing, and other technologies. The use of digital surgical technology commenced in the 1990s and has only recently been applied in the field of oral and maxillofacial surgery. Digital surgery technology was developed from CT three-dimensional reconstruction technology, computer-aided design and production, reverse engineering technology, rapid prototyping technology, and surgical navigation technology. Thus far, this technology has been widely used for oral and maxillofacial fracture repair, deformity correction, defect repair, and reconstruction fields [13, 14]. Our research group applies digital surgery to treat pediatric mandibular fractures; we adopt several steps in our fully digital surgical treatment process for pediatric mandibular fractures. Firstly, data collection, 3D measurement, and analysis. Secondly, computer-assisted design simulates fracture reduction, titanium plate design, and digital guide plate design. Third, 3D printing produces occlusal plates and shaping templates. Fourth is effect evaluation, in which we perform a comparative evaluation of the actual and simulated surgical effects. Prior to surgery, a patient's thin layer CT data is imported into Mimics software to perform 3D reconstruction, reposition, and then design surgical plans for the fracture block. Finally, we accurately print a 3D solid model of the patient's fracture site. This strategy can help surgeons more intuitively understand the type of fracture, degree of displacement, tooth embryo development, and 3D spatial positioning in the jawbone. The application of 3D bending templates to pre-form the printed titanium plate can make it more compatible with the outer plate of the mandible, thus preventing displacement of the fracture end after fixation with titanium nails. This will avoid repeated bending of the titanium plate during surgery and help determine the placement position of the titanium plate, and implantation of the length of the titanium nail, thereby significantly reducing the surgical time and improving the overall surgical effect. In our postoperative follow-up, 21 cases experienced excellent fracture healing, one case experienced good fracture healing, and 22 patients showed significantly improved opening after surgery when compared to the pre-surgical status. The surgery did not cause damage to teeth, tooth germ, or nerves, and the preoperative virtual design closely fitted with the actual postoperative effect, with mean upper deviation (0.65 ± 0.09) mm, average lower deviation (-0.57 ± 0.14) mm. Our data suggested that digital surgery assisted by 3D printing made the surgery more intuitive and quantitative; and improved surgical accuracy. This mode of surgery has clear advantages for treating jaw fractures in children.

The traditional dental arch splint is the main choice for intermaxillary fixation, its clinical effect is positive, but it still has some shortcomings; the application of dental arch splints requires that the teeth must be intact and not loose [15]. Due to incomplete eruption of the permanent teeth in the oral cavity of children, along with the short crowns of deciduous teeth and root resorption causing loosening of the deciduous teeth, it is impossible to establish a stable occlusal relationship in children. When using dental arch splints, fixed appliances, and other methods to treat jaw fractures in children, there are various shortcomings, such as a weak retention force, easy detachment, and notable effects on eating and the maintenance of oral hygiene. Subsequently, the growth of bacteria causes damage to teeth and oral mucosa, *etc*. The bite plate was first used in orthognathic surgery. This plate simulates jaw movement using preoperative model surgery; this leads to the generation of a bite plate based on the occlusal relationship between the upper and lower jaw after jaw movement, thus determining the position and occlusal relationship of the jaw during surgery [16, 17]. Although traditional splints have low production costs and can be worn and removed easily by children, they require the production of impressions and models; these splits also require complex operations and lengthy processes. Furthermore, errors in the production process can easily lead to poor postoperative recovery in children [18, 19].

3D printing technology is a technique that involves layer-by-layer processing and stacking to form a three-dimensional physical object. This has become an important means of transforming virtual surgical designs into real surgical treatment [20, 21]. The bite plate used by our research group is prepared using computer virtual design and 3D printing technology based on data generated by specific software. Prior to surgery, a bite plate was designed on the occlusal relationship of the upper and lower jaw after a reduction in Mimics software. Then, the tooth model data were paired and fused with the patient's bone tissue imaging data to generate an accurate digital tooth model of the patient. The bite plate aligns with the shape of the restored crown and arch; this can more accurately restore the occlusal relationship of a child, facilitate the restoration of mandibular continuity during surgery, and guide fracture reduction. The application of this occlusal plate in children with mandibular fractures has the following advantages: (1) Guiding fracture reduction and restoring the occlusal relationship of the child; (2) It has a certain fixing effect on loose teeth; (3) The fixation effect of tension band bone fracture can reduce the implantation of internal fixation devices in the direction of the mandibular alveolar bone; (4) Easy to operate and minimally invasive, removing the occlusal plate only requires cutting and pulling out the ligature wire, with minimal pain and minimal psychological impact on the child. For children with complex upper and lower jaw fractures, both upper and lower bite plates can be designed simultaneously. Holes can be designed between the two central incisors on the lip aspect of the bite guide plate and between the first and second premolars on both sides. After the upper and lower bite plates are fixed in place in the dentition, ligature wires can be used to pass through the lip holes to fix the upper and lower bite plates together, thus playing a key role in intermaxillary ligation and fixation. The lightly cured bite board designed and produced during the digital process is more accurate than a bite board made of traditional self-curing plastic. Following surgery, children can eat soft food while maintaining oral hygiene. This simplifies the production process of traditional self-curing plastic splints and effectively avoids the poor recovery of bite relationships due to issues relating to poor patient cooperation, limited mouth opening, and tooth loosening and displacement. It also prevents the continuous release of self-curing plastic monomers from irritating the oral mucosa. In this study, 21 pediatric patients experienced good postoperative occlusal recovery; one case had poor occlusal recovery due to not wearing the occlusal plate throughout the entire process. This study's results clearly demonstrate that combining digital technology with 3D printing can more accurately restore the occlusal relationship of pediatric patients. Children with fractures have strong self-healing and reconstruction abilities, and even those who are not satisfied during surgery can achieve satisfactory therapeutic effects through later permanent tooth eruption and jaw development.

The limitation of this study is that the retrospective nature of this study inherently results in flaws, and the low sample size restricts its validity and generalization of the results. At the same time, there is a lack of long-term follow-up (children are advised to follow up until adulthood), which requires in-depth exploration in later research. In addition, digital technology requires repeated communication between designers and surgical implementers to achieve ideal results. The 3D-printed jaw model is an isolated model that removes structures such as muscles, nerves, and blood vessels, which is different from actual surgical operations. It requires surgeons to have extensive clinical experience.

5. Conclusions

Our research finds that digital surgery has significant advantages in treating mandible fractures in children. It is possible to simplify surgical operations, reduce surgical time and difficulty, and improve accuracy and safety, thus improving the efficacy of surgical treatment for jaw fractures in children. Our data suggest that this minimally invasive, safe and accurate approach is worth promoting and applying on a wider basis in clinical practice. But nonsurgical treatment is still the main choice for mandible fractures in children.

ABBREVIATIONS

CT, computed tomography; CBCT, cone beam CT.

AVAILABILITY OF DATA AND MATERIALS

The datasets generated and/or analyzed during the current study are not publicly available due to [1. Privacy protection: Clinical data involves patients' personal information, including sensitive privacy such as name, age and gender. In order to protect patients' privacy, our research group has the responsibility to ensure that this information is not obtained and used by unauthorized personnel. 2. Informed consent of patients: According to the agreement in the informed consent form, clinical data can be used for specific research purposes, and shall not be disclosed or used for other purposes. This is an important measure to protect the rights and interests of patients.] but are available from the corresponding author on reasonable request.

AUTHOR CONTRIBUTIONS

KZ—designed the research study. CCZ and CS—performed the research. DW, TYG and JL—provided help and advice on the research. DKY, CL and YD—analyzed the data. CCZ—wrote the manuscript. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This study was approved by the Medical Ethics Committee of The First Affiliated Hospital of Bengbu Medical College (Reference: 174, 2021). All parents of the patients signed an informed consent form.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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