The use of 3-Dimensional Biomodel in Planning Paediatric Craniofacial Surgery

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Abstract: Objective: This study aimed to review the usefulness and advantages of the application of 3-dimensional (3D) biomodel in planning for paediatric craniofacial surgery.

Methods: This study involved 11 paediatric patients (aged 5 months to 6 years old) presenting with congenital craniofacial abnormalities that had their 3D biomodels fabricated prior to the surgical intervention from 2009 to 2014. Standard craniofacial surgical protocol was practiced in our centre and data from the protocol were used for this review.

Results: There were 12 biomodels fabricated involving cases of 6 Crouzon syndromes, 1 Apert syndrome, 2 isolated craniosynostosis, 1 Tessier type 4 oro-oculofacial cleft and 1 meningocoele. The 3D biomodels fabricated were used for pre-surgical planning, pre-operative surgical procedure simulation to achieve precision, education purpose and communication tools between surgeons and patients’ guardian.

Conclusion: Three-dimensional biomodel can be considered as a useful tool in providing valuable information and assisting complicated craniofacial surgery.

Key words: 3D biomodel, stereolithography, paediatric craniofacial surgery, craniosynostosis.

Introduction

Complicated paediatric craniofacial conditions such as congenital cranial dysraphism, syndromic craniosynostosis and isolated craniosynostosis require the surgeons to comprehensively understand the anatomy and the characteristic dysmorphology of the skull deformities in order to predict and plan the segmental bone movement to overcome the structural discrepancy, achieve optimal result and prevent complications.

Because of such complexity of the surgical procedure in craniofacial surgery, the fabrication of 3-dimensional (3D) biomodel as part of the pre-operative preparation can provide a reliable source and additional information for the surgeon to thoroughly plan the surgery. Apart from the anomalies, the understanding should also include the complex interaction and ideal timing of the surgical intervention and the continuous skeletal growth in paediatric patients.

The introduction of stereolithography for fabrication of 3D biomodel can be considered as an innovative advancement in biomedical engineering in assisting complicated craniofacial surgery since it was first reported in 1987⁷. Following an article on stereolithography published in 1990 to display a 3D skull anatomy³, more studies have subsequently been published to focus on the development of the technique and improving the accuracy of model manufacturing, as well as reporting applications of stereolithography in various clinical situations⁸⁻¹⁰. Other than technical aspects, there were studies conducted to assess the perception of different group of subjects namely the surgeons, surgical trainees, lab technicians and patients in relations to the usefulness of biomodels to its respective surgical cases³⁴.

There are different types of manufacturing methods available and different materials that can be used to fabricate 3D biomodels. These include starch model from a 3D printing method, acrylic from a stereolithographic method and epoxy resin from a fused deposition modelling method. Biomodels fabricated by stereolithography have been reported to have a higher accuracy compared with milled models and 3D computed tomography visual models⁷.⁸. The stereolithographic technique can also overcome anatomical undercutting problem, which is a major drawback of milled models during model processing⁷.⁸.

The technique is valuable for pre-operative 3D assessment of extensive pathologic and traumatic defects prior to surgical reconstruction due to its ability to reproduce the desired specific bone area. The technique also allows the reproduction of closed cavities, visualization of intraosseous canals and pathological...
expansion when fabricated using a transparent material. Apart from fabricating biomodels, the technique can be used to design and assist fabrication of customized splints and prostheses, determining size of bone grafts for reconstructive procedures and fabrication of scaffolds for bone regeneration.

This study was aimed at reviewing the usefulness and advantages of the application of 3D biomodel fabrication in assisting surgical preparation for paediatric craniofacial deformity patients in University of Malaya Medical Centre (UMMC) and Universiti Kebangsaan Malaysia Medical Centre (UKMMC).

**Materials and Methods**

This study involved 11 paediatric patients presented with craniofacial deformities who visited the Neurosurgery and Maxillofacial clinics in UMMC and UKMMC between 2009 and 2014. We included patients ranged from 5 months to 6 years old who were diagnosed with syndromic craniosynostosis, isolated craniosynostosis and other craniofacial pathology requiring surgical intervention and had their 3D biomodels fabricated prior to the surgery. Craniofacial cases without fabrication of biomodels were excluded.

All the surgical procedures were performed in either UMMC or UKMMC. The patients' medical records were retrieved and data were evaluated and summarized in table form. Demographic data, diagnosis, types of operation, follow-up period, post-operative complications and the function of the biomodels were documented in table form. All patients were clinically assessed during post-operative reviews. Consents were obtained prior to commencing of this study.

**Fabrication of 3D biomodels**

The fabrication of 3D biomodels involved a series of laboratory procedure which was conducted at Centre for Bio-Medical Technology Integration laboratory (CBMTI Sdn. Bhd), University of Malaya. A 1 mm computed tomography (CT) scan of the patient's skull was used in the processing of the 3D biomodel. OsiriX medical image open-source processing software was used for image processing. In our centre, we use a ZPrinter450 (Z Corporation, Burlington, MA) to fabricate the 3D biomodel. The 3D printing is a clean and highly automated process. In general, the printing process involves 3 phases namely preparation, printing and depowdering. During preparation phase, the printer automatically creates an optimum operating environment for the printing process. The machine will fill the build chamber with a layer of powder so that the biomodel, when completed, rest on this powder which act as a support for easy removal. The second phase involves the layers printing process according to the layers that have been set in the chosen software. At this stage, the binder solidifies the powder in that cross-section of the model, leaving the rest of the powder dry for recycling. At this point, a specific chamber in the printer will lowers the powder bed to prepare for the next layer. This cycle will automatically repeats itself until the model is complete. Once completed, the biomodel is suspended in the powder for curing. At the end of the curing time, the printer machine automatically removes most of the powder from around the model by applying vacuum pressure and vibration to the bottom of the build chamber. All powder loading, removal and recycling during the third phase is part of a closed-loop system supported by persistent negative pressure for containing airborne particles within the machine. Infiltrating material is then applied to provide adequate strength to the biomodel. Figure 1 shows some of the 3D biomodels fabricated and its utilization for this study.

Figure 1. Fabricated 3D biomodels
(A) 3D biomodel for case 5.
(B) Segmentalization of biomodel for case 2 for conventional surgical simulation.
(C) Intracranial aspect of biomodel for case 2 allowing detailed anatomical visualization.
(D) Simulation for monobloc distraction osteogenesis for case 4.
Results

There were 6 female and 5 male patients involved in this study. These cases comprised of 6 Crouzon syndromes, 1 Apert syndrome, 2 cases of isolated craniosynostosis, 1 Tessier type 4 oro-oculofacial cleft and 1 meningocele case. All cases had 3D biomodels fabricated prior to their surgery. In total, we have fabricated 12 biomodels for 12 surgical procedures involving 11 patients.

We performed 3 fronto-orbital advancement procedures for the 2 Crouzon and 1 Apert syndrome cases, 4 monocles distraction osteogenesis for 4 Crouzon syndrome cases, 1 craniotomy procedure, 1 bilateral box osteotomy with medial advancement of the orbit, 1 unilateral box osteotomy for superior repositioning of orbit, 1 skull remodelling and 1 posterior vault advancement. The follow-up period ranges from 6 to 56 months. All these data were summarized in Table I.

The biomodels fabricated were utilized for pre-surgical planning, surgical simulation involving conventional surgery and monocles distraction osteogenesis, education purpose and communication tool between the surgeons and the patients' guardians (Table II).

In term of complications, there were 2 cases of infection, 2 cases of dural tear and 1 bony structural restriction. The 2 infection cases were associated with local surgical wound and plate-related. The infected plate was surgically removed uneventfully while the surgical wound infection was successfully treated with prescription of antibiotic. The complications and its management were summarized in Table I. The fabrication of biomodel resulted in the increase in operation cost by the range of RM800-1600 per biomodel depending on its size (approx. USD250-500).

<table>
<thead>
<tr>
<th>Case</th>
<th>Age during operation</th>
<th>Gender</th>
<th>Diagnosis</th>
<th>Operation</th>
<th>Functional outcome</th>
<th>Complication</th>
<th>Management of complication</th>
<th>Follow-up (months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6 years old</td>
<td>Female</td>
<td>Apert syndrome</td>
<td>Fronto-orbital advancement and cranioplasty</td>
<td></td>
<td></td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>3 years old</td>
<td>Female</td>
<td>Isolated right coronal suture craniosynostosis</td>
<td>Bilateral box osteotomy, medial advancement of the orbit and frontal remodelling</td>
<td></td>
<td></td>
<td></td>
<td>32</td>
</tr>
<tr>
<td>3</td>
<td>5 months old</td>
<td>Female</td>
<td>Crouzon syndrome Obstructive sleep apnea Bilateral hearing loss</td>
<td>Fronto-orbital advancement</td>
<td></td>
<td>Orbital protection Resolving OSA</td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>4</td>
<td>4 years old</td>
<td>Female</td>
<td>Crouzon syndrome Obstructive sleep apnea</td>
<td>Monobloc distraction osteogenesis</td>
<td></td>
<td>Orbital protection Resolving OSA</td>
<td></td>
<td>18</td>
</tr>
<tr>
<td>5</td>
<td>3 years old</td>
<td>Male</td>
<td>Crouzon syndrome Obstructive sleep apnea</td>
<td>Fronto-orbital advancement and cranioplasty Monobloc distraction osteogenesis</td>
<td></td>
<td>Orbital protection Resolving OSA</td>
<td></td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>2 years old</td>
<td>Female</td>
<td>Crouzon syndrome</td>
<td>Posterior vault advancement</td>
<td></td>
<td></td>
<td></td>
<td>30</td>
</tr>
<tr>
<td>7</td>
<td>1 year 7 months</td>
<td>Male</td>
<td>Fronto-naso-orbital meningioma Bilateral craniotomy Excision of encephalocele Reconstruction with calvarial bone graft</td>
<td></td>
<td></td>
<td>Surgical removal of plate-intra-operative repair + antibiotic</td>
<td></td>
<td>24</td>
</tr>
<tr>
<td>8</td>
<td>1 year 6 months</td>
<td>Female</td>
<td>Sagittal suture craniosynostosis</td>
<td>Skull remodeling</td>
<td></td>
<td>Local wound infection</td>
<td>Antibiotic</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>4 years old</td>
<td>Female</td>
<td>Crouzon syndrome Obstructive sleep apnea</td>
<td>Monobloc distraction osteogenesis</td>
<td></td>
<td>Orbital protection Resolving OSA</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>10</td>
<td>8 months old</td>
<td>Male</td>
<td>Crouzon syndrome Obstructive sleep apnea</td>
<td>Monobloc distraction osteogenesis</td>
<td></td>
<td>Orbital protection Resolving OSA</td>
<td>Dural tear</td>
<td>Intra-operative repair + antibiotic</td>
</tr>
<tr>
<td>11</td>
<td>1 year 7 months</td>
<td>Male</td>
<td>Tessier type 4 (Oro-oculofacial cleft)</td>
<td>Right orbital osteotomy for superior positioning</td>
<td></td>
<td>Orbital protection</td>
<td></td>
<td>6</td>
</tr>
</tbody>
</table>
Table II. The advantages of 3D biomodel in paediatric craniofacial surgery

<table>
<thead>
<tr>
<th>The advantages of 3D biomodel</th>
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</thead>
<tbody>
<tr>
<td>• Tool for communication between surgeon-patients' guardians (i.e. explaining procedures,</td>
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<tr>
<td>risks of operation and consent).</td>
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<tr>
<td>• Provide pre-surgical intra-cranial visualization of surrounding bone structures thus</td>
</tr>
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<td>providing assistance for better surgical planning.</td>
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<tr>
<td>• Enable pre-surgical simulation of both conventional surgery and distraction osteogenesis</td>
</tr>
<tr>
<td>for the anticipated movement, distance and fixation of the osteotomized segments.</td>
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<tr>
<td>• Enable detailed assessment of craniofacial bone deformity.</td>
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<tr>
<td>• Enable pre-surgical splint fabrication to assist surgical movement and segment fixation</td>
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<tr>
<td>during operation.</td>
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<tr>
<td>• Valuable tool for teaching and education</td>
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</table>

Discussion

The use of 3D biomodel has proven to be beneficial in all the 11 patients involved in our study. In the aspect of pre-surgical planning, the biomodels provided a full 3D and valuable intra-cranial visualization of surrounding bone structures which allow the surgeons to conduct a surgical simulation thus providing assistance for better surgical outcome (Fig. 1). Vital areas such as the infra temporal fossa and intracranial structures namely crista galli, cribiform plate and the undercut area below the sphenoid wings can be directly visualized for surgical planning. In this aspect, the accuracy of the biomodels can be considered as acceptable for clinical manipulation as supported by the reported percentage errors of stereomodels from Asaumi et al. and Choi et al. were 0.63% and 0.56%, respectively.9,10.

In syndromic craniosynostosis cases, the main objective of surgical intervention is to release the affected suture thus decompresing the intracranial space and simultaneously advancing the fronto-facial skeletal components to allow the visceral organs to develop without any restriction.11 As demonstrated in our study, the syndromic craniosynostosis cases underwent fronto-orbital advancement procedures either via conventional surgery or monobloc distraction osteogenesis. We have found that the fabrication of 3D biomodels prior to the monobloc distraction osteogenesis procedures were extremely useful as it allow us to pre-bend the distractor footplates thus minimizing operating time and simulate the distraction procedure by applying the actual device on the biomodel to determine the correct vector of activation and estimating the distance for adequate advancement (Fig. 1D). As demonstrated in our study, the fabrication of 3D biomodels especially in syndromic craniosynostosis cases allowed direct visualization of the intra-cranial region and other important area such as the midfacial region thus allowing us to plan and perform the pre-surgical simulation to achieve optimum result as shown in Figure 2 and 3.

The other advantages of using 3D biomodels in our study were its utilization as an educational tool and performing detailed assessment of the craniofacial bone deformity at any stage of the surgical intervention. These advantages were also reported in other studies.5,6,12 Other than the advantages discussed above, fabrication of surgical splint using 3D biomodel pre-surgical simulation to guide the advancement of the midface segment during an operation in a Crouzon syndrome case has also been reported.13

One major factor contributing to the small number of cases involved in this study was due to the additional cost for biomodel fabrication that the patients need to bear prior to the surgery. Sailer et al.6 reported of the expensive cost being the main disadvantage of this technique. However, the developments of other manufacturing techniques such as fused deposition and 3D printing have reduced the manufacturing complexity and time thus making the technique more affordable to patients.6, Chow and Cheung, in a study involving a survey among patients having their 3D biomodels fabricated prior to a surgery found that the patients felt that the costs of their biomodels were reasonable.6 We also found that the biomodels help to improve the communication between surgeons and patients' guardians especially during explanation of procedures, discussing risks of operation and taking consent.

In general, complications in craniofacial surgery are relatively uncommon14,15. These may include unfavourable bone fracture, blood loss, infection, respiratory complications and dural tear with cerebrospinal fluid (CSF) leak. By using 3D biomodel,
complications in relation to the hard tissue can be prevented by appropriate pre-surgical planning and simulation. As summarized in Table I, only one of the complications was related to the hard tissue (case 9). There were 2 cases of dural tear which were repaired intra-operatively and 2 cases of infection which, one was a surgical wound infection (case 8) and one having post-operative infected plate at the right fronto-zygomatic fixation area (case 5). For the latter, the infection resolved after the plate was removed. Even though infections are uncommon in craniofacial surgery, when occurs, it can be potentially life-threatening due to its association with CSF leak and persistent communication of the intracranial cavity to the external surroundings.

In both centres, 3D biomodel fabrication has become an integral part of biomedical engineering as it can be utilized in product design, mechanical manufacturing and 3D prototyping. Apart from craniofacial surgery, other medical areas that benefited from its application are orthognathic surgeries, reconstructive surgeries, pathologies and trauma. The continuous advances in this biomedical field will help to facilitate better diagnosis, treatment planning, 3D surgical simulation and fabrication of prostheses in various types of cranio-maxillofacial surgery.

Conclusion

In conclusion, fabrication of 3D biomodel can be considered as a useful tool in assisting complicated surgical procedure in paediatric craniofacial field. Continuous research and development is required to ensure its relevance and benefits to patients with craniofacial deformity.

Acknowledgement

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Conflict of interest

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