Received: 26 October 2016 | Accepted: 14 February 2017
DOI: 10.1111/vsu.12683

ORIGINAL ARTICLE

The application of 3-dimensional printing for preoperative planning in oral and maxillofacial surgery in dogs and cats*

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Abstract

Objective: To describe the application of 3-dimensional (3D) printing in advanced oral and maxillofacial surgery (OMFS) and to discuss the benefits of this modality in surgical planning, student and resident training, and client education.

Study design: Retrospective case series.

Animals: Client-owned dogs (n = 28) and cats (n = 4) with 3D printing models of the skulls.

Methods: The medical records of 32 cases with 3D printing prior to major OMFS were reviewed.

Results: Indications for 3D printing included preoperative planning for mandibular reconstruction after mandibulectomy (n = 12 dogs) or defect nonunion fracture (n = 6 dogs, 2 cats), mapping of ostectomy location for temporomandibular joint ankylosis or pseudoankylosis (n = 4 dogs), assessment of palatal defects (n = 2 dogs, 1 cat), improved understanding of complex anatomy in cases of neoplasia located in challenging locations (n = 2 dogs, 1 cat), and in cases of altered anatomy secondary to trauma (n = 2 dogs).

Conclusion: In the authors' experience, 3D printed models serve as excellent tools for OMFS planning and resident training. Furthermore, 3D printed models are a valuable resource to improve clients' understanding of the pet's disorder and the recommended treatment.

Clinical relevance: Three-dimensional printed models should be considered viable tools for surgical planning, resident training, and client education in candidates for complex OMFS.

1 | INTRODUCTION

The field of veterinary oral and maxillofacial surgery (OMFS) is rapidly evolving. In recent years, there has been progress and innovation in surgical treatment options, increased willingness of clients to pursue advanced surgical care for their pets, and practitioners striving to match the

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standard of care established in human medicine.[1,2] However, OMFS poses unique challenges to the veterinary surgeon and several considerations are warranted prior to undertaking major surgery in the maxillofacial region of dogs and cats. These considerations include complex and delicate anatomy and geometry of the facial structures; potential complications such as hemorrhage, nerve damage or altered occlusion; functional and esthetic outcome; quality of life; and client expectations.

Advanced diagnostic imaging is an essential component of preperative planning in OMFS. Specifically, the value of computed tomography (CT) has been well established as a source of diagnostic and prognostic information in candidates for OMFS.[3-8] CT is especially useful to determine the extent of injuries in maxillofacial trauma,[9] to compare the dimensions of osseous relative to soft tissue defects in congenital and acquired palatal lesions,[10] and to assess margins and bone involvement of oral tumors. However, the limitation of conventional CT imaging consists of rendering 3-dimensional (3D) anatomy into a 2-dimensional (2D) representation, which affects the understanding of spatial relationships. To overcome this limitation, several software programs allow manipulation of Digital Imaging and Communications in Medicine (DICOM) files obtained by CT for volume rendering (3D imaging). Nonetheless, even 3D constructs viewed on a flat screen may not allow a complete and confident understanding of complicated anatomic details,[11-13] especially in cases with aberrant anatomical features. Conventional CT may not suffice for precise surgical preparation and decision-making.[14]

Three-dimensional printing, also known as rapid prototyping, additive manufacturing, or solid-freeform technology, is a precise computer-directed process whereby models are fabricated via successive layering of material.[12,13,15] Three-dimensional printing has been applied in industrial design since the 1980s and, due to advances in the technology, has been adopted by the medical field in the last decade.[16] In contrast to traditional manufacturing methods, printed items can be constructed cost efficiently without the need for mass production, allowing the production of individual products.[15] Furthermore, 3D printing more readily permits creation of complicated geometries that may otherwise be impossible to achieve through traditional subtractive processes. Jetted photopolymer printing is one of the leading technologies used for the fabrication of 3D printed skulls. This technique is analogous to traditional 2D color inkjet printing in that an array of jetting nozzles follows a linear trajectory and is triggered at a precise moment in time to deposit a small amount of liquid at a precise location. However, the process differs in that the jetted pigment droplet utilized in 2D printing is substituted with a photopolymer that solidifies via ultraviolet activation shortly after deposition. Repeated passes of photopolymer deposition build up an object's height. Typically, 3D printed objects created via this method are created from a combination of at least 2 materials: a "build" material and a "support" material. Build material produces the desired geometry, whereas support material is sacrificial and only serves to support overhangs and voids during the printing process. Postprocess, the support material is separated from the build material via high-pressure water to reveal the target geometry.

Three-dimensional printed haptic models allow surgeons, students, and pet owners to develop a superior understanding of anatomical features, through tactile and visual spatial feedback. The ability to interact directly with a custom model of patient-specific anatomy and pathology is expected to improve preoperative planning.[13] The application and benefits of 3D printing in OMFS in humans have already been demonstrated.[17-20] In a recent review of 103 articles dealing with 3D printing in the human medical field, 5 of the included articles were pertinent to surgical planning, training, and patient education, while 24 discussed 3D printing in the context of bone and craniomaxillofacial reconstruction.[15] The use of 3D printing as a teaching and surgery-planning tool for complex OMFS cases was relatively recently introduced in veterinary medicine.[6,8,21]

The present study reports the application of 3D printing in advanced OMFS in dogs and cats and discusses the benefits of this modality with regards to surgical planning, resident and student training, as well as client communication.

2 | MATERIALS AND METHODS

All previously manufactured 3D printed skulls used by the Dentistry and Oral Surgery Service at the William R. Pritchard Veterinary Medical Teaching Hospital of the University of California–Davis were saved in a catalogued library. The pet's name and medical record number were notated on the individual containers housing the models. The 3D printed skulls were examined, and patient medical records were reviewed. The following information was gleaned from the medical records of patients with 3D printed skulls (summarized in Table 1): species, breed, patient age at time of CT scan, patient weight at time of CT scan, diagnosis (reason for 3D printing), and surgical procedure performed.

Transverse, 0.625-mm, collimated CT images of the head were obtained for all patients before surgery. The CT was performed using a LightSpeed 16 (GE Healthcare, Milwaukee, Wisconsin) CT scanner with kVp = 120 and auto-mA. The CT DICOM files were then converted to a 3D stereolithography (STL) format, using an automated script within the software package InVesalius 3.0 (Ministry of Science and Technology, Campinas, Brazil). Following this conversion, the data were represented as a 3D mesh defined

TABLE 1 Demographics and clinical presentation of patients with 3D printing of the skull

Species	Breed	Age (years)	Weight (kg)	Diagnosis	Surgical procedure performed and comments
Dog	Rough Collie	10	25.7	Bilateral rostral mandibulectomy for squamous cell carcinoma	Mandibular reconstruction
Dog	Labrador Retriever/Chow mix	11	25	Rostral mandibular squamous cell carcinoma	Mandibulectomy but reconstruction never pursued
Dog	Smooth Collie	0.75	22.5	Bilateral mandibulectomy to treat gunshot wound	Mandibular reconstruction
Dog	Golden Retriever	11	29	Segmental mandibulectomy for peripheral odontogenic fibroma	Mandibular reconstruction
Dog	Labrador Retriever	4	24.6	Bilateral rostral mandibulectomy for papillary squamous cell carcinoma	Mandibular reconstruction
Dog	Standard Poodle	9	22.2	Bilateral rostral mandibulectomy for peripheral odontogenic fibroma	Mandibular reconstruction
Dog	Labrador Retriever	11	32	Bilateral rostral mandibulectomy for canine acanthomatous ameloblastoma	Mandibular reconstruction
Dog	German Shepherd	8	40	Segmental mandibulectomy for canine acanthomatous ameloblastoma	Mandibular reconstruction
Dog	Chow	5	22	Segmental mandibulectomy for canine acanthomatous ameloblastoma	Mandibular reconstruction
Dog	Australian Shepherd	8	34	Bilateral rostral mandibulectomy for canine acanthomatous ameloblastoma	Mandibular reconstruction
Dog	Norwegian Elkhound	8	25	Bilateral rostral mandibulectomy for canine acanthomatous ameloblastoma	Mandibular reconstruction
Dog	Husky	4	35.3	Bilateral rostral mandibulectomy for peripheral odontogenic fibroma	Mandibular reconstruction
Dog	Poodle mix	1	5.7	Defect nonunion of the caudal mandible	Mandibular reconstruction
Dog	Miniature Poodle	Young adult	4.3	Defect nonunion caudal mandibular fracture	Mandibular reconstruction
Dog	Chihuahua	5	3.6	Defect nonunion caudal mandibular fracture	Mandibular reconstruction
Cat	DSH	5	5.6	Defect nonunion caudal mandibular fracture	Mandibular reconstruction

(Continues)

TABLE 1 (Continued)

Species	Breed	Age (years)	Weight (kg)	Diagnosis	Surgical procedure performed and comments
Dog	Doberman	5	30	Defect nonunion mandibular fracture secondary to gunshot wound	Mandibular reconstruction
Dog	Chihuahua mix	0.6	4.3	Defect nonunion mandibular fracture	Mandibular reconstruction
Dog	Lhasa Apso	13	8.3	Bilateral defect nonunion mandibular fractures	Bilateral mandibular reconstruction
Cat	DSH	10	3.1	Defect nonunion caudal mandibular fracture	3D printing elucidated decision to recommend against surgery
Dog	Golden Retriever	1.5	7.7	Craniomandibular osteopathy causing secondary TMJ ankylosis	3D printing in part elucidated decision to recommend against surgery
Dog	Mastiff	0.33	19.2	Temporomandibular pseudoankylosis	Maxillary and mandibular ostectomy
Dog	Pit Bull Terrier	1	21.1	Pseudoankylosis of left temporomandibular joint secondary to trauma	Zygomectomy/coronoidectomy
Dog	West Highland White Terrier	6	7	Craniomandibular osteopathy causing secondary TMJ ankylosis and pseudoankylosis	Segmental mandibulectomy
Cat	DSH	0.67	2.8	Acquired palatal defect (electrocution injury)	3D printing in part elucidated decision to recommend against surgery
Dog	Golden Retriever	0.67	19.8	Congenital palatal defect	Palatal defect repair
Dog	French Bulldog	0.75	10.3	Congenital palatal defect	Palatal defect repair
Dog	Cavalier King Charles Spaniel	10	12.1	Caudal maxillary squamous cell carcinoma	Caudal maxillectomy
Dog	French Bulldog	10	17.2	Multilobar osteochondrosarcoma at zygomatic arch and maxillary bone	Multiple palliative debulking surgeries
Cat	DSH	6	9.2	Mandibular periosteal osteoma	Marginal excision of osteoma
Dog	Mixed breed	Young adult	11.8	Severe maxillofacial trauma—loss of majority of maxillary and nasal bones	Salvage skin flap procedure
Dog	Pit Bull Terrier	4	24.7	Historic maxillofacial trauma, with recurrent conjunctival inclusion cyst	Orbitectomy/zygomatectomy

Abbreviations: 3D, three-dimensional; TMJ, temporomandibular joint.

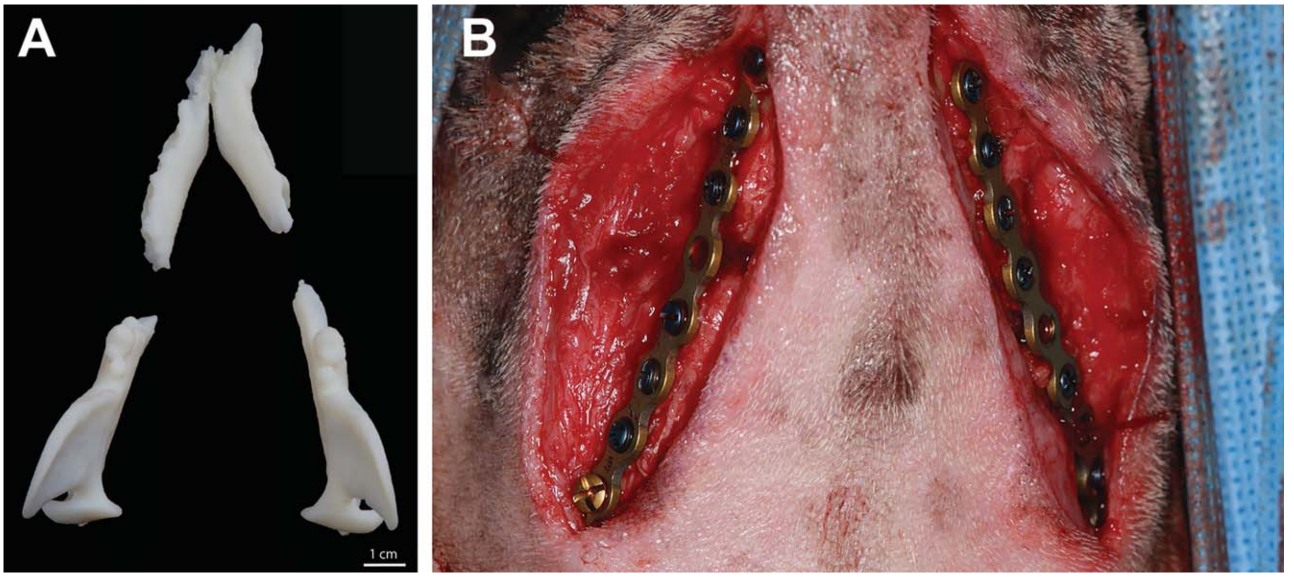

FIGURE 1 Bilateral defect nonunion mandibular fractures in an 8.3 kg, 13-year-old dog. A, Photograph of the 3D printed mandible intervention used for preoperative planning. B, Intraoperative photograph of the same dog after placement of titanium plates; the titanium plates were contoured to the 3D printed mandible preoperatively (dog is in dorsal recumbency, with the rostral aspect pointing toward the top of the image)

by points connected into triangular faces to create surfaces, which was necessary for reconstruction and 3D printer interpretation.

Upon completion of definition of target geometry into an STL mesh, the files were digitally inspected for imperfections in the form of holes, flipped triangular faces, and other defects that may result in errant printer interpretation. This process was typically accomplished by a series of automated error-checking scripts in the software package Netfabb (Autodesk Inc, San Rafael, California), but manual repairs were required in extreme cases.

After each mesh was corrected of defects, it was uploaded to the 3D printer's proprietary software package Objet Studio (Stratasys, Rehovot, Israel). The role of this software is to assign materials, orient the model, and divide the model into a series of horizontal 2D slices to be sent to the printer for deposition. Each slice included precise x-y plane information for build and support material. The slices ranged in thickness from 16 to 32 microns, depending on printer configuration. The printer utilized was an Objet Connex Polyjet Printer (Stratasys).

3 | RESULTS

Between 2013 and August 2016, 3D models of the skull were printed for 32 patients, including 28 dogs and 4 cats, ranging in age from 0.33 to 13 years (mean 5.7 years, median 5 years).

Indications for 3D model manufacturing included the following: preoperative planning for mandibular reconstruction following mandibulectomy (n = 12 dogs) or defect nonunion fracture (n = 6 dogs, 2 cats), mapping of ostectomy for temporomandibular joint ankylosis or pseudoankylosis (n = 4 dogs), assessment of palatal defects (n = 2 dogs, 1 cat), enhanced conception of complex anatomy in cases of neoplasia located in a challenging area (n = 2 dogs, 1 cat), and in cases of altered anatomy secondary to trauma (n = 2 dogs).

The most common indication for 3D printing was to assist in the planning of mandibular reconstruction. Of the 20 patients with this indication, 12 dogs had 3D models printed in anticipation of mandibular reconstruction secondary to mandibulectomy, while 6 dogs and 2 cats had 3D models printed in anticipation of mandibular reconstruction secondary to defect nonunion fracture(s) (Figure 1). Eighteen of 20 pets subsequently underwent mandibular reconstruction. Mandibular reconstruction was abandoned after the 3D printed skull was created in 2 cases, based on client's preference or surgeon's recommendation. For example, 3D printing of a cat's skull enabled surgeons to realize prior to surgery that the caudal fragment of the mandibular defect nonunion fracture was too small and thin to adequately accommodate a plate and screws, and thus the client was advised on the low chance of a successful outcome (Figure 2). Perceived benefits of 3D printing for mandibular reconstruction included preplanning the optimal surgical approach; selecting a specific titanium locking plate in advance, which allows for better cost estimate to relay to the client and ensures the necessary plate is stocked and available; and precontouring the plate to fit based on the 3D printed model. For reconstruction of bilateral rostral mandibulectomy sites, the plate was precontoured to the 3D model after

FIGURE 2 Defect nonunion mandibular fracture in a 3.1 kg, 10-year-old cat, after failed fracture fixation. Photograph of the 3D printed mandible, showing the lateral aspect of the right mandible. The 3D model was printed to-scale, allowing surgeons to conclude that the caudal fragment was too small and thin for screw placement, prompting a guarded prognosis for successful surgical outcome

mandibulectomy was simulated by amputating the rostral mandibles of the 3D model. For reconstruction of segmental mandibulectomy sites or defect nonunion fractures, computer-assisted mirroring of the contralateral intact mandible was utilized to print the model with an intact mandible onto which the plate could be contoured in advance of surgery (Figure 3).

Ankylosis or pseudoankylosis of the temporomandibular joint is a relatively rare condition diagnosed in pets that causes debilitating decreased range of motion of that joint, possibly due to previous trauma, craniomandibular osteopathy, or neoplasia. This condition affected 4 dogs in our population, for which 3D printed models allowed precise planning of the location of the ostectomy, potentially decreasing morbidity and mortality.[8]

Three-dimensional printing was not performed in every case of acquired or congenital palatal defect that was surgically treated during this time period. However, 3D printing was selected in 2 dogs and 1 cat, based on particularly dramatic and challenging palatal defects (Figure 4). The 3D printing led to the recommendation against surgical repair in 1 of the cases and to pursue surgical repair in the other 2 cases.

Our population includes 3 cases of neoplasia affecting an area challenging to access surgically, prompting the manufacture of 3D printed skulls to enhance the surgeons' conception of complex anatomy preoperatively. One case consisted of a squamous cell carcinoma of the right caudal maxilla of a dog, another involved a multilobar osteochondrosarcoma of the right caudal maxilla of a dog, and the third involved a sizable periosteal osteoma on the lateral aspect of the left mandible of a cat (Figure 5). These 3 patients underwent surgery, the former achieving surgical cure and the latter 2 with a goal of marginal excision. The benefits of 3D printing in these cases included thorough preoperative planning of the surgical approach, and assistance with client communication, in order to establish realistic expectations and goals of surgical intervention.

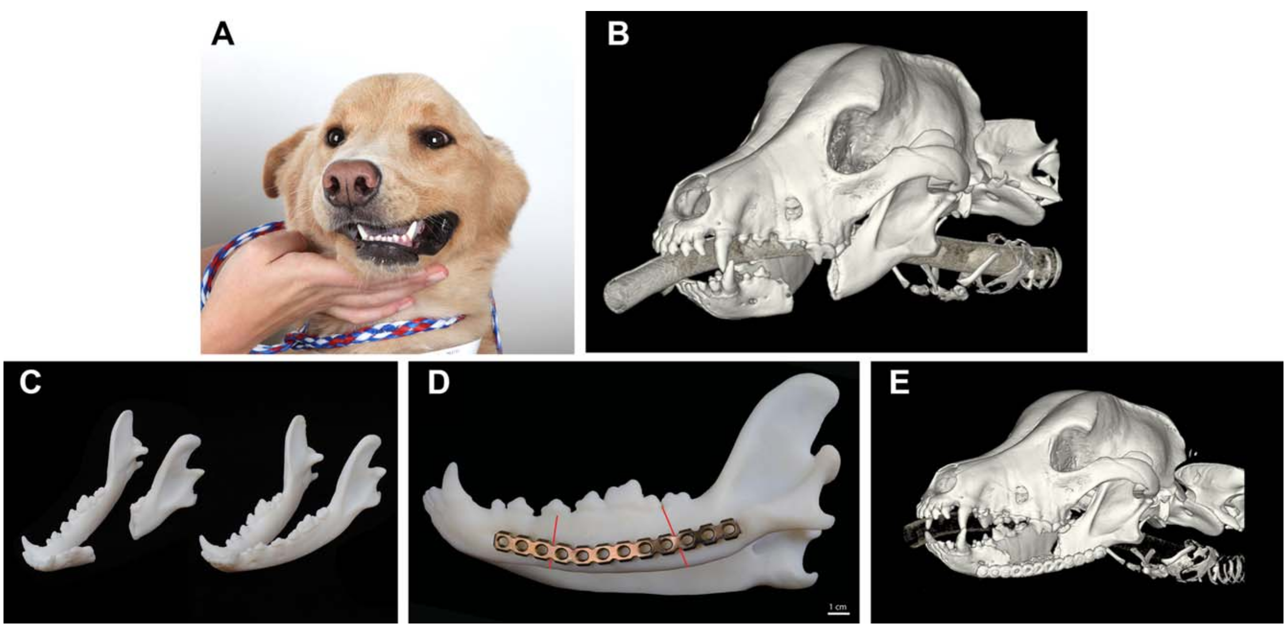

FIGURE 3 Left mandibular segmental defect in a 22 kg, 5-year-old dog, after excision of a canine acanthomatous ameloblastoma via segmental mandibulectomy. A, Photograph of this dog prior to mandibular reconstruction. Note the significant malocclusion. B, Preoperative digital volume rendering image of the dog. C, Photograph of 3D printed mandibles of this dog, showing the pre-existing left mandibular segmental defect on the left. The 3D model on the right was derived from computer-assisted mirroring of the contralateral intact right mandible to simulate the intact anatomy. D, Photograph of the left lateral aspect of the 3D printed mandible in image "C," illustrating how the 3D printed model is used to pre-contour a titanium plate before surgery. Red lines indicate previous osteotomy sites. E, Digital volume-rendering image of this dog, immediately after mandibular reconstruction

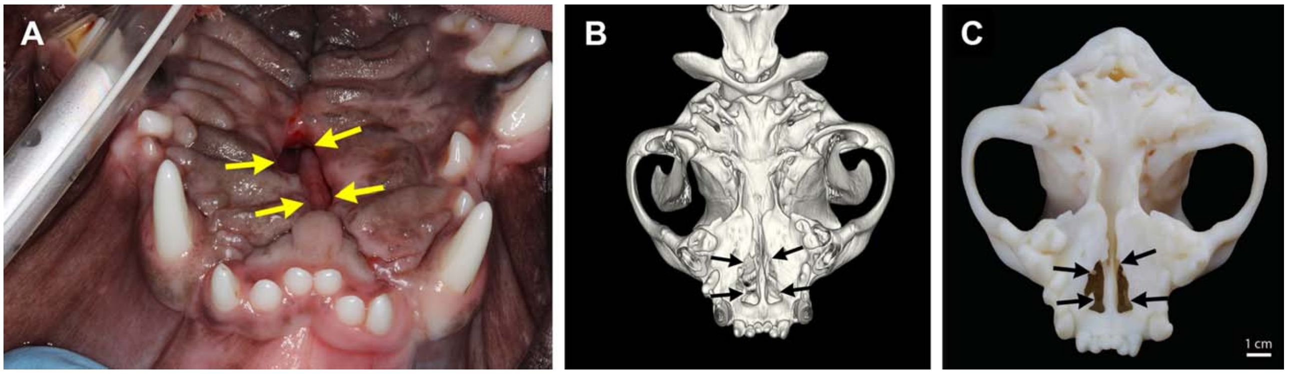

FIGURE 4 Cleft of the secondary palate in a 10.3 kg, 9-month-old dog. A, Preoperative photograph of the cleft palate. B, Manipulated computed tomography DICOM files to create a digital volume-rendering image of this dog. C, Photograph of the 3D printed skull of this dog, where the cleft is significantly larger than initially appreciated on clinical examination. In all images, arrows point to the margins of the cleft defect. Figure 4A,B reprinted with permission from Peralta S, Nemec A, Fiani N, Verstraete FJM. Staged double-layer closure of palatal defects in dogs: 6 cases (2006-2012). *Vet Surg*. 2015;44(4):423-431

Unique anatomy secondary to maxillofacial trauma prompted the manufacture of 3D printed models in 2 dogs. One dog was bitten in the face as a puppy, resulting in malocclusion and ocular trauma; the dog was subsequently presented to us for orbitectomy and zygomectomy to access and excise a conjunctival inclusion cyst in the region of its previously enucleated eye. The other dog suffered maxillofacial trauma resulting in the loss of the majority of the maxillary and nasal bones; skin flaps were used for salvage reconstruction. In these instances, 3D printed models enhanced anatomic conception and surgical planning.

4 | DISCUSSION

The present study reports on the benefits and indications of 3D printing in veterinary OMFS. In the authors' experience, 3D printed models improve preoperative planning and intraoperative guidance, enrich veterinary student and resident training, and facilitate client education and communication.

4.1 | Preoperative planning

The 3D printing offers surgeons a precise, custom model that enables them to tailor a surgical plan with added confidence.[15] Surgical steps can be simulated in advance,[11,19,22] such as planning of osteotomy lines and precontouring titanium locking plates for mandibular reconstruction. Jiang et al utilized 3D printed skulls to draw osteotomy lines as part of the preoperative planning of total inferior border ostectomy in their patients.[23] Similarly, we have used 3D printed skulls to draw osteotomy lines as part of the preoperative planning of small animals undergoing surgical treatment of temporomandibular joint pseudoankylosis/ankyloses. This diagnostic tool enabled us to reach a consensus on the surgical approach and plan. Cohen et al[24] described some of the benefits of 3D printing for mandibular reconstruction surgery in man, specifically the ability to select and contour titanium reconstruction plates preoperatively, thereby reducing surgical time[25] and plate handling. In agreement with these reports, we have used 3D printed skulls for precontouring reconstruction plates in 19 patients; in the authors' experience, preselecting and pre-contouring

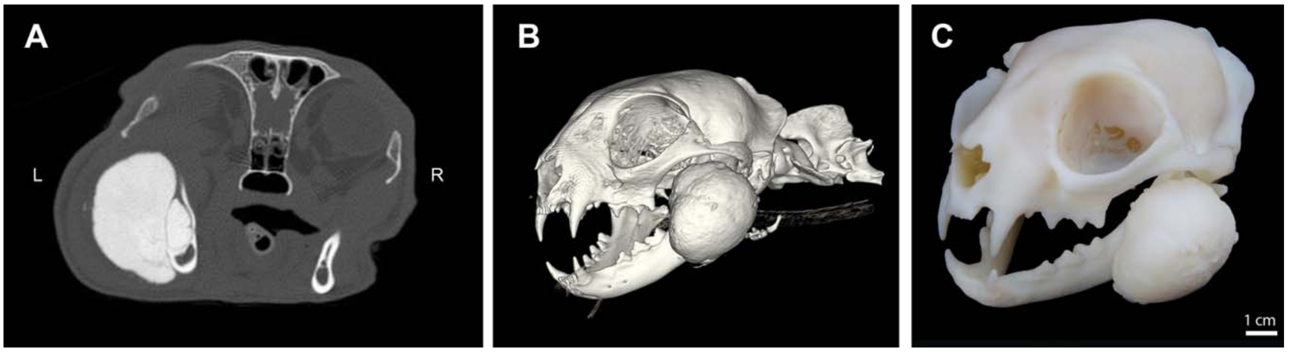

FIGURE 5 Left mandibular periosteal osteoma in a 9.2 kg, 6-year-old cat. A, Transverse section of the preoperative CT study, obtained at the level of largest diameter of the left mandibular periosteal osteoma. B, Digital volume rendering image of the same cat. C, Photograph of the corresponding 3D printed skull used by surgeons to plan their surgical approach and plan for marginal excision

titanium plates save at least 15 minutes of time in the operating room.

4.2 | Intraoperative guidance

Computers and monitors allow surgeons to view preoperative CT studies while operating, but these images only offer a 2D perspective of a 3D structure. The 3D printed replicas of a patient's anatomy may be brought into the operating room and accurately represent the skeletal anatomy underlying soft tissues.[26] Combined with superior preoperative planning, intraoperative guidance derived from 3D printed models has been shown to reduce intraoperative hemorrhage[13,24] and surgical time,[26-28] thereby shortening duration of general anesthesia and wound exposure.

4.3 | Training of veterinary students and residents

Acquiring knowledge of the surgical anatomy and the topographical relationship of anatomical structures are intrinsic components of student and resident training. Traditionally, this information is accessed via textbook and dissection of cadaver specimens, with further expertise gained through surgical experience on living patients.[11,15] One limitation of such approach is that anatomy textbooks and cadaver dissection primarily portray normal anatomy, whereas OMFS is often performed in areas of anatomy effaced by congenital defects, trauma, or neoplasia; 3D printing can overcome this limitation by providing haptic models of custom anatomy. These models allow visual and tactile senses to synergistically enhance the understanding of challenging anatomical and pathological conditions.[29] The incorporation of 3D printing in the training of neurosurgeons,[30] cardiothoracic surgeons,[31] urologists,[32] and general surgeons is well documented.[13] In addition, a program at the University of North Carolina at Chapel Hill has relied on 3D printing to create patient-specific models specifically designed to train surgical residents.[29] Training students and residents for patient-specific procedures using custom-designed anatomy models is expected to facilitate and improve their understanding of complex OMFS procedures, while potentially reducing the need for cadaver specimens, as well as morbidity and mortality in patients.

4.4 | Client education and communication

Veterinary OMFS aims at preserving or improving the patient's quality of life while managing and meeting clients' expectations. Preoperative discussion should include, but is not limited to, possible complications, expected esthetic outcome, and anticipated functional outcome. Clients lacking medical background may find traditional 2D CT difficult to understand. By contrast, 3D-printed models enhance a client's understanding of the condition, treatment plan, and intended outcome, thus serving to bolster informed consent.[13] By viewing and holding an accurate representation of their pet's unique pathology, a client is likely to reach a deeper understanding of the need for OMFS, its potential associated risks, its envisioned outcome, and the level of skill exercised by the veterinarian who specializes in OMFS.

4.5 | Limitations

Most limitations of 3D printed models are inherent to the manufacturing process itself, such as the time required to produce the 3D model. Depending on the scale of the skull specimen, it typically takes 18 to 24 hours to complete the printing process. This delay implies that the patient will undergo at least 2 anesthetic episodes, to obtain CT images, and to perform surgery. However, the need for 2 separate anesthetic events does not pose a major hurdle, as candidates for 3D printing are generally complex cases that benefit from a staged procedure to allow for thorough diagnosis and surgical planning. Motion artifacts would affect the accuracy of the 3D model, prompting the authors to scan all patients in this study under general anesthesia. However, CT images may be acquired under heavy sedation in certain cases. Another limitation of 3D printed models is that they do not perfectly mimic the detail and texture of the structures.[13] While 3D printing is reliably accurate,[33] the biomechanical properties of living tissues cannot be precisely replicated at present. Furthermore, our 3D printed models solely replicate bony tissues and exclude soft tissues, which must be taken into account when planning the surgical approach and repair. Another limitation is that 3D printing can aid in the determination of surgical margins for tumor excision, but 3D printed models do not show the full microscopic or even macroscopic extent of neoplasia into surrounding osseous and soft tissues, and thus the models must be used in conjunction with the traditional 2D CT images to establish oncologic surgical margins. Finally, the cost of production may be considered a limitation; however, in our experience, clients have agreed to pay the fee for printing 3D models each time this modality has been recommended. Cost is directly proportional to the volume and weight of material expended during the printing process, with the addition of an hourly rate for machine usage. Following the evolution of other technologies, future advances in 3D printing should decrease production time and cost, as well as improve the realism of replicated tissues.

5 | CONCLUSIONS

Three-dimensional printed models can be produced to serve the needs of veterinary maxillofacial surgeons, enhancing surgical planning, veterinary training, and client communication. This modality is ideally suited for implementation in a collaborative university setting, as the lifecycle from acquisition of diagnostic images to production of a 3D model involves a team of radiologists and radiology technicians, oral and maxillofacial surgeons, computer scientists, material scientists, and biomedical engineers.[11] As the technology continues to improve, 3D printing is destined to rise in applications across all disciplines of veterinary medicine. Our goal is to expand the use of 3D printing in our practice to assess and treat complex cases of maxillofacial trauma, neoplasia, and aberrant anatomy.

ACKNOWLEDGMENT

We thank Dr Chrisoula Toupadakis Skouritakis and Mr John Doval from the Media Laboratory, Department of Surgical and Radiological Sciences, University of California, Davis, for the artwork.

CONFLICT OF INTEREST

The authors report no financial or other conflicts related to this report. The authors do not have conflict of interest with any of the materials or companies described in the manuscript.

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How to cite this article: Winer JN, Verstraete FJM, Cissell DD, et al. The application of 3-dimensional printing for preoperative planning in oral and maxillofacial surgery in dogs and cats. *Veterinary Surgery*. 2017;00:000-000. https://doi.org/10.1111/vsu.12683