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Ancillary procedures necessary for translational research in experimental craniomaxillofacial surgery

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Abstract

Introduction—Swine are often regarded as having analogous facial skeletons to humans and therefore serve as an ideal animal model for translational investigation. However, there's a dearth of literature describing the pertinent ancillary procedures required for craniomaxillofacial research. With this in mind, our objective was to evaluate all necessary procedures required for peri-operative management and animal safety related to experimental craniomaxillofacial surgical procedures such as orthotopic, maxillofacial transplantation.

Methods—Miniature swine (n=9) were used to investigate peri-operative airway management, methods for providing nutrition, and long-dwelling intravenous access. Flap perfusion using near-infrared laser angiography and facial nerve assessment with EMG were explored.

Results—Bivona(R) tracheostomy was deemed appropriate versus Shiley since soft, wire-reinforced tubing reduced the incidence of tracheal necrosis. PEG tube, as opposed to esophagostomy, provided a reliable route for post-operative feeding. Femoral venous access with

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dorsal tunneling proved to be an ideal option being far from pertinent neck vessels. Laser angiography was beneficial for real-time evaluation of graft perfusion. Facial EMG techniques for tracing capture were found most optimal using percutaneous leads near the oral commissure. Experience shows that ancillary procedures are critical and malpositioning of devices may lead to irreversible sequelae with premature animal death.

Conclusion—Face-jaw-teeth transplantation in swine is a complicated procedure which demands special attention to airway, feeding, and intravascular access. It is critical that each ancillary procedure be performed by a dedicated team familiar with relevant anatomy and protocol. Emphasis should be placed on secure skin-level fixation for all tube/lines to minimize risk of dislodgement. A reliable veterinarian team is invaluable and critical for long-term success.

Keywords

Swine study; Face transplant; Translational study; Craniofacial; Craniomaxillofacial; Ancillary procedure; PEG tube; Hickman catheter; Tracheostomy; Laser angiography; Facial electromyography; Maxillofacial Transplant

Introduction

Craniomaxillofacial surgeons and researchers alike are constantly seeking new innovations for improved outcomes in both pediatric and adult patients (1-3). As such, large animal studies often serve as the ideal vehicle for scientists and engineers testing novel concepts and techniques (4,5). Unfortunately, translational research in large animals has been tempered by unfamiliar facial skeletal anatomy coupled with the vital functions affected by orthotopic facial transplant research including breathing, drinking, and feeding (6).

Similar studies by Nobel laureate Joseph Murray relied on a dog model for preliminary kidney transplant investigation (7), while Starzl et al utilized the non-human primate model for early liver transplant studies (8). In parallel, our goal was to investigate the use of ancillary procedures required for experimental craniomaxillofacial surgery such as face-jaw-teeth transplantation. This was a significant challenge given the absence of relevant literature available and thus the impetus for this study. Within this manuscript, we describe the main challenges encountered and propose remedies for the establishment of a pre-clinical swine model.

Materials and Methods

This study was initiated in September 2011 following approval from our institution's Animal Care and Use Committee (ACUC) and has been conducted in strict accordance with the NIH guidelines for the Care and Use of Laboratory Animals. Male and female Yucatan miniature swine (n = 9) weighing between 10-20 kilograms were used. All animals were sedated using 15 mg/kg Ketamine (100 mg/mL concentration, Lake Forest, Illinois) and 1mg/kg Xylazine (Anased(R), Shenandoah, Iowa) intramuscularly and maintained with a mixture of isoflurane and oxygen (2-3 L/min). Continuous heart rate, blood pressure and respiratory functioning were monitored throughout all phases of anesthesia and recovery.

A multidisciplinary craniofacial team within our university was established with collaboration from Research Animal Resources, which included veterinarians and technicians. Preliminary swine cadaver studies were led by the study's principal investigator [C.G.] and revealed relevant anatomical discrepancies in comparison to humans. Regular discussions followed prior to the first live surgery. Original planning included the use of a human Shiley tracheostomy device for airway management (9), an esophagostomy tube for feeding based on previous investigations in feline (10), and a tunneled intravenous external jugular vein catheter (11). Intra-operative near-infrared laser angiography was needed for assistance with alloflap design and concern over facial vascularity (12). Varying pedicle designs and bone cuts for Le Fort-based maxillofacial transplantation were assessed due to the novelty of the procedure [Figure 1]. With a secondary goal being to assess long-term facial motor recovery post-transplant (13), facial electromyography was trialed on a limited basis using elementary half-face skin dissections in an effort to define ideal facial muscle targets for needle stimulation and corresponding topographic locations for lead placement.

Technical Details

After sterile prep, a 2 cm midline incision was made over the larynx. The subcutaneous tissue, cutaneous coli, and sternohyoideus muscles were retracted and a puncture was made within the cricothyroid membrane. The tracheostomy device was inserted through the membrane and the surrounding tissues were closed securely around the device. Numerous stay sutures were placed bilaterally along the trachea with heavy silk to aid replacement if the tube were to become dislodged. Post-operative lateral cephalograms were taken to ensure proper positioning. After surgery, the tracheostomy tube was suctioned both on an hourly schedule and as-needed. Feeding PEG tubes and tunneled femoral vein Hickman catheters were placed using standard technique (11,14).

Results

Overall, this study was challenging given the lack of published research in this field and is the overarching impetus for this publication. The majority of ancillary procedures now being utilized by our team have been improved following numerous practice sessions [Table 1,2]. Following several swine cadaver/plastic model surgeries ($n = 5$), three live surgeries were completed to assist our engineering colleagues in developing a novel Computer-assisted Planning and Execution (CAPE) system. All major dental, skeletal and aesthetic inconsistencies were overcome using the technology in light of a major size mismatch between donor and recipient (4-6). However, all three face-jaw-teeth transplant recipients suffered premature death related to ancillary procedures - thereby demonstrating the need for further research.

The first swine recipient expired towards the completion of the procedure due to an airway-related complication as the final bone cuts were being made in preparation for transplantation. The second recipient survived the face-jaw-teeth allotransplant overnight, but expired on post-operative day one due to complications surrounding the femoral intravenous catheter. This originated from inadvertent displacement and resulted in compartment syndrome/hind limb ischemia. On recovery, the animal demonstrated hind

limb paralysis necessitating decompressive fasciotomy. Although urgent fasciotomy restored perfusion, the additional anesthesia was lethal and the animal expired on post-operative day one.

The third animal survived face-jaw-teeth transplantation but also expired on post-operative day one. This premature death was related to a complication surrounding the PEG tube. At some point during recovery and moving the animal back into the cage, the PEG tube became dislodged. Soon thereafter the swine expired on post-operative day one during anesthesia induction for revisional gastrostomy surgery. Of note, the transplant itself was technically successful with adequate perfusion at the end of the operation and assisted us greatly in gathering valuable data for our team's technology development. As expected, the face-jaw-teeth alloflap demonstrated gravity-related venous congestion. Efforts surrounding computer-assisted surgery and cutting guide modifications helped to improve reconstructive outcomes in both the second and third live surgeries (4-6) [Figure 2]. In summary, all three peri-operative complications (i.e. central line, feeding tube, airway obstruction) were independent of the actual face-jaw-teeth transplant (3/3, 100%).

Airway Experience

The first surgery used a standard Shiley tracheostomy as previously described (9). However, intra-operatively, it was realized that the human Shiley appliance had a sub-optimal fit, specifically due to the swine's large amount of subcutaneous fat and significant anterior-posterior (A-P) distance from skin-to-anterior trachea. Although it was possible to ventilate the swine with positive pressure under general anesthesia, the inadequacies of the standard-sized human tracheostomy manifested themselves when the swine began to awaken and flex/extend its neck.

The swine trachea is different from humans - it is angulated and does not run parallel to the external neck as expected. It courses deeply towards the thorax at a more obtuse angle away from the external neck. Moreover, the axis of neck flexion in the swine is more inferior as compared to a human, and in this case series, in relatively close proximity to the tracheostomy site. This may result in frequent pressure of the rigid device against the posterior tracheal wall during extreme neck movements. In this particular face transplant model, the infraorbital nerve is divided during harvest of the face-jaw-teeth alloflap. This results in diminished mid-facial sensation, which may lead to forceful head movements against the cage for assistance with proprioception. As such, a swine with a firm human Shiley appliance may be at high risk for posterior tracheal wall necrosis due to repetitive neck rotation [Figure 3].

Moving forward, we switched to an extra-large Shiley tracheostomy appliance (Covidien Shiley, Mansfield, MA) (common size used for a morbidly obese patient) with an increased length and more obtuse curvature. It was hypothesized that the increased A-P distance between the flange and cuff and the overall length would help to accommodate the increased amount of subcutaneous tissue [Figure 4]. Despite being of appropriate length and angle, the rigidity of the plastic tubing was again suspicious for posterior tracheal wall necrosis. Therefore, we changed to a soft, wire-reinforced, non-compressible, plastic Bivona^(R) custom order appliance (Smiths Medical, Dublin, OH) [Figure 5]. This modification proved

efficacious and to date remains our preferred option for peri-operative airway management [Supplemental Video **Submission 1**].

Feeding Tube Experience

The original plan was to use an esophagostomy tube based on reports related to ease-of-placement and low rate of complication (10). During the first experiment, a red rubber catheter was placed for esophageal access through a lateral stab incision. The 14F catheter was passed along the lateral neck down within the esophagus and sewn securely into position. However, upon recovery from anesthesia, the animal began to cough repeatedly with force and the tube became retroflexed through the mouth (rather than descending distally within the esophagus towards the stomach). Therefore, for the next surgery we switched to a percutaneous endoscopic gastrostomy (PEG) tube. This was placed using a pediatric endoscope and seemed straightforward and well tolerated by the swine (N=5). Vigilance is required to maintain proper PEG tube positioning and therefore our team advises the chronic use of a protective jacket [Figure 6].

Femoral Intravenous Line Experience

Based on our laboratory's experience with swine hind limb transplantation, a tunneled Hickman intravenous catheter was selected first and placed within the external jugular vein [Figure 7]. The dorsal tunneling was effective in preventing self-induced trauma by the swine (11). However, as the Le Fort-based facial alloflap was being designed, it was noted that the alloflap's inflow/outflow design and necessary anastomoses were dependent on the neck's venous drainage system. Therefore, all other options were considered including the subclavian and/or femoral veins. After careful consideration, the femoral vein was selected in an effort to preserve the head and neck venous drainage system [Figure 8]. Femoral lines have several drawbacks including the need for a longer tunneling distance (from groin-to-dorsum as compared to neck-to-dorsum). Subcutaneous tunneling is mandatory since groin catheters are at risk for kinking during ambulation and remain vulnerable to damage or removal by the animal (i.e. chewing).

Laser Angiography Experience

The SPY Intra-operative Perfusion Assessment System (LifeCell Corp., Branchburg, NJ) allows monitoring of tissue perfusion and venous outflow using intravascular injection of the fluorescent dye indocyanine green (ICG) and visualization with a near-infrared laser (12). For the Le Fort-based, face-jaw-teeth alloflaps, perfusion of both hemi-faces was present on three consecutive occasions. Most importantly, the snout being the farthest area from the pedicle showed perfusion from bilateral pedicle inflow [Figure 9].

Facial Electromyoneurography (EMG) Experience

A half-face dissection was performed to identify the surface landmarks corresponding to the underlying facial musculature and for topographical assessment of ideal needle electrode placement [Figure 10]. Both surface and percutaneous electrodes were studied. An ADInstruments electrophysiology system (Colorado Springs, CO) was employed to assess compound muscle action potential (CMAP) recordings over time in hopes of establishing a

protocol for assessing neuromuscular recovery following maxillofacial allotransplant. CMAPs were recorded pre-operatively from snout musculature of the donor/recipient swine using percutaneous needle electrodes following stimulation of the facial nerve trunk [Figure 11]. This taught us that the *depressor rosti*, *depressor labi superioris* and *labial depressor* muscles are best stimulated in a location along the oral commissure - as a means of testing the buccal branch of the facial nerve.

Discussion

Basic science research draws from a variety of avenues including both small and large animals (13, 15-20). However, in order for surgeons and biomedical engineers to collaborate, develop, and enhance futuristic modalities related to computer-assisted technology, larger-scale anatomy is required. Therefore, researchers looking to improve outcomes in craniofacial surgery should be encouraged to first assess safety and reliability of new techniques in large animal laboratories (4-6) [Figure 12].

Because of the numerous reasons noted throughout the literature, those planning to engage innovative developments in craniomaxillofacial surgery are likely to choose swine [Table 3] (21-23). Similarly, our laboratory was able to develop a preliminary platform, referred to as a Computer-assisted Planning and Execution (CAPE) system (4-6) with full translational capabilities [Figure 16]. Although cadaveric swine and human surgeries were advantageous in the beginning, the live swine surgeries (n=3) were much more revealing to the engineers and non-clinicians with respect to pre-clinical expectations and acquiring knowledge/insight related to dynamic musculoskeletal impedance.

Rigor mortis, found in all cadavers (human and swine), limits real-time assessment of obstacles related to the masticatory muscles - which are pertinent in many areas of craniomaxillofacial surgery including face-jaw-teeth transplantation. It behooves the craniofacial researcher to learn from our experience presented here. As expected, our successes and failures have required an exorbitant amount of time, energy, manpower, and grant funding, and therefore it is incumbent to share these experiences for the betterment of the specialty.

The welfare of all laboratory animals remains top priority and thus developing these ancillary procedures in the future will ultimately improve safety. Swindle writes that “*a successful tracheostomy can be placed in the dorsal recumbent position at the preferred level of the cricothyroid membrane*” in swine (21). However, there are no descriptions of the appliance chosen and/or guidance on proper size or length, which may be because this type of survival surgery has not yet been attempted. There are also no recommendations on long-term maintenance of tracheostomies, no warnings of tube rigidity in swine, and no mention of the tube's propensity for tracheal wall necrosis in the setting of orthotopic Le Fort-based, maxillofacial transplant investigation.

Post-operative airway management for the purpose of craniofacial research is paramount. It was found that continuous suctioning of the tracheostomy with gentle irrigation was required on an hourly basis to prevent obstruction from thick secretions. Unfortunately,

inner-cannulas are not currently available on custom tracheostomies. Animal caretakers must also be well familiarized with techniques for suction clearance in an emergency. A strong portable suction machine should be kept near the swine's cage in the event of mucous plugging. One should also be familiar with human tracheostomy protocols since this particular area is lacking significant research (24).

As for post-operative nutrition, Bollen et al recommends direct gastric intubations for both medicine and nutritional delivery (22). Although this seems viable, research such as ours would require daily sedation for post-operative feeds over weeks/months, which is simply not feasible. Hooda et al supports the use of parenteral amino acid therapy via a central line catheter (23). Although reasonable, this method adds significant cost and labor. As such, we consider the percutaneous gastric tube (PEG) tube to be most appropriate - in that it provides the ideal route for enteral nutrition irrespective of the level of facial transplantation being studied (6). However, one must be aware that inadvertent dislodgement in the peri-operative setting can quickly lead to death. As such, we recommend well-fitting laboratory jackets be worn at all times [Figure 2] (22).

Long-term intravascular access for drug administration and blood sampling is also challenging. Lombardo et al reported success with long-term 11F jugular catheters in swine with a low incidence of infection and thrombosis (26). However, in craniofacial surgery, the external jugular vein/carotid artery anatomy are pertinent for regional perfusion and free tissue transfer anastomoses - thereby making this option less favorable (5, 27, 28).

The use of near-infrared laser angiography was found to be critical for flap design given the swine's skin thickness, and played a vital role in pre-operative planning and intra-operative assessment (11). Although the vascular network of a human's face is well-described and understood, the arterial and venous descriptions of a swine's face are poorly detailed. One valuable finding from this study was the determination of a “*reversed facial-skeletal ratio*” in swine versus humans. The “*maxilla-to-face ratio*” for swine was determined to be much greater and in reverse relation when compared to humans. This is most likely due to the fact that swine have prominent maxillary tuberosities, as compared to humans who have relatively larger faces and smaller maxillae and rely therefore much less on their nose (e.g. snout) for feeding and protection [Figure 17].

For research like ours related to face-jaw-teeth transplantation, these findings are critically important - since those seeking to create a new craniofacial model in swine may assume the common facial artery/vein pedicle design to be feasible (as is most commonly used worldwide for human facial transplants) (29, 30). However, facial alloflaps designed solely on the facial vessels in swine will fail due to their small caliber. Due to the aforementioned “*face-to-maxilla*” ratio imbalance, the swine's internal maxillary vessels are consistently larger and the internal system is much more pertinent for swine facial transplantation. These findings were also elucidated by laser angiography and have allowed us to design an orthotopic maxillofacial transplant model for translational investigation (4-6).

Our experience with facial EMG testing in swine was “eye-opening”. With no available literature, it was difficult to proceed for several reasons including skin thickness and

disproportionate facial muscles (as compared to humans). By completing half-face skin dissections, we found the percutaneous electrodes to be more valuable and effective. This study was able to decipher an ideal location for facial muscle input - just lateral to the oral commissure within the lip depressors, which are innervated by the buccal branch [Figure 10]. One main drawback of facial EMG is its requirement for general anesthesia, which adds significant time and expense. However, for the specialty of craniofacial surgery - such as elucidating patterns of facial nerve recovery status post transplantation (31), this may be worthy and justifiable when coordinated with CT scanning evaluation.

One weakness of this study is its retrospective design and small number of surgeries. However, large quantities and statistical comparison of ancillary procedures would be impractical considering the necessary time, funding, and manpower needed for this type of experiment. We therefore feel that by learning through experimentation and adjusting with each success and failure, one is able to succeed in an area with very little precedence. The goal is to share these valuable lessons with the craniofacial research community so as to facilitate further large animal experiments in Le Fort-based, maxillofacial transplantation (31-33).

Conclusion

The facial skeleton is responsible for providing one's appearance and identity, unlike its overlying soft tissues, and therefore previous animal models evaluating soft tissue-only face transplants will not provide the necessary insight to advance this field. Also difficult is the fact that pre-clinical craniofacial research lends itself to high complications given its close relation to the nose, mouth, trachea, esophagus, and brain. Therefore, it is imperative that all research teams become experts with ancillary procedures related to airway management, feeding tube placement, and central line access. Each one should be practiced by a consistent team of dedicated personnel. Constant collaboration and communication between an experienced craniofacial surgeon and veterinarian staff member is critical for the welfare of the animals and project's long term success. Particular emphasis should be given to protective garments and stay sutures - since tube dislodgement and/or device malpositioning may jeopardize animal survival.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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The views expressed in this article are those of the authors and do not necessarily reflect the official policy, position, or endorsement of the Department of the Navy, Army, Department of Defense, nor the U.S. Government.

Appendix 1

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Figure 1.
Illustration depicting various levels of Le Fort-based, maxillofacial transplantation in swine as similar to humans.

Figure 2. Photograph of swine on post-operative day one following Le Fort-based facial transplant. Custom Bivona tracheostomy being well tolerated while ambulating. Maxillofacial transplant is viable on exam with gravity-related congestion. This animal expired prematurely due to a complication surrounding PEG tube dislodgement.

Figure 3. Posterior tracheal wall necrosis found during necropsy after using standard Shiley tracheostomy (*blue arrow*).

Figure 4.
Challenging tracheostomy insertion due to increased amount of subcutaneous tissue with skin-to-trachea distance around 6 cm.

Figure 5. Intra-operative markings for Bivona tracheostomy placement (*top left*), actual placement with bilateral tracheal stay sutures in place (*top right*), animal on x-ray table following completion (*bottom left*), and final x-ray confirming acceptable placement (*bottom right*).

Figure 6. PEG tube placement by two-surgeon team (*top center*), fiberoptic pediatric endoscope inserted and fundus location is visualized with abdominal wall trans-illumination (*bottom left*), and PEG tube being sewn securely to abdominal wall (*bottom right*).

Figure 7. Hickman catheter inserted into left external jugular vein (*left*) and tunneled dorsally with protective wrap in place (*right*).

Figure 8. Right femoral Hickman catheter placed (*left*) and then tunneled dorsally with skin-level stay sutures (*right*).

Figure 9.

Near-infrared laser angiography showing perfusion to snout. Left-sided neck vessels have been divided in preparation for transplant [top center]. Quantitative analysis image [bottom left] and color depictions are also shown for direct correlation [bottom right].

Figure 10. Half-face facial dissection showing placement of electrode into *depressor labii superioris* and *depressor rostris* muscles.

Figure 11.
Electromyography (EMG) of right facial nerve in swine being performed (*left*) and simultaneous tracing (*right*).

Figure 12.

Frontal view of swine recipient following successful orthotopic Le Fort-based, maxillofacial transplantation as similar to humans. Microvascular anastomoses have been completely bilaterally in the neck in addition to bilateral facial nerve reconstruction.

Figure 13.

Plastic models are utilized pre-operatively for the development of innovative strategies related to CAPE system, which has been shown to optimize skeletal alignment, aesthetic harmony, and dental relation in the setting of a large size-mismatch discrepancy between donor and recipient.

Figure 14.

Three-dimensional CT scan demonstrating optimal skeletal alignment and dental relation status post face-jaw-teeth transplant in the setting of a large size-mismatch between donor and recipient. Custom Bivona tracheostomy is also seen in position.

Figure 15. Left-sided oblique intra-operative views of a Le Fort-based, maxillofacial transplant completed in a live swine recipient (*left*) and human cadaver recipient (*right*).

Figure 16.

Panoramic, intra-operative photograph demonstrating the use of surgical navigation on the near side in conjunction with novel CAPE system. On far right side, the engineering team from the Johns Hopkins University Applied Physics Laboratory employs a laptop computer and Polaris camera for immediate surgeon feedback. This type of complex surgery requires two large surgical teams working simultaneously, as identical to human facial transplantation.

Vascular anatomy

- 1 Maxillary v.
- 2 Linguofacial v.
- 3 Transverse facial v.
- 4 Superficial temporal v.
- 5 External carotid a.
- 6 Internal carotid a.
- 7 Nasofrontal a.

Figure 17.
Illustration depicting the complex three-dimensional vascular anatomy of a swine's craniofacial skeleton.

Table 1
Advantages and disadvantages of pertinent ancillary procedures applicable to pre-clinical craniomaxillofacial investigation in swine

ANCILLARY PROCEDURE	ADVANTAGES	DISADVANTAGES
<i>Surgical Airway</i>		
Shiley tracheostomy	<ol style="list-style-type: none"> 1 Easy to obtain 2 Relatively low cost 3 Surgeon familiarity 	<ol style="list-style-type: none"> 1 Inadequate spacing for thick subcutaneous tissue in swine 2 Rigid plastic throughout the appliance risking injury to tracheal wall
Bivona® tracheostomy	<ol style="list-style-type: none"> 1 Accommodates large amount of subcutaneous fat in swine neck 2 Can be ordered with various lengths depending on size and age of swine at time of surgery 3 Metal reinforced soft plastic reduces risk of airway collapse and tracheal wall necrosis/perforation 	<ol style="list-style-type: none"> 1 Require custom order 2 Increased relative cost
<i>Feeding Access</i>		
Esophagostomy	<ol style="list-style-type: none"> 1 Relative low cost for red rubber catheter 2 Minimal time for insertion 	<ol style="list-style-type: none"> 1 Poorly tolerated by swine 2 Potential for kinking and malpositioning 3 Neck position is less than ideal for craniofacial research
Percutaneous Endoscopic Gastrostomy (PEG) tube	<ol style="list-style-type: none"> 1 Dependable and constant in terms of function and position 2 Position away from neck and dorsal tunneling is ideal for craniofacial-specific research 	<ol style="list-style-type: none"> 1 Increased cost 2 Technically challenging 3 Requires two-team approach
<i>Intravenous Access</i>		
Cervical tunneled catheter	<ol style="list-style-type: none"> 1 Cervical venous anatomy is constant 2 Neck region is clean 3 More difficult for large animal to chew when in posterior neck position 	<ol style="list-style-type: none"> 1 May interfere with craniofacial research involving jugular vein anatomy 2 If ventral, may be easily chewed or grasped by animal 3 Requires one to get close to the face at times of blood draw and intravenous administration (e.g. risk of being bitten by animal)
Femoral tunneled catheter	<ol style="list-style-type: none"> 1 Remains far from craniofacial surgical site 2 Once tunneled dorsally, it easy to obtain access when animal is standing erect 	<ol style="list-style-type: none"> 1 Requires dorsal tunneling to avoid animal chewing 2 Femoral region is more likely to become infected with time

Table 2

Number of animals studied per ancillary procedure.

Procedure	Number of animals
Standard Shiley tracheostomy	N = 1
Extra-large Shiley tracheostomy	N = 1
Bivona tracheostomy	N = 4
Esophagostomy	N = 1
Percutaneous Endoscopic Gastrostomy (PEG) tube	N = 5
External Jugular tunneled catheter	N = 4
Femoral tunneled catheter	N = 2
Laser angiography	N = 4

Table 3

Advantages of using swine as a translational model for Le Fort-based, maxillofacial transplantation and various other areas in craniomaxillofacial surgery.

• Ideal relationship between pterygoid plates, palatine bones and maxillary tuberosities as compared to human skull
• Quick growth of the swine's craniomaxillofacial skeleton with the head size reaching maturity at around eight months
• Bone turnover is equal to humans making the swine critical for bone healing experiments
• Chewing pattern and transmission of the masticatory forces are similar to humans
• Large circulating blood volumes allows for more complex surgeries as opposed to smaller animals
• Massachusetts General Hospital (MGH) swine are uniquely available as a swine leukocyte antigen (SLA)-defined breed - which is ideal (versus other large animals (ie. dogs, non-human primates, sheep) for pre-clinical research in vascularized composite and solid organ transplantation