Proceedings of The National Conference
On Undergraduate Research (NCUR) 2013
University of Wisconsin La Crosse, WI
April 11 – 13, 2013

Three-Dimensional Modeling of the Pediatric Airway

Courtney E. Kodweis
Department of Biomedical Engineering
University at Buffalo, The State University of New York
332 Bonner Hall
Buffalo, New York 14260-1660

Rapid Prototyping Center
Milwaukee School of Engineering
1025 N. Broadway
Milwaukee, WI 53202

Faculty Advisor: Dr. Subha Kumpaty, Ph.D.

Abstract

Alterations of the structure of the airway in pediatric patients can impair the respiratory function of the individual, resulting in several possible life-threatening symptoms. The treatment of such structural anomalies often occurs through surgical intervention or pharmaceutical treatment. Currently, physicians use 2-D images of the airway to develop a plan for surgery and to educate parents on their child's condition. The predisposition of this method for error requires that a new, more efficient model be constructed to allow for more detailed surgical planning and patient/parent education. Furthermore, the complicated nature of upper airway surgery, particularly in children, requires that a model be developed to allow for more extensive, hands-on physician training, prior to commencing surgical intervention. In this research, models of the pediatric airway were constructed using selective laser sintering, an additive manufacturing technique used to build complex models from 3-D data. For this research, high-resolution, minimum slice thickness computed tomography (CT) and magnetic resonance imaging (MRI) scans of both the healthy and defected pediatric airway were acquired. Using the MIMICS (Materialise, Leuven, Belgium) software package, the pediatric airway was isolated from each CT or MRI scan, yielding a 3-D geometric model. The files were then converted from a standard medical imaging file format to the standard transformation language format used by additive manufacturing machines. FreeForm (Sensable, GeoMagic, Willmington, MA) software was then used to smooth the external surfaces of each model, prior to sending it to the machine for build. The models were assessed by physicians via jpeg images. The process for creating three-dimensional models of the pediatric airway from raw image data has been catalogued in this research.

Keywords: selective laser sintering, pediatric airway, three-dimensional model

1. Introduction

The clinical assessment of the pediatric airway is currently dependent upon, and limited to, the capabilities of the various imaging modalities commonly employed in clinical practice. At present, physicians rely on two-dimensional computed tomography (CT), magnetic resonance (MRI) and endoscopic images, to mentally reconstruct the three-dimensional airway for assessment, diagnosis, and treatment planning purposes. While necessary, this method is pre-disposed to human error and has the capacity to result in further patient health complications due to insufficient treatment and/or incorrect diagnosis. The objective of this research is to develop a process for creating highly-

accurate, patient-specific three-dimensional models of the pediatric airway to be used, in conjunction with medical images, in clinical practice for educational, training, and treatment planning purposes.

2. Background

2.1. The Pediatric Airway

The pediatric airway, in the most basic sense, is made up of the nasal cavity, pharynx, larynx, trachea, bronchi and alveoli. Physiologically, these structures are responsible for supplying life-sustaining oxygen to the blood stream, while simultaneously clearing toxic carbon dioxide from the body[1]. As a result, structural defects and diseases, in any of these structures, can have severe consequences and, in some cases, may be life-threatening. Figure 1 shows a labeled drawing of the pediatric airway that may be referenced throughout this paper's review.

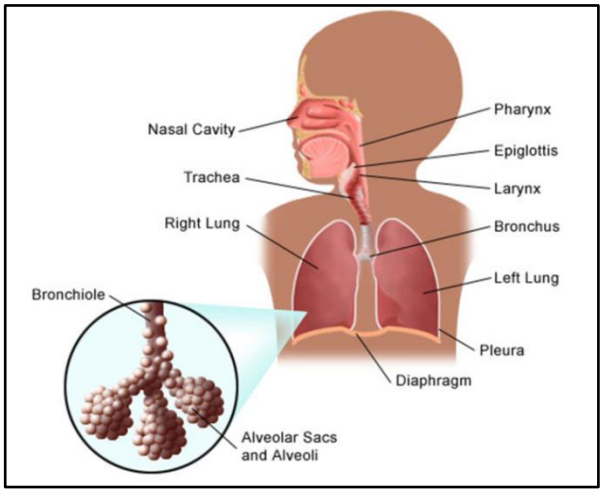

Figure 1. Pediatric airway anatomy[2].

2.2. Imaging Techniques

To view the upper respiratory tract of pediatric patients physicians typically use one of three imaging techniques: endoscopy, magnetic resonance, or computed tomography. Endoscopy is currently the favored approach as it allows physicians to obtain an understanding of both the anatomic and functional components of the airway, while maintaining a degree of comfort for the patient. The need for the insertion of a video-enabled tube into the patient's airway, however, can result in health complications and requires the use of both flexible and rigid endoscopes to ensure an accurate image of the airway is obtained. Magnetic resonance, on the other hand, provides physicians with a clearer understanding of airway function, lesion characteristics and the potential effects of surgical intervention without invading the airway or using radiation. However, to obtain a clear image, it requires the sedation of young children, decreasing its appeal for regular use and applications with respect to sleep-related disorders. Computed tomographic imaging is the third imaging modality used for the visualization of the pediatric airway. A CT scan results in the compilation of several x-ray images taken with a rotating source and detector. While the use of radiation is not favored for pediatric practice, CT provides the physician with a more complete understanding of the structural components of the airway, providing clear visualization of the bone, lesions and any mucosa-covered bone abnormalities not noticeable or measurable using endoscopic techniques[3,4]. The high bone contrast and structural clarity of the pediatric airway in computed tomographic image scans makes CT an ideal tool for developing a structurally-accurate three-dimensional model of the pediatric airway.

2.3. Computational Fluid Dynamics

Computational fluid dynamics (CFD) is an engineering tool used to calculate flow fields in complex geometries. The clinical application of CFD involves the characterization of the structure and function of the human anatomy displayed in medical images through mathematical algorithms. The resulting three-dimensional computer simulation model is utilized for assessment, diagnosis, treatment evaluation, and clinical research. The use of this technology to characterize the pediatric airway is currently in the developing stages, with only some of the physiological characterizations complete. So far, CFD has been proven to be instrumental in evaluating pediatric respiratory treatments, particularly the pre- and post-operative function of the upper airway in pediatric patients with obstructive sleep apnea (OSA) and the effectiveness of airway-based medicine delivery systems (inhalers) through extensive airflow simulations and pressure/stress-based assessments[5,6]. However, while useful for the comparable assessment of treatment, this technology has been unable, thus far, to produce a fully characterized, physiologically-accurate model for clinical practice. Zubair, et al. reveal such efforts and catalog the essential physiological characteristics CFD fails to account for with respect to modeling airflow through the infant nasal cavity[7]. Due to its reliance on imaging techniques and complex mathematical algorithms, this technology is limited in its capacity to provide a clinically applicable model.

2.4. Rapid Prototyping

Rapid prototyping (RP), also known as additive manufacturing, is defined by Rengier, et al. "as an approach or methodology used to quickly manufacture physical models using 3-D computer-aided design (CAD) data" [8]. There are currently seven rapid prototyping technologies available: stereolithography (SLA), selective laser sintering (SLS), solider process, fused deposition modeling (FDM), laminated object manufacturing (LOM), 3-D printing, and multiphase jet solidification (MJS)[9]. All seven technologies build models or parts in a layer-by-layer fashion from the bottom up. However, each of the seven technologies uses a different mechanism and has a different arsenal of specified materials, making additive manufacturing an extremely versatile technology.

Historically, additive manufacturing has been used, in industry, to create physical prototypes of products or parts for display, testing and evaluation. In more recent years, the applications of rapid prototyping have expanded into the medical realm, revolutionizing prosthesis development and medical education. Currently, rapid prototyping is being used, in conjunction with medical imaging techniques, to develop patient-specific models of human anatomy for education, training, and surgical planning purposes. In addition, it is being utilized to develop personalized artificial implants and limbs for patients not meeting the common standards of mass-manufactured alternatives[8]. The speed and detail with which rapid prototyping can be accomplished, as well as the various mechanical properties it can simulate, make it an ideal anatomy and physiology modeling tool for the clinical setting.

Recent efforts, related to modeling the pediatric airway, have successfully developed models of the adult upper airway for use in computational fluid dynamics analysis validation, using SLA and magnetic resonance images[10]. In contrast, the research presented here utilizes SLS, in conjunction with magnetic resonance and computed tomographic imaging, to develop models of the pediatric airway, from nasal cavity to the first generation bronchi, for clinical assessment. SLS was chosen, in particular, for this research due to its ability to build without supports, allowing for a higher degree of detail in, and smaller size of, the part to be developed.

2.4.1. selective laser sintering (sls)

Selective laser sintering uses a plastic, metal or ceramic powder, in conjunction with a CO_2 laser, to create three-dimensional models, layer-by-layer. In this process, the heat from the CO_2 laser is used to fuse, or sinter, together the powdered material into a solid slice of the model, adding a layer each time[9]. Parts or models created with this technology typically have complex geometry or intricate details, require durability or will be used for testing in the future. The various colors and mechanical properties of materials associated with the SLS allow for its application to a wide variety of fields[11]. Figure 2 provides a schematic drawing of the SLS machine, comprised of a powder bed, piston, deflection mirror, and CO_2 laser.

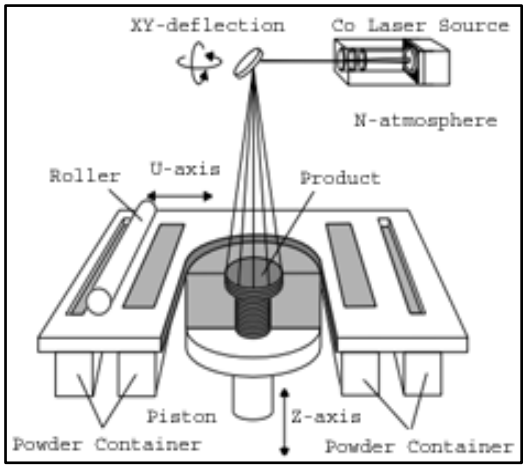

Figure 2. SLS machine parts schematic drawing[11].

3. Methodology

3.1. Data Acquisition

All medical images acquired for this research were de-identified prior to their release to the investigator and considered exempt under the Milwaukee School of Engineering Institutional Review Board's category 4, protocol number 2198. Physician affiliation was acknowledged, as required. Physician identification was facilitated through literature research and professional recommendations. Over the course of several weeks, eight physicians were contacted. Three of the eight were able to supply medical images, but only two of the eight were able to release medical images adequate for this research. In all, three CT scans and one MRI were acquired for processing. All acquired medical images were imported into MIMICS (Materialise, Leuven, Belgium). Prior to software manipulation, medical images were assessed for airway clarity and compatibility with the software. Physicians were contacted with further requests, as necessary.

3.1.1. medical image details

The CT scans acquired for this project were provided by Dr. Ravindhra Elluru, Pediatric Otolaryngologist at Cincinnati Children's Hospital Medical Center, and taken using a Toshiba Aquilon One CT Scanner (Toshiba America Medical Systems, Inc., Tustin, CA). All scans were of slice thickness 0.5mm and were received in the digital imaging and communications in medicine (DICOM) format. Three chest CT scans, of three different patients, as well as associated patient age and respiratory condition information, were released to the investigator. For the purpose of this research, patients were referred to by an assigned letter as Patient A, B, or C. Patient A was a three month old infant with a laryngeal cleft, esophageal atresia, and left main stem bronchomalacia. Patient B was another three month old infant with esophageal atresia, but with normal larynx and lower airway, or bronchi. Patient C was a nine month old infant with a ventricular septal defect (VSD) and right arch/aberrant subclavian. The CT scan of Patient A was used to create a model of the pediatric lower airway exhibiting bronchomalacia. The CT scan of Patient B was to be used to develop a model of the condition of esophageal atresia as manifested in the three-month old airway. Such a model was not developed during this project. The anatomy of the right arch/aberrant subclavian found in Patient C was determined to be too complex, a factor which was impacted by the resolution of the image.

The MRI scan used in this research was provided by Dr. Adam L. Dorfman, Pediatric Cardiologist at University of Michigan's C.S. Mott Children's Hospital. The scan was of slice thickness 1.2mm and was received in the DICOM file format. A single cardiac MRI was released to the investigator with the supplemental information of patient age. For the purpose of this research, the patient of which the cardiac MRI was taken will be referred to as Patient D. Patient D was a three month old infant with a congenital heart defect. The airway of this infant was normal. The

MRI of Patient D was used to create a model of the pediatric nasal cavity. Information on, and an assessment of, this model are included below.

3.2. Image Processing

The axial anatomic orientation associated with each medical image acquired was processed. Maximum grayscale contrast for each scan was set prior to processing. The "new mask" tool was used to create a blank mask over the medical image. Threshold values were determined (using the thresholding tool) for the airway wall throughout the scan. It should be noted that the threshold values for the airway wall vary based on the medical image and, thus, standardization is not ideal. The edit mask tool was then initiated and pre-determined threshold values were input for the manual threshold tool. Manual highlighting of the airway, in each slice, commenced. Careful effort was made to ensure complete and consistent mask development. Upon completion, the mask was used to calculate a three-dimensional computer model of the airway. Figure 3 shows the MIMICS interface for the lower airway model developed. Brief analysis was conducted with each image scan to ensure that no superfluous parts were present. Upon base-level assessment of the 3-D model, a .jpg image, shown in Figure 4, below, was sent to the collaborating physician for a confirmation of anatomical accuracy. Adjustments were made to the computational model as feedback became available. Conversion of the work to a standard transformation language, or STL, file, followed. Further processing of the model occurred in FreeForm (Sensable, GeoMagic, Willmington, MA), a virtual clay modeling interface associated with a haptic feedback device. Only the manual smoothing modality was used in processing the model, to remove any sharp, single-slice edges that would have resulted from errors in work in MIMICS. A quality assessment of the computational model was performed prior to releasing the model for build.

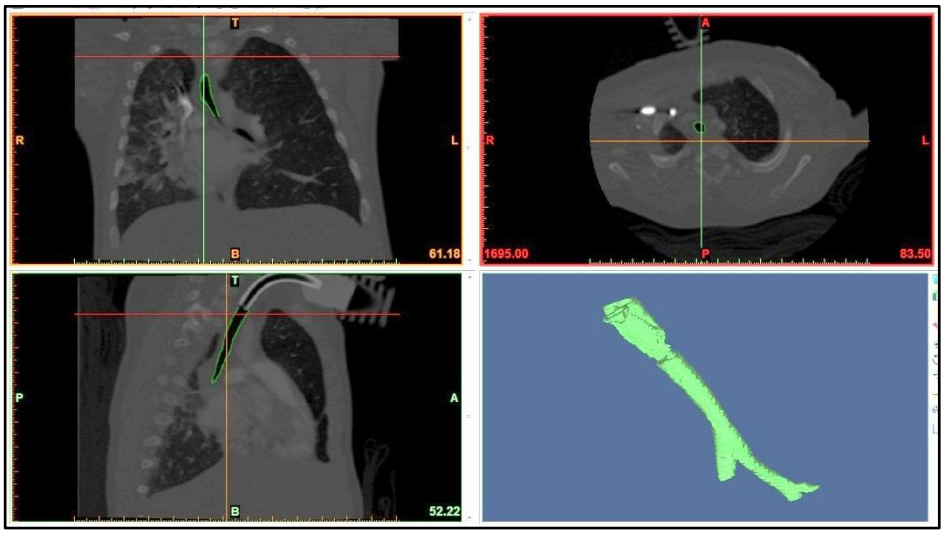

Figure 3. MIMICS software interface for Patient A's chest CT scan with a 3-D computer model of the lower airway. Upper left to bottom right: coronal, axial, sagittal and three-dimensional views. Grayscale views are directly correlated to the CT scan, provided. The green outline of the airway in the grayscale views is the result of the manual threshold process. The outline created is used to generate the three-dimensional airway model shown on the bottom right.

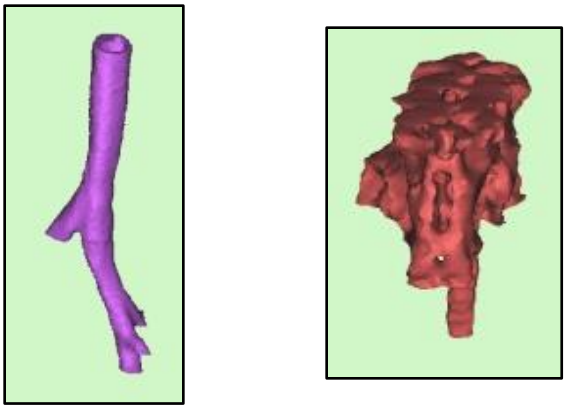

Figure 4. Three-dimensional computer renderings of patient-specific airways.

From left to right: lower airway model developed from Patient A's chest CT scan; nasal cavity model developed from Patient D's cardiac MRI.

3.3. Model Development

All models were developed in the Milwaukee School of Engineering Rapid Prototyping Center under the supervision of its professional staff. The completed STL files were imported into Magics (Materialise, Leuven, Belgium). In the Magics software, the model's size and wall thickness were assessed to ensure it would be compatible with the build. Models of incompatible size were built at a 2:1 ratio, as needed. As space became available, the models were integrated into the build platform and sent to the printer. All models were built on the Sinterstation 2500*plus*, with the Duraform PA material, at a layer thickness of four thousandths of an inch. The time for the development of each model, from start to finish, was variable and is included in the model description below. Following the build, excess powder was removed from the model using an air-based sanding technique. Upon completion, models were placed into a plastic bag for transport and storage.

4. Results

The results of this research can be surmised from the models developed through an assessment of their strengths and weaknesses as well as of the process used in their development. The models developed in this project are presented in Figure 5, followed by a brief description and analysis of each model.

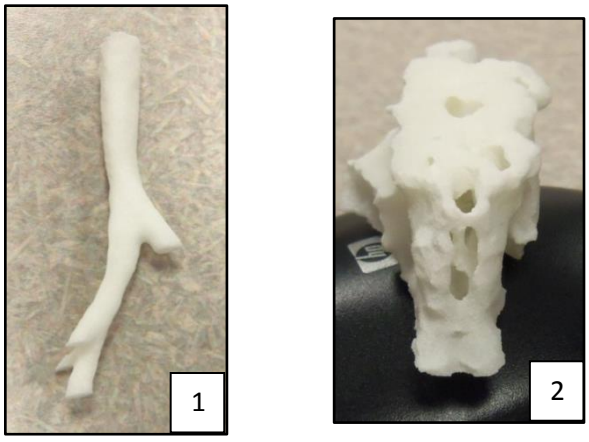

Figure 5. Three-dimensional models produced with SLS technology.

From left to right: lower airway model developed from Patient A's chest CT scan; nasal cavity model developed from Patient D's cardiac MRI.

The model shown in Figure 5.1 is a 2:1 scaled replica of a lower airway with bronchomalacia, developed from the chest CT scan of Patient A. The model took four hours and fifteen minutes to build, and was built at double the size to ensure adequate wall thickness. The lower airway was chosen, exclusively, for modeling, as the patient had a breathing tube that restricted modeling beyond the point shown. Extension beyond the second generation bronchi was also avoided, to maintain a hollow model with a high degree of structural integrity. The anatomical accuracy of the model was confirmed by a physician and is revealed through an examination of the MIMICS work and high resolution CT scan images. Based on such a comparison, it can be stated that the model effectively replicates the lower airway anatomy projected in the CT scan provided, with only a single error that is manifested in a closure of one of the second generation bronchi. Such an error can be attributed to a misjudgment on the part of the investigator in MIMICS and the small size or deformation of the airway being modeled. Regardless, the development of such a model serves as a proof of concept of pediatric airway modeling and provides a basis for future research work.

The model shown in Figure 5.2 is an attempt at a replica of a normal pediatric nasal cavity, developed from the cardiac MRI of Patient D, the three-month old infant with a congenital heart defect. The model was built over a five and a half hour period, is to scale, and spans from the nostril region to the main-stem bronchi, a total of 3.5 in. The anatomical accuracy of the model cannot be readily confirmed by an analysis of the model and medical images provided. The delineation between contrasting grayscale levels, throughout most of the nasal cavity, in the MRI, was not adequate for modeling. Since the MRI was taken for the purpose of examining the heart and blood vasculature of the patient, the magnetic field was set to show high contrast in these areas and, thus, had less defined contrast throughout the rest of the body. As a result, the boundaries of the nasal cavity were not clearly defined, and modeling required an exercise of judgment on the part of the investigator, to define boundaries, where few existed. In order to effectively model the nasal cavity, either a head MRI, purposefully taken for modeling the nasal cavity, or a head CT is required. The notable anatomic modeling accomplishment associated with this model that has been confirmed by the cardiac MRI data is the clarity with which the nostril region and nasal septum are replicated. This result was possible due to the high contrast that the nasal cartilage produced in that region. Thus, this model, though possibly inaccurate due to the medical images acquired, reveals promise in the nasal cavity modeling efforts; promise that can be envisioned, following the reception of access to a head CT or MRI.

Throughout this project, several limiting factors to modeling the pediatric airway were identified. Such factors included model size, material singularity, medical image quality and specificity, clinical practice and physician collaboration. These factors served to inhibit, or may in the future inhibit, the pediatric airway model development process in some way. The model size, while manageable for rapid prototyping technology, in at least one way, ultimately restricts the RP build technologies available to SLS, due to the importance of the model lacking supports. Similarly, the singularity, or exclusivity, of the material used in each build process, restricts the model's material to that of the build and annihilates the possibility of modeling physiology that requires more than one material consistency. The limiting factors of medical image quality and specificity, in addition to the effects of clinical practice, are probably the most pivotal in pediatric airway modeling. If the investigator lacks access to medical images of high resolution, minimal slice thickness, and catered to the region to be modeled, the probability of success at modeling the airway is low. The importance of obtaining quality images with region specificity and a preservation of the natural airway (an airway without breathing tubes) cannot be stressed enough. Maximizing the resolution and contrast of each medical image are key factors that would support the success of the model development, by increasing the anatomical accuracy and minimizing MIMICS development time. Finally, the limiting factor expressed as "physician collaboration" may be unavoidable, short of working in that physician's lab. The difficulties associated with schedule compatibility and medical image availability makes physician collaboration slightly more difficult than collaborating with a business partner or research associate. While the limiting factors detailed, here, have the capacity to negatively impact the project, at hand, the identification of these factors serves to increase the awareness of future researchers and promotes future research in this field.

5. Future Directions

There is great potential for future research following the development of an anatomically-accurate three-dimensional model of the pediatric airway. Further research will focus on enhancing the mechanical and material properties of the model to improve its capacity for pre-surgical planning and training. Depending on the success of this work, the model will then be used to assess the fluid dynamic properties of the upper airway, and develop standards for physician diagnosis. Future research will also involve the continued evaluation and improvement of the anatomic features of the model. Such work will focus on developing models from a combined computed tomographic and magnetic resonance image file, creating a model that reflects characteristics present in either image type, so as to maximally portray the strengths of each imaging modality in the model. Finally, the creation of a process for developing such a model, regardless of its accuracy, will not be as significant unless it is effectively implemented into clinical practice. Future research work may also focus on assessing the feasibility of, and developing an infrastructure for clinical use of the methods described here.

6. Conclusion

Models of the pediatric lower airway and nasal cavity were successfully produced in this research. Further work must be conducted to develop a more anatomically accurate model of the pediatric nasal cavity, and to extend airway modeling beyond the lower airway and other types of defects. The limiting factors identified in this research offer future investigators insight into some of the caveats of pediatric airway modeling. Overall, the results of this research indicate the potential of this modeling process to revolutionize pediatric airway clinical assessment and diagnosis. The research, catalogued here, has created many opportunities for related further investigation.

7. Disclaimer

The goal of developing a highly accurate and patient-specific model of the entire pediatric airway was not met in this research. However, it was determined that medical images of the chest, neck, and head, required to develop a complete airway model, are not typically available of a single patient. Thus, this research served to develop models of airway components, rather than the entirety of the airway. Regardless of this minor setback, modeling components of the pediatric airway is still advantageous for clinical medicine, as it would decrease the cost and time associated with regularly producing such models.

8. Acknowledgements

The author wishes to express appreciation to the National Science Foundation and the Milwaukee School of Engineering Rapid Prototyping Center for funding the Research Experience for Undergraduates (REU) program and this research. The author would also like to thank the advisor of this research, Dr. Subha Kumpaty, for his perspective, patience, and guidance throughout this research. The author would like to express gratitude to Dr. Ravindhra Elluru, from the Cincinnati Children's Hospital Medical Center, for providing the high-resolution CT scans used in this project, and Dr. Adam Dorfman, from the University of Michigan C.S. Mott Children's Hospital, for providing the MR data used in this project. Further recognition is given to Dr. Rohit Rao, Dr. Rita Agarwal, Dr. Ronald Litman, Brandon Tomlin, Caleb Nitz, Danielle Beski, Loretta Krenitsky, Denise Gergetz and Pamela Gorzalski for their professional assistance and support of this project. Finally, the author would like to thank Ann Bloor, Betty Albrecht and the REU 2012 team, for their support and encouragement, without which this research would not have been possible.

The material is based upon work supported by the National Science Foundation under Grant No. EEC-1062621. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

9. References

1. Frederic H. Martini et al., "The Respiratory System," Human Anatomy, 3ed. Prentice Hall, New Jersey, (2000): 620-646.
2. Yale Medical Group, "Anatomy of the Respiratory System in Children," Yale School of Medicine, 31 July 2012, http://www.yalemedicalgroup.org/stw/Page.asp?PageID=STW027285.
3. Robert E. Wood, "Evaluation of the Upper Airway in Children," Current Opinion in Pediatrics 20 (2008): 266-271.
4. Beverley Newman, "Computed Tomographic and Magnetic Resonance Imaging of the Pediatric Airway," International Anesthesiology Clinics 35, no. 3 (1997): 1-11.
5. Ying Wang et al., "Evaluation of the Upper Airway in Children with Obstructive Sleep Apnea Undergoing Adenoidectomy Using Computational Fluid Dynamics," IEEE Xplore (2009).
6. Jan W. De Backer et al., "Clinical Applications of Image-based Airway Computational Fluid Dynamics: Assessment of Inhalation Medication and Endobronchial Devices," Medical Imaging 2009: Biomedical Applications in Molecular, Structural and Functional Imaging, Proc. Of SPIE 7262 (2009): 1-9.
7. Mohammed Zubair et al., "Review: A Critical Overview of Limitations of CFD Modeling in Nasal Airflow," J. Med. Biol. Eng. 32, no. 2 (2012): 77-84.
8. Fabian Rengier et al., "Beyond the Eye – Medical Applications of 3D Rapid Prototyping Objects," Digital Radiography, European Medical Imaging Review 1 (2008): 76-80.
9. M. McGurk et al., "Rapid Prototyping Techniques for Anatomical Modeling in Medicine," Ann R Coll Surg Engl 79 (1997): 169-174.
10. Goutham Mylavarapu et al., "Validation of Computational Fluid Dynamics Methodology Used for Human Upper Airway Flow Simulations," Journal of Biomechanics 42 (2009): 1553-1559.
11. "Selective Laser Sintering," Milwaukee School of Engineering Rapid Prototyping Center, 28 June 2012, http://www.rpc.msoe.edu/machines_sls.php.