Metric system and database for sinus nasal cavity volume quantification based on 3D modeling

Ellen Óttarsdóttir

Thesis of 60 ECTS credits
Master of Science in Biomedical Engineering

January 2013

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Abstract

In this work a method to assess and standardize sinus nasal inflammation is established. Medical images and 3D modeling are employed to calculate the sinus cavity volumes and to discriminate the tissue composition, air and mucosa membrane. The two thesis objectives are: A development of a grouping system for a non-invasive assessment of sinus nasal inflammations and to design a database system to collect information, measurements and statistics from the medical modeling service at Landspitali University Hospital, Iceland. Three dimensional software is used to segment sinus nasal cavity volumes of thirty randomly chosen patients, both healthy and infected, using Computer Tomography (CT) images. Volumes are used to calculate ratios and graphs used to divide the subjects into six groups according to how affected they are. Microsoft©Access is used to create a database that keeps all the information from the modeling service in one place and is developed to be easily accessible for all parties on the hospital server, hospital staff and engineers. For the treatment of anatomically difficult cases it is often impossible to access the area of interest without performing a surgery. In other cases the uncertainties of the outcome of treatments are great. Medical modeling is implemented into medicine by using data from medical scanners for model generation, thereby giving the ENT department a non-invasive method of classification of sinus infections using medical modeling, which would be useful both pre- and post-operation/treatment. A co-operation is needed between doctors and engineers in order to utilize this technique to the fullest. Consequently, it is vital that data is kept in one place for safe storage and to keep track of the most recent information. In addition, the database can be used to gain easier access to information for cost calculations, statistics, material use and scanning protocols.

Keywords: Sinus nasal cavity, Rapid prototyping, medical modeling, segmentation, data mining

Útdráttur

Markmið ritgerðarinnar eru tvö: í fyrsta lagi að hanna stigakerfi fyrir sýkingu í kinn-, ennis- og nefholum, sem krefst ekki aðgerðar eða meðferðar innan líkama sjúklingsins til að öðlast betri skilning á alvarleika sýkingar svo hægt sé að taka ákvörðun um að veita rétta meðferð. Í öðru lagi að hanna gagnagrunn sem tekur saman öll gögn, sem þjónusta með læknisfræðileg líkön á Landspítala Háskólasjúkrahúsi tekur að sér, og tengir saman sjúkrahússtarfsfólk og verkfræðinga. Þrívíddar hugbúnaður er notaður til að finna rúmmál andlitshola þrjátíu sjúklinga. Viðföngin, bæði heilbrigðir og sjúkir einstaklingar, eru valdir handahófskennt úr tölvusneiðmyndasafni spítalans. Hlutfall er fundið á milli mældra rúmmála og línurit notuð til að mynda sex hópa eftir alvarleika sjúkdóms. Gagnagrunnur er gerður í Microsoft©Access sem heldur utan um allar upplýsingar sem líkanaþjónustan hefur tekið að sér og á að vera aðgengilegur fyrir alla aðila á netþjóni spítalans. Í erfiðum tilfellum eru sýkt svæði ekki aðgengileg án skurðaðgerðar, í öðrum tilfellum er erfitt að meta árangur meðferða/aðgerða. Læknisfræðileg líkanagerð er framkvæmd með því að taka læknisfræðilegar myndir til hönnunar líkansins. Þess vegna er mikilvægt fyrir háls-, nef-, og eyrnadeild spítalans að fá stigskerfi sem hjálpar til við flokkun og sjúkdómsgreiningu svo ákvarða megi meðferð/aðgerð, sem ætti að vera gagnlegt bæði fyrir og eftir meðferðir/aðgerðir. Samvinnu er krafist af heilbrigðisstarfsfólki og verkfræðingum svo útkoman verði sem best. Þess vegna er einnig mikilvægt að gögn séu geymd á einum stað, bæði fyrir örugga geymslu og til að allir aðilar geti fylgst með nýjustu upplýsingum. Auk þessa, geymir gagnagrunnurinn upplýsingar um útreikninga, efniskostnað og myndstaðla svo eitthvað sé nefnt.

Lykilorð: Kinnholur, ennisholur, nefholur, hröð líkanaprentun, læknisfræðileg líkanagerð, þrívíddarvinnsla, gagnageymsla

Ritgerðin heitir á íslensku: Mælikerfi og gagnagrunnur fyrir sinus nasal cavity byggt á þrívíddarvinnslu.

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List of abbreviations

ENT - Otolaryngology department

RP – Rapid Prototyping

LSH – Landspitali University Hospital

CT – Computer tomography

MRI – Magnetic resonance imaging

3D – Three dimension

CAD – Computer aided design

STL – Stereolithography

SLS – Selective laser sintering

FDM – Fused deposition modeling

3DP – Three dimensional printer

HU – Hounsfield unit

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1. Introduction

This chapter will give an explanation of the project aims and list an overview of the topics regarding the work of this thesis; on Medical Modeling and Rapid Prototyping (RP) technology describing the main features and applications especially in the clinical field. An introductive chapter will summarize the modeling and rapid prototyping service at University Hospital Landspitali (LSH) with a description of some challenging clinical cases and finally an introduction will be summarized regarding quantification and analysis of sinus nasal volume and how a database for the RP service at LSH is built.

The main objectives of this project are:

1.   To develop a metric system to measure and quantify inflammation within sinus nasal cavities using Spiral Computer Tomography (CT) data and 3D modeling techniques.

2.   To create a database for medical modeling and RP services at LSH that holds together data for various projects, including cost calculations and files for printing. The database is a tool to connect doctors and engineers and to keep the data for the service in one place, accessible from both ends.

1.1. Medical Modeling

Medical modeling is generally applied to represent biological systems under certain conditions: visualizing anatomy and changes in geometry in 3 dimension (3D), representing difficult geometry, simulate biological conditions and surgical treatments and study tissue properties or correlate different characteristics [1]. Computer modeling and simulation of human body and its behavior are very useful tools for preparation for a surgical procedure or too evaluate if a surgery is needed. The modeling is designed according to established criteria and objectives, anatomically complex models have such a high number of parameters that they cannot all be identified and accounted, so the modeling work is usually limited to

describe accurately certain characteristics and approximating or even ignoring others [2]. This needs a great knowledge of the human anatomy.

Biomodeling is the same as medical modeling except that it always ends with a physical model, it is defined as the creation of highly accurate physical models of human anatomy directly from medical scan data. The process involves capturing human anatomy data, processing the data to isolate individual tissue or organs and eventually use rapid prototyping techniques to provide the physical model [3]. Figure 1 shows the modeling processing flowchart. When making a medical model, the patient is first sent to a CT scan or Magnetic Resonance Imaging (MRI). The images are then imported into 3D software where the anatomy is analyzed and the model designed. When the model is ready for display, the designer, regarding to the asking doctor, decides on how it will be represented. It can be presented using a simulation video, a simulation of the processed model on a computer screen in 3D or by printing it out using Rapid Prototyping techniques.
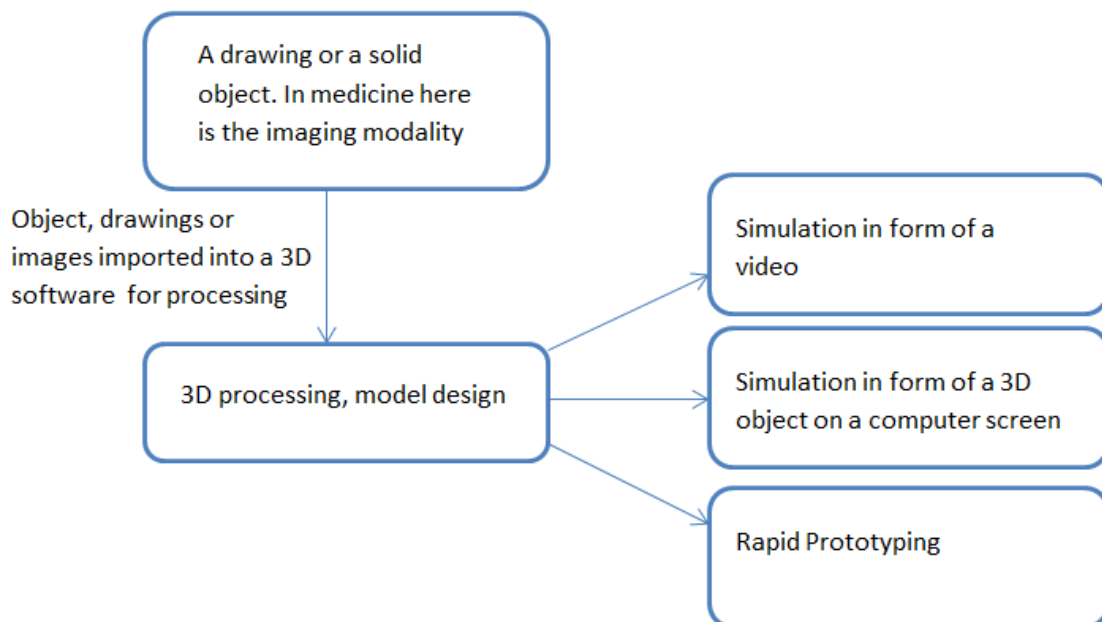
Figure 1: Modeling processing flowchart

Rapid Prototyping (RP) technologies are used for models that are being used for the purposes of surgical planning, evaluation, as a diagnostic support and for educational display; in figure 2 the applications of rapid prototyping in bioengineering are shown. RP technologies for manufacturing medical models are under constant development. In the design process the specialist has to minimize material cost, so he has to make sure that trapped volumes are small or none at all and only make a model of the view of interest. It is important to correctly orient the model in the printing process for the best use of space and materials. With better techniques, it is made possible for doctors to insert materials into the human body to replace broken or defected parts.
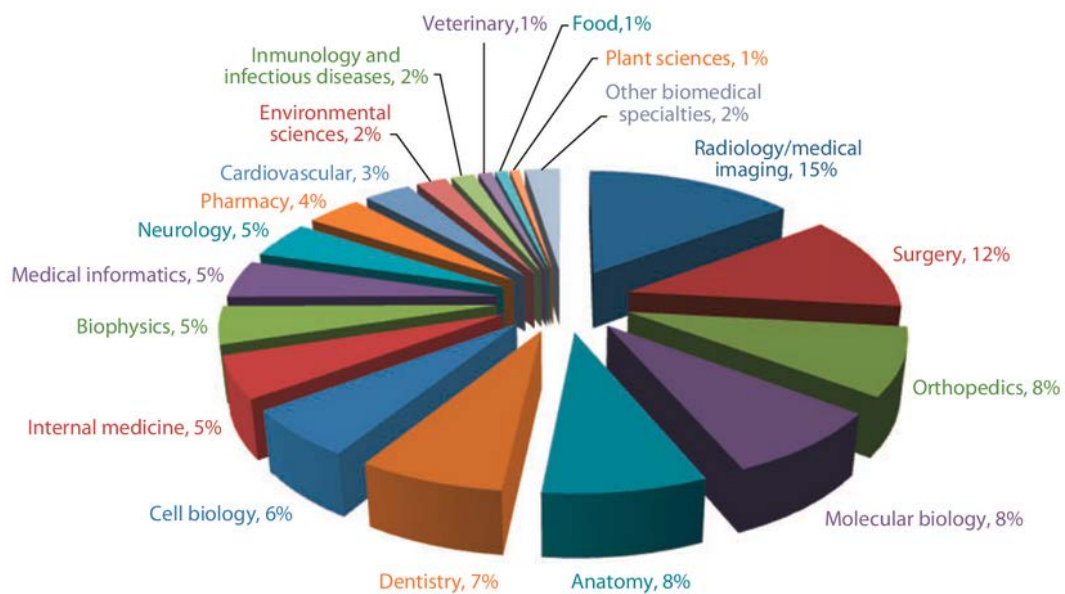
Figure 2: Application for rapid prototyping in bioengineering [10]

Medical training and education benefits from three dimensional printing that allows detailed view of a model with 0.1 mm layer thickness [4].

Scaffolds are more frequently used. A development in the printing techniques helps with including cells and growth factors.

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Tissue engineering has been developing over the last decade but a lot of improvements are yet to be made. Very strict rules apply regarding what materials can be used in the human body. Scaffolds require biocompatibility, vascularization, chemo taxis, and they have to be non-immunogenic. If rules are not followed it can cause, infections, blood clots or damage to the surrounding tissues, causing serious harm or even death [5].

Implants are e.g. made from metal in total hip replacement, in dentistry and for nails and screws in medicine and for reconstruction of the face and the skull. These implants shown in figure 3, are also possible to make from titanium from RP [6].
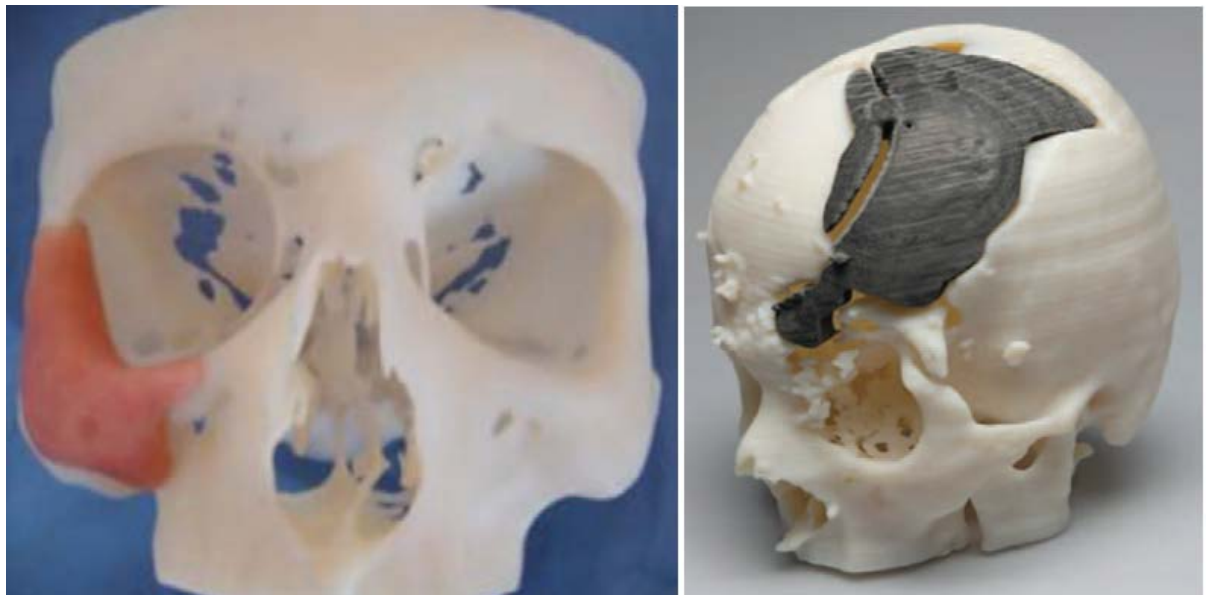
Figure 3: Right reconstruction of face, Left reconstruction of skull [9]

1.2. Rapid Prototyping

A prototype is a physical model that has been developed. It is a model that gives an idea of how the designed object is. The need to have hands on models has been essential for a long time. RP refers to making models or prototypes with a fast method. It took up to 2 months to produce a good model from wood, casting or clay. In the early 1980's a need for more speed and accuracy was becoming a problem [7]. RP is used for five phases in the industry [8][9]:

1. Information for market research

2. Concept; virtual or soft prototype phase of a design

3. Engineering for study; to find the best and most simple solution, where a model is made and tested

4. Tooling that is a preparation for manufacturing

5. Production when the tooling phase is over

It is possible to use RP for presenting implementation, the form and the rough outlines. These prototypes play roles of experimentation, learning, testing and proofing, communication, integration, scheduling and for marker making [8]. The process begins with a medical image and ends with a physical model.

1.2.1. History

The history of RP goes back to 1970 when an algorithm was developed, describing a 3D object for solid modeling [10]. In 1986 Charles Hull, often called the father of the rapid prototyping, introduced the first commercial RP machine, stereolithography (STL) by his company called 3D systems. Figure 4 shows the machinery and its parts. First, the model is drawn and put into computer aided design (CAD) files. The model is then sliced into many layers with a predefined thickness, using computer software. Finally, the file is transferred to the machinery for printing. The machine consists of a scanning device with mirrors to guide the light to the right spot, an ultraviolet laser, a building platform, a resin container and a re-coating blade. The building platform is located in the resin container. It is located at the top of the resin surface at the beginning of a process and moves down by the layer thickness for each slice segmented by the 3D software and the re-coating blade covers the cross section with liquid resin. The object is then manufactured by solidification of resin by the computer controlled movable ultraviolet laser, controlled by the scanning system. When the model is complete, the building platform is raised to the surface [11].
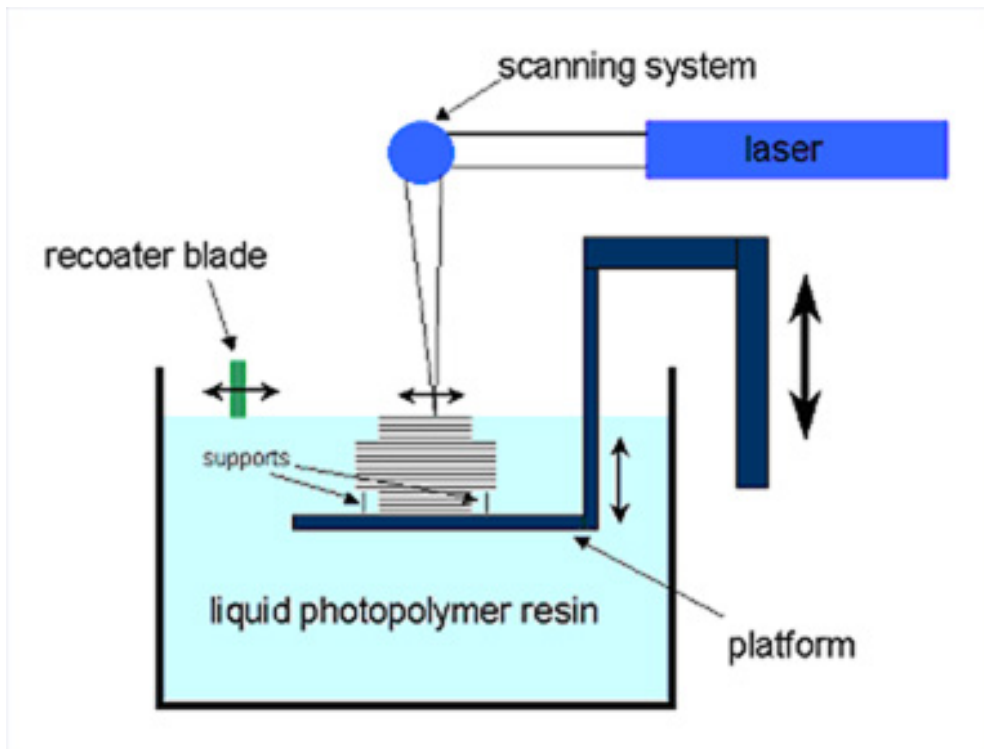
Figure 4: Stereolithography machine [9]

Models are increasing in complexity so the RP techniques have to develop constantly. Over the last years techniques have developed to be able to manufacture usable objects with a final shape and finish. More than 30 different techniques have been developed over the last 25 years [8]. This method, STL, of RP is well developed and reliable, with high accuracy and good surface finish [9]. The sales, support and training are well-known. Material waste is low and the models fulfill medical standards, can be sterilized and selectively colored even though the models are transparent. The disadvantage is a high cost of machines and maintenance. The materials used are very expensive and trapped volumes are problematic. With the development recent year's this method is less used than others [13]. Applications for STL are e.g. in aerospace, motorsport, electronics, architecture, medicine, consumer products, etc. [14].

1.2.2. Technologies

The RP machines usually work non-stop and without the need for a human hand so the work can be started at the end of a working day to be complete the next morning. The finishing work is different between methods; some models are ready for use after printing while others need some more finishing. There are three types of Rapid Prototyping machines: liquid-based, solid-based and powder-based. Even though technologies are numerous, only the most commonly used will be introduced here [12][6][8].

Selective Laser Sintering (SLS) was introduced in 1990 [7]. It is similar to STL but instead of using liquid resin and an ultraviolet laser it uses a high power CO^2 laser to fuse plastic, metal or ceramic powders [15]. SLS has two powder chambers, one is the building platform that lowers when the model is built and the other rises allowing the roller to move powder over to the building chamber for a new layer. First, the model is drawn and put into computer aided design (CAD) files. The model is then sliced into many layers with a predefined thickness. Finally the file is transferred to the machinery for printing. A powerful laser locally fuses thin layers of fine powder. The building platform lowers, allowing fresh powder to be applied and the next layer is scanned on top of the previous layer, shown in figure 5. Local melting also forms a bond between the layers. The models are very strong and accurate but the surface finish is not good and they are not suited for sterilization [15]. Even though the material range is wide they are expensive and the machines are big and expensive [12]. Applications are e.g. for military, medicine, design evaluation, product performance and engineering design verification [16].
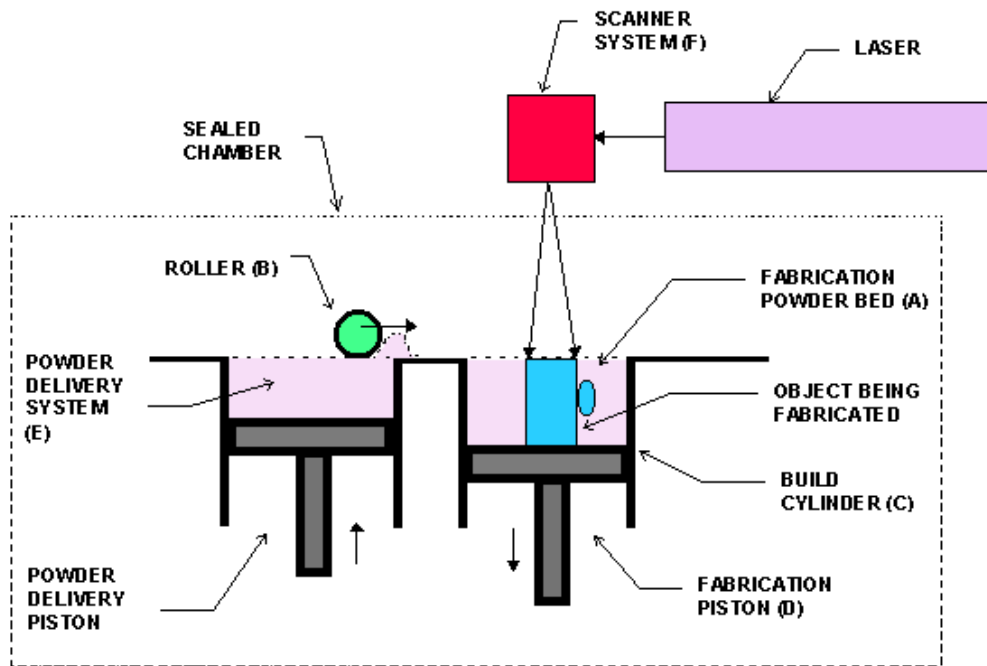
Figure 5: Selective laser sintering [16]

Fused Deposition Modeling (FDM) was introduced in 1996 [7]. FDM uses thermoplastic materials that are fed to a heated extrusion head. The model is drawn and put into computer aided design (CAD) files. The model is then sliced into many layers with a predefined thickness. Finally the file is transferred to the machinery for printing. The extrusion head keeps the material just above the melting point so when it is transferred to the building platform it hardens immediately; figure 6 shows how the method works. The building platform lowers an exact layer thickness and the next layer is deposited on to the previous layer that bounds due to melting. The machines are relatively cheap to buy and run. The materials are opaque but the quality is not as good as in SLS and it is difficult to get a model with small features to be good. Examples of materials are ABS, Polycarbonate and elastomers. The models are very strong but the building process is slow. Applications are e.g. medicine, design evaluation, product performance, engineering models, presentation models, patient and food and high heat applications [17][18].

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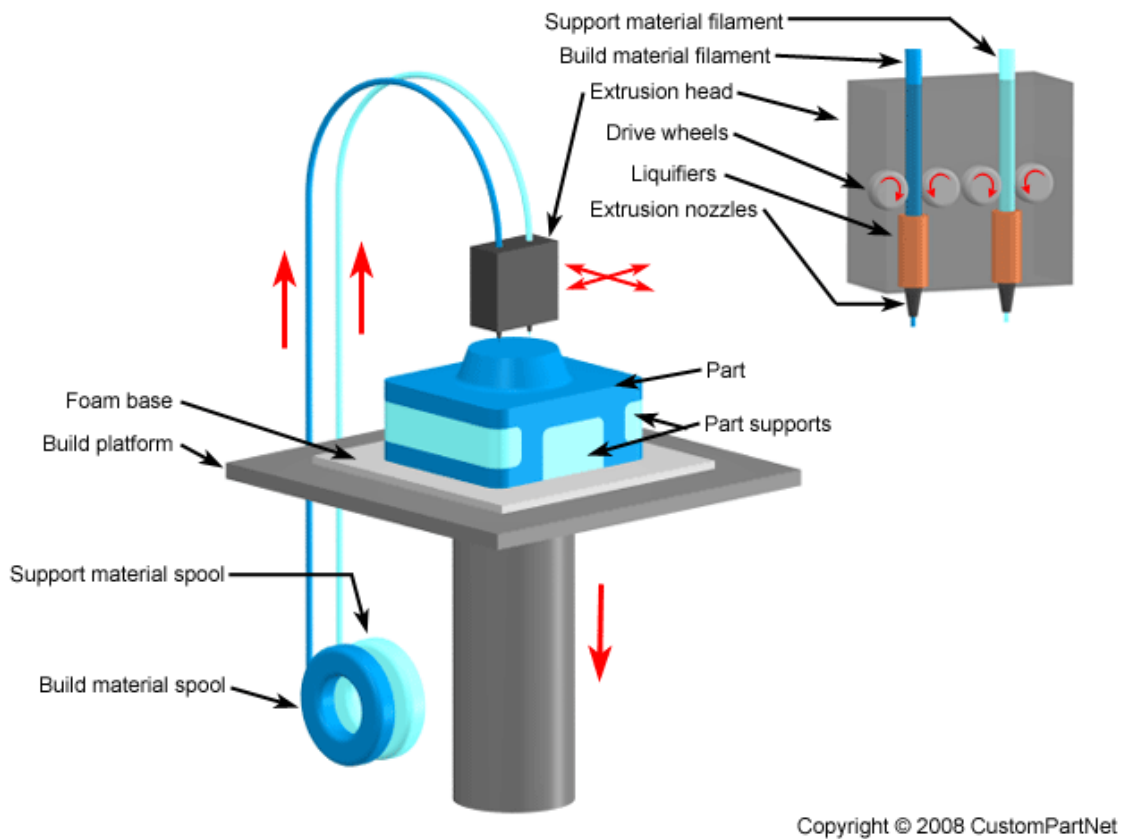
Figure 6: Fused deposition modeling [18]

3D Print (3DP) Technology was introduced in 1996 [7]. The model is made and put into computer aided design (CAD) files. The model is then sliced into many layers with a predefined thickness. Finally the file is transferred to the machinery for printing. Powder material is glued together layer by layer by a print head similar to those used in inkjet printers. The machine holds two powder chambers, one that feeds powder by a leveling roller to the building chamber and the other that holds the building platform, figure 7 shows how the process is. These machines are small and cheap; in purchase, maintenance and running cost. They are easy to use and are very fast in building models, in different colors. The accuracy and the surface finish are lower than in other techniques [12]. The printing time is only a matter of hours but the drying time and final finishing takes some time, depending on the model. The cost can differ a lot between models, the powder amount varies and the expense can be difficult to calculate unless the designer is certain of the amount of trapped volumes. If

trapped volumes are in the model, the cost is very hard to calculate. The binder/glue usage is specified by the machine but not the powder usage. The designer has to be rather sure of how much of the powder is trapped to be able to calculate the accurate cost.
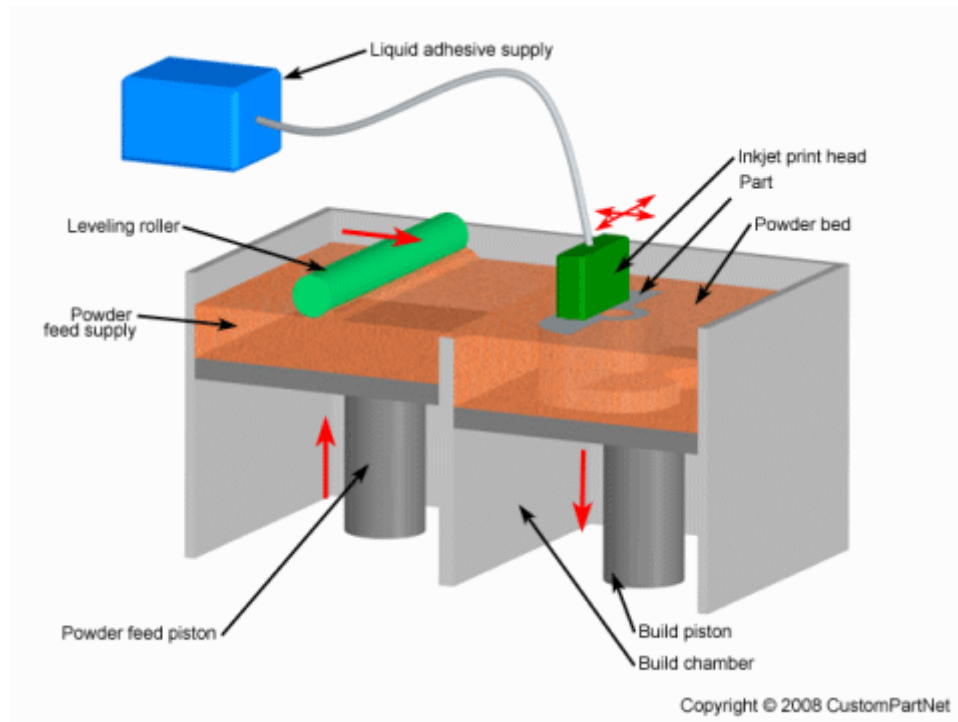
Figure 7: 3D printing[19]

The physical models produced by a 3DP are in general not ready for evaluation but they still need an infiltration. The prototyping process glues together a special type of plaster powder material and at the end of the printing process the surface appears porous and opaque. If model is not infiltrated it loses material from surface, from the cavities and is rather fragile. Depending from the used infiltration technique, different mechanical proprieties can be provided to the model. The process of bonding loose powder to solidify into parts is compatible with many types of materials. While the 3D printer remains exactly the same, users can change the building material to produce parts with a wide range of properties to meet various application requirements. Z Corp. offers five materials to provide performance enhancements for specific applications [19]:

1   *High-Performance Composite Material* makes strong, high-definition parts and is the material of choice for printing color parts. This is the most widely used, high-performance composite material that enables color HD3DP on the 600-dpi platform 3D printer. Fine resolution on small features and excellent strength make this material suitable for applications ranging from concept modeling to sand-casting patterns. It consists of a heavily engineered plaster material with numerous additives that maximize surface finish, feature resolution, and part strength. This material is ideal for: High-strength requirements, delicate or thin-walled parts, color printing and accurate representation of design details.

2   *Direct Casting Metal Material* creates sand-casting molds for non-ferrous metals. This material is a blend of foundry sand, plaster, and other additives that when combined produce strong molds with good surface finishes. Direct casting metal material can withstand the heat required to cast non-ferrous metals. Users of this "ZCast®" process can create prototype castings without incurring the costs and lead-time delays of tooling.

3   *Investment Casting Material* fabricates parts that users dip in wax to produce investment casting patterns without molds or geometric constraints. The material consists of a mix of cellulose, specialty fibers, and other additives that combine to provide an accurate part while maximizing wax absorption and minimizing residue during the burn-out process. Users utilize investment casting material to create high-quality castings with excellent surface finishes in a number of industries.

4   *Snap-Fit Material* creates parts with plastic-like, flexural properties, which are ideal for snap-fit applications. Z Corp. has optimized this material for infiltration with the Z-Snap™ epoxy. Users utilize snap-fit material to create plastic-like parts that snap into other components and assemblies.

5   *Elastomeric Material* creates parts with rubber-like properties. Optimized for infiltration with an elastomer, this material system consists of a mix of cellulose, specialty fibers, and other additives. Users utilize elastomeric material to produce accurate parts that are capable of absorbing the elastomer, which gives the parts their rubber-like properties.

Model properties are modified through an infiltration process which follows the 3DP. The printed structure is a strong but porous matrix, and infiltration fills the pores. Model parts can be infiltrated with resins allowing the part to take on the physical properties of a cured resin. This capability provides users with greater versatility without having to change the primary materials in the 3D printer. For concept and visualization models, users can infiltrate parts with wax or water. It can also be infiltrated with high-strength epoxy, creating very hard, rigid parts in a fraction of the time that it takes to have them machined [19].

Table 1: Comparison of rapid manufacturing processes [20]

Technology	Min layer thickness	Precision	Building speed	Materials	Material Type	Surface finish
Stereolithography	0.0010 in	150 - 300 μm	Average	Thermo-plastics	Liquid	smooth
Selective Laser Sintering	0.0040 in	-	Fast	Thermo-plastics	Powder	average
Fused Deposition Modeling	0.0050 in	350 - 500 μm	Slow	Waves, thermo-plastics	Solid	Rough
3D printing	0.0020 in	250 - 400 μm	Very fast	Waxes, polymers	Powder	Rough

Table 1 compares the RP techniques and gives an idea of what technique is to be used for various cases. Lower layer thickness gives more precision. All these methods use elastomers but there are also techniques available that use metals for the building of models.

1.2.3. Biocompatible Materials for rapid prototyping applications

The human body contains highly corrosive environment. Some scaffolds are made for implants that are designed to be mechanic and to stand loads but others are supposed to be biodegradable leaving a new regenerated tissues behind. Materials suitable, in vivo, for RP in medicine are ceramics, metals and polymers:

Alumina Al_2O_3 is a very strong material used e.g. in a hip replacement [21].

Zirconia ZrO_2 is a very hard material that hardens with time that can lead to fractures, thus it is very good to mix it with Alumina [21].

Hydroxyapatite HA is used to produce bone or to stimulate bone growth. SLS and STL can produce insert able objects from this material [22].

Stainless steel is used in pins, plates and screws [22].

Titanium implants are made by STL and more techniques for individual patients to repair mandible and maxilla defects. Titanium and its alloys are able to integrate into bone, it usually doesn't bond with bone but by subjecting it with NaOH and use heat treatments it bonds with the surrounding bone [23].

The above materials are the most commonly used but there are many more materials available.

1.3. Medical modeling and Rapid Prototyping service

Medical modeling has been practiced at LSH since 2003, with its main goal to assist in the health practice. Doctors can order 3D images and models from CT and MRI images for use in surgery planning, treatment evaluation, preparation and education. The models give better understanding of the problem. They give a better view of the internal organs and tumors and give vital information about density and a size of tumor/illness. Doctors are realizing how

important it is to use this technology and how they can use it, see examples in figure 8. The following applications are currently being used at LSH:

1. Used for diagnostics, supporting visualization in difficult anatomical cases.

2. Planning surgeries and treatments in orthopedic and maxilla facial operations.

3. Patient follow up in craniofacial trauma, studying changes in bone and soft tissue.

4. Patient compliance providing computer simulating in maxilla lengthening
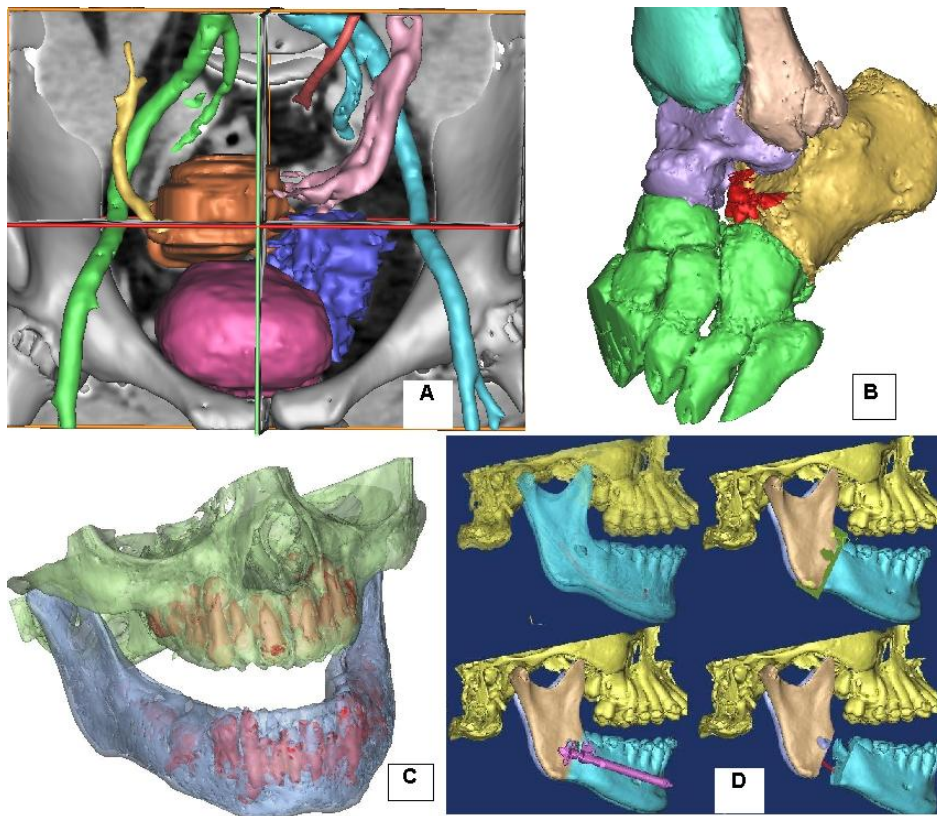
Figure 8: Different clinical applications of medical modeling in Iceland: (A) diagnostic support, (B) surgery planning, (C) challenging medical case, (D) surgery simulation

Figure 9 shows the procedure for the service to work. If a doctor wants to use the service, the only thing needed now is a CT or MRI scan in 3D quality and to order the model via email to the engineer in charge.
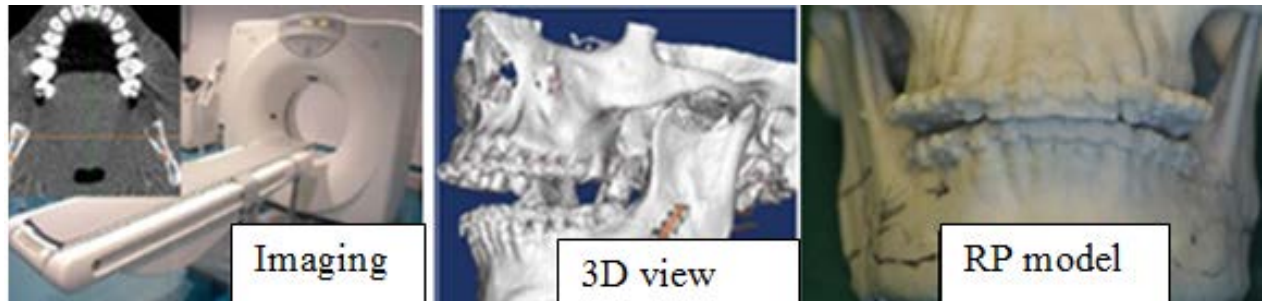
Figure 9: The procedure needed

1.4. Patient cases

Patient cases addressed by LSH are shown in next chapters.

1.4.1. Tumor in the minor pelvis

Figures 10 and 11 show a 48 year old patient, which had a tumor in the minor pelvis and some urological problems. A model was made for diagnostic aid. The model provided valuable information about the anatomy around the tumor. The model showed that the left ureter was compressed by the tumor, explaining the urological problems.
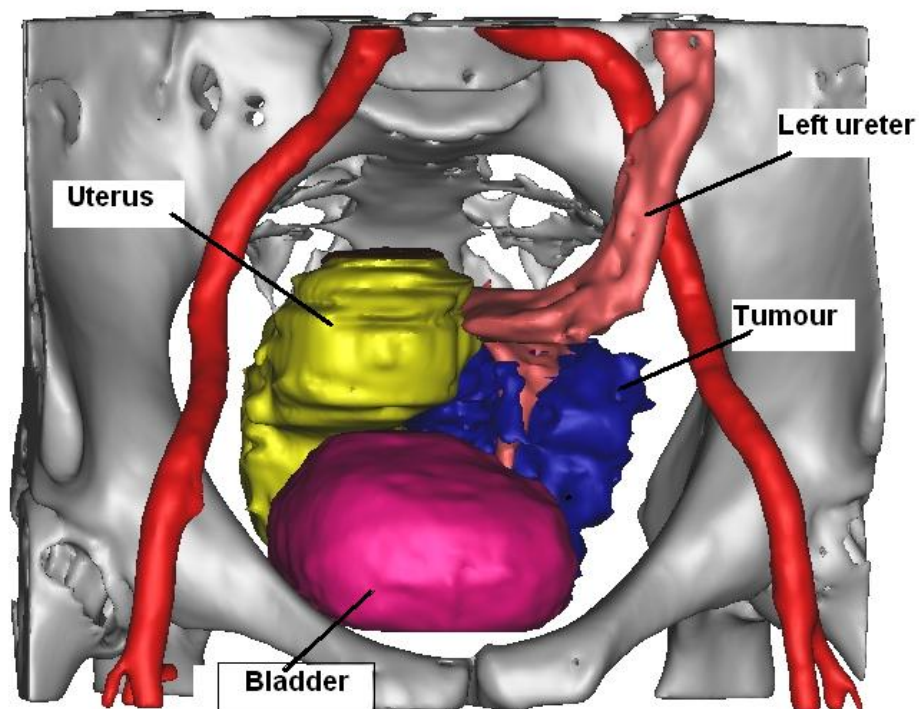
Figure 10: 3D reconstruction of the organs inside the minor pelvis
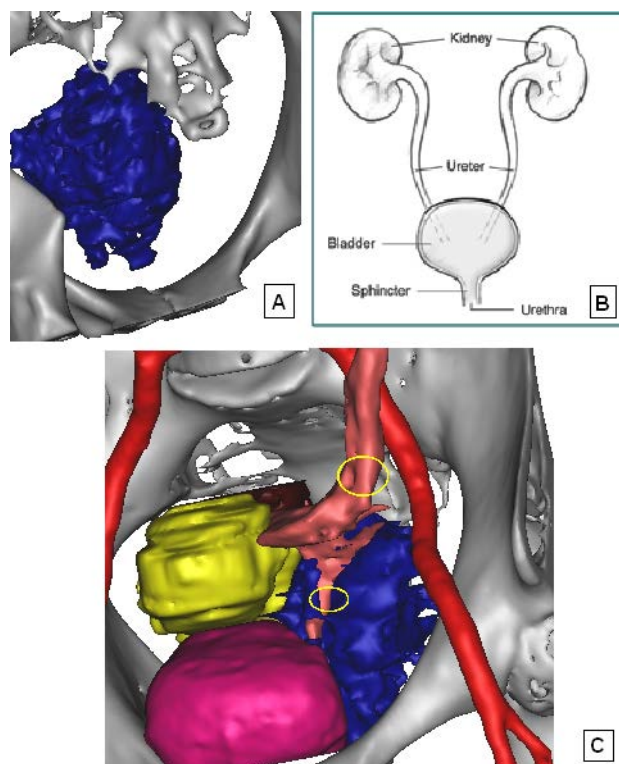
Figure 11: Sponge structure of the tumor (A). Kidney-bladder connection (B). Ureter compression and dilation areas (C)

1.4.2. Rare maxilla facial malformation

Figure 12 shows a model that was made in order to see how to treat a rare maxilla malformation. The patient is a 4 year old girl with all her un erupted milk teeth. The model was developed to show that the teeth are all available in the jawbone with a bone surface that needs to be removed. By using this method the surgeon can see more clearly what the plan should be, whether the teeth should be removed and/or extracted.
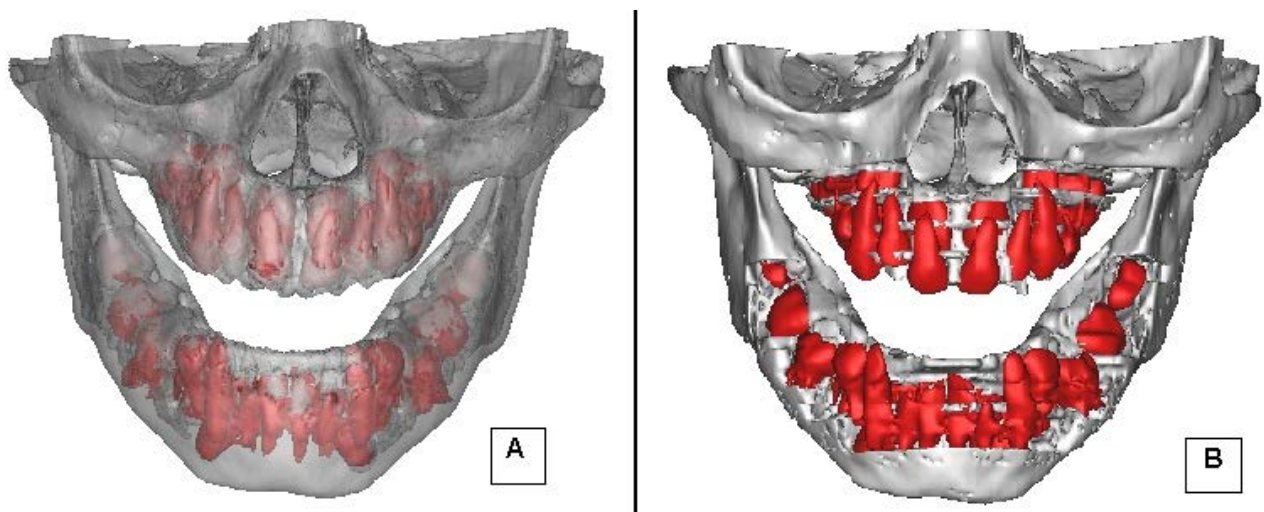
Figure 12: Visualization of the teeth trough the jawbone (A). Segmentation of the teeth for rapid prototyping (B)

1.4.3. Support of prosthesis design

The patient is a 55 year old man with the right foot amputated, see figures 13 and 14. The model is used to design prosthesis that will be applicable to the stump. The model is designed by mirroring the left foot onto the right one and subtracting the right side. That gives a model that fits the stump and can be used to produce the prosthesis.

Figure 13: Patient left and right foot.
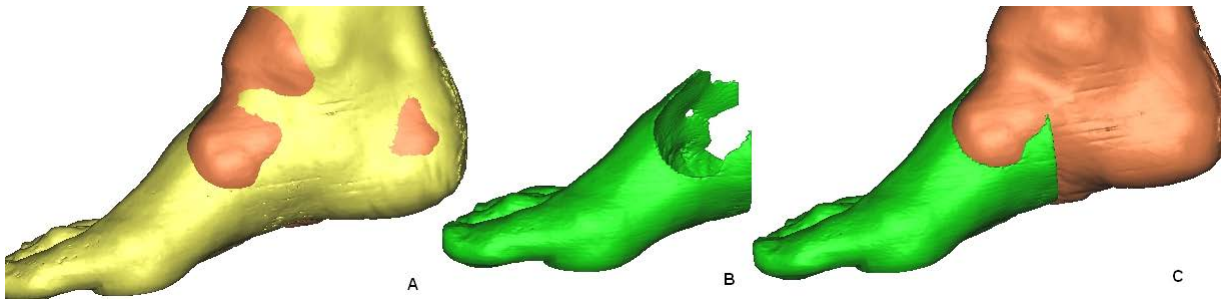
Figure 14: Registration of the healthy mirrored left foot on the right amputated (A), result from the image subtraction (B), fitting of the prosthesis prototype (C)

1.4.4. Surgery simulation and results from maxilla lengthening

Figures 15 and 16 show a simulation for a planned surgery on the patient face due for maxilla lengthening. Post-operative measurement and comparison between the real patient outlook and simulation demonstrate the reliability of the simulation tool to predict the treatment result.
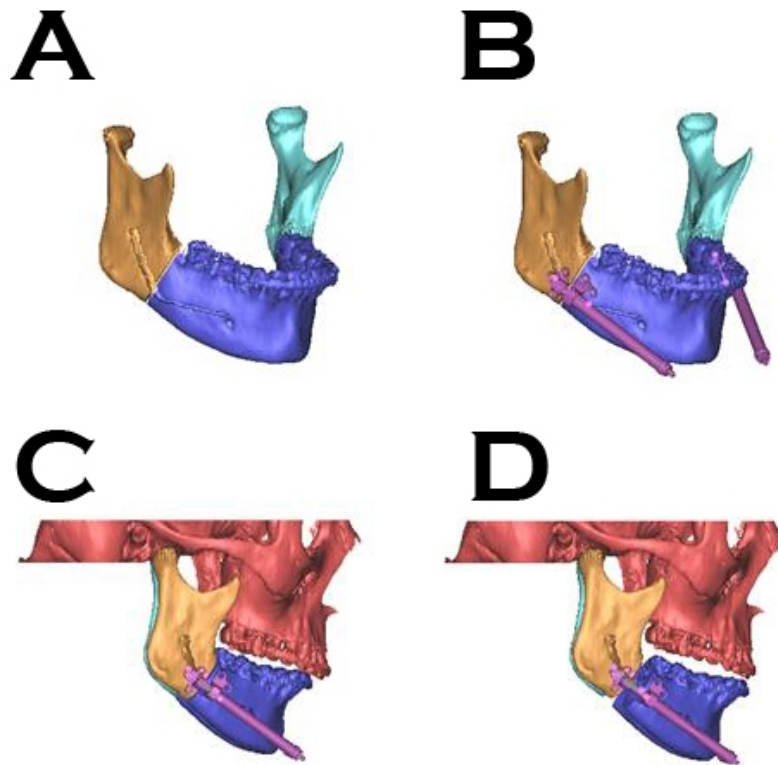
Figure 15: The different steps for the computer simulation
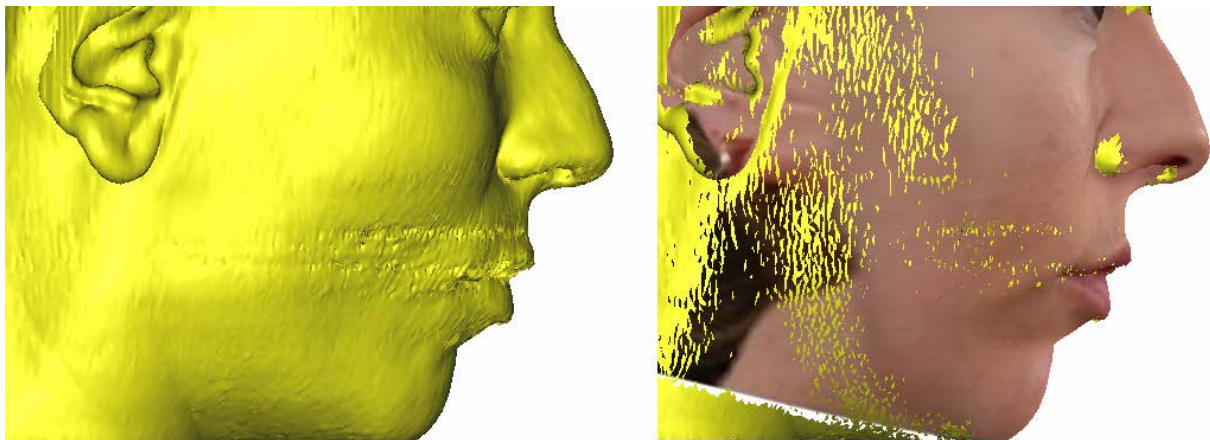
Figure 16: Results from the surgery simulation

1.4.5. Planning treatment in multiple fracture

Number of cases, as shown in figure 17, came in from orthopedics because of multiple fractures in the foot where it's difficult to localize sediments and mini fractures.
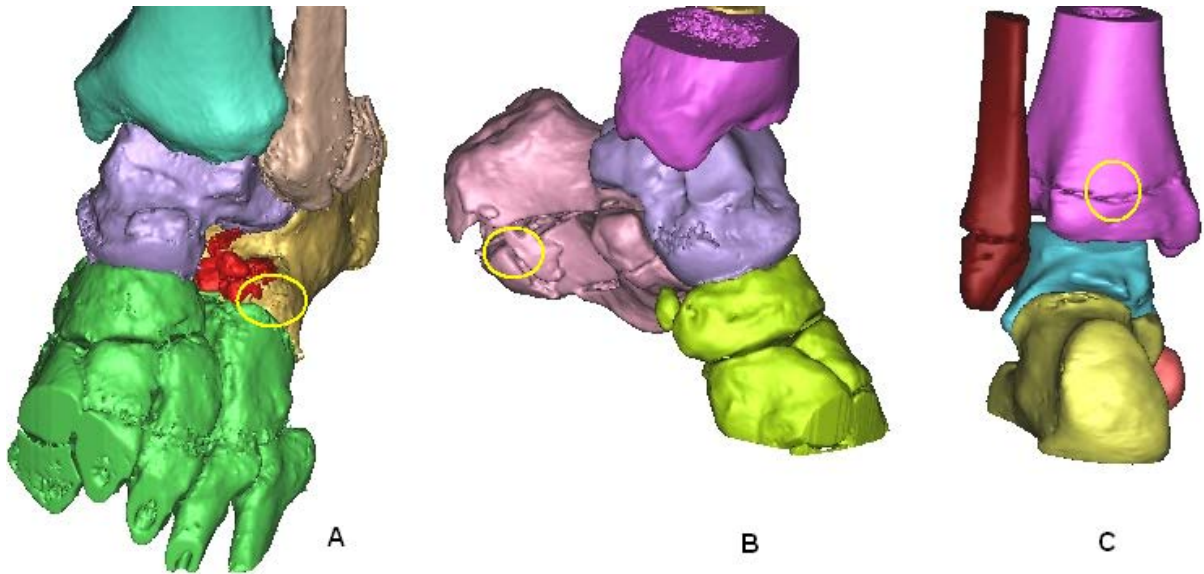
2. Analysis of sinus nasal volume

2.1. Introduction on sinus nasal cavity morphology

The air that flows through the nose is hydrated and filtered. The nose protects the airways from deleterious influence of gas, aerosol and pathogens. It acts as an area of voice resonance and produces nitric oxide for regulation of lower airways. It also is a chemosensoric organ responsible for smell. The cleaning functions of the nose filters 95% of particles out of inspired air. Sneezing is provoked by foreign bodies in the nose and is to eliminate the filtered particles from the nose. Mucociliary clearance is an interaction between nasal mucus and ciliary beating. The mucus is also slightly acid to prevent infections. Optimal clearance is achieved at 37°C and 100% humidity. Nasal mucus is about 10-15 μm thick with two layers. Nasal mucus contains 90% water, glycoproteins and ions; this combination has influence on the clearance. The amount of transudate and their respective proteins will increase when there is a local inflammation. Immune defense is in the epithelium and in nasal secretion[24].

The Para-nasal sinus is an air-filled space within the facial bone and consists of 4 spaces, as shown in figure 18: the maxillary sinus, the ethmoid sinus, the sphenoid sinus and the frontal

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sinus. The frontal sinus protects the brain and reduces the weight of the cranium [4]. Under physiological conditions the Para-nasal sinuses are sterile but after sinus surgery the sterility rate decreased to 97% [25].
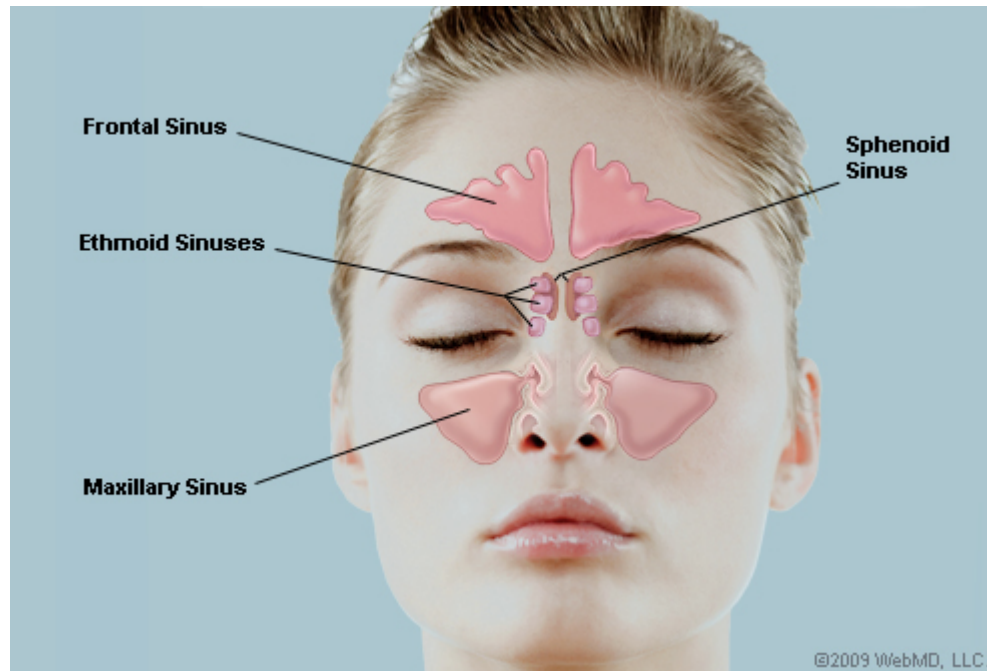
Figure 18: Sinuses used in the measurements [26]

Anterior rhinoscopy investigates blood vessel patterns, the quality of nasal mucosa and properties of secretion. Nasendoscopy inspects the middle nasal meatus, the anterior wall, sphenoethmoidal recessus and the superior nasal meatus. Imaging techniques, CT and MRI are very helpful in evaluating the amount of sinusitis without invasion into the body. Ultrasound is also used but is not sufficient for detection of mucosal swelling, and the same goes for the conventional x-rays. Rhinomanometry measures nasal airflow based on the Trans nasal pressure difference. It is prone for measurement errors or up to 15-25%. Rhinoresistometry is similar to rhinomanometry but gives better results. Acoustic rhinometry is used to evaluate volume and geometrical determinations. Long-term rhinoflowmetry measures air flow in 24 hours. Gives idea of how the nasal cycle is and measures the duration of working/resting phases. Measurements of nasal expiratory nitric oxide are influenced by

lower airways. There are high variation between individuals so accuracy reports are not available for this technique[27].

Chronic Rhino Sinusitis is one of the most frequent health problems in humans. The burden of the diseases is high, and includes mainly allergies and infections [28].

Commonly, children suffer from upper airway infections, the elderly have decreased elasticity and changed amount of nasal mucosa, especially postmenopausal women and some diseases result in dry nose, e.g. diabetes. Many treatment processes are available and include both medical and surgical solutions. Objective staging of disease load is mandatory both to set the diagnosis and also to evaluate treatment outcome. To date this staging is missing[29].

Research has been done in measuring the width, length, depth and volumes of these sinuses and development from birth estimated. Much of it has been done using conventional x-rays og two-dimensional CT. The research has not been looking at the stage of disease but only sizes and development. A scoring system of the anomalies in the four sinuses is available for development of the sinuses in children decided from the size of the sinuses [30]. The sinuses are fully developed at 20 years of age so surgical interventions for children have to be uniquely tailored because of the undeveloped sinuses. This research was not able to do an accurate comparison between cases. The sinuses are all similar in size but differ between sexes, where males have larger ones. One group made manually segmented CT images for safe robot assistance in functional endoscopic sinus surgery, made risk analysis from the bones but was not evaluating the state of mucus membrane. Segmentation is safer and more accurate done manually. If it is done automatically, it has to be reviewed and corrected afterwards. Previous studies have been focusing on surgery planning by estimating sizes of sinuses rather than in evaluating the stage of the disease. One research measures the thickness of canine fossa to develop Doppler equipment. A scoring system for non-neoplastic sinus

disease is available [28]. One is based on the site of disease rather than the degree of sinus opacification and gives a clear definition of sinus disease. No major difference is found in the references between the left and right sides but difference is great between races. Research done to date has not been using the newest CT technology and there are no references about measuring mucosal inflammation and/or dividing the materials inside the sinuses by type available. In the literature there is research that states that a staging system is necessary but seems not to be available. Early diagnostics and right treatment choice is vital to prevent continuous loss of function and development of the disorders [31][32][33][34][35][36][37][38]. To front these problems it is necessary for doctors to have a staging system to classify what the status of the sinus of interest is and so they can speak the same language, so to speak.

2.2. Anthropometry of sinus nasal cavity using CT scan data and image processing

In order to analyze and quantify volumes within the nasal cavity we use spiral CT data and special medical image processing platform which allow the segmentation of the different regions of interest, the tissue quantification and calculation of the volumes. .

2.2.1. Image acquisition

For this work 30 CT data sets were randomly chosen from the LSH PACS system, the only selection criteria was the scanning protocol which is a sinus scan in all cases, meaning that the scanning volume include the maxillary, sphenoid and frontal sinuses. Selected images have the Spiral CT protocols shown in table 2:

Table 2: Spiral CT protocols

kV	mAs	width [pxl]	height [pxl]	pixel size [mm]	Field of view [cm]	gantry tilt [°]	No. slices	thickness [mm]
100 - 120	20.20	512	512	0.277 - 0.352	14.20 - 18	0	286-185	0.900

In digital imaging, a pixel or picture element is the smallest piece of information in an image. A voxel instead, is a volume element representing a value on a regular grid in three dimensional spaces. The voxel data sets have a limited resolution, as their position is only exact in the center of each voxel. The value of a voxel may represent various properties; in CT scans it accounts for the opacity of the material to X-rays. Each pixel assigned the attenuation value of the corresponding voxel. Linear attenuation coefficients are rescaled to an integer range that encompasses 4096 values, between -1000 and 3095. From these intensity readings, the density or attenuation value of the tissue at each point in the slice can be calculated. MIMICS uses a scale called CT number or Hounsfield unit (HU), expressed by the following equation [39]:

$$HU = 1000 * \frac{\mu_{pixel} - \mu_{water}}{\mu_{water}} \ (3)$$

Where μ_{pixel} represents the attenuation value for the assessed tissue and μ_{water} is the attenuation value for water.

2.2.2. Image processing and segmentation

The data set was imported into MIMICS for image processing. The process was different between patients because of different methods in segmenting healthy subjects and the ones with inflammations. Frontal sinuses, sphenoid sinus and the maxillary sinuses were measured in all subjects, figure 18 shows where the sinuses are located. Segmentation tools were used to calculate volumes, the whole sinus volume and tissue volumes. This method offers a non-invasive approach to see if the patient has inflammations and also for pre and post treatment volumes

MIMICS from Materialise is a type of software that is especially made to simplify and enhance the accuracy in medical modeling [40]. It imports DICOM, JPEG, TIFF, BMP or Raw image data. It is developed for image processing for highly accurate 3D models of

patient anatomy. It also measures in 2D and 3D and exports an STL file for RP. Included in the software are the segmentation tools described below and some more complicated ones like 3matic that makes it possible e.g. to design an implant and do a finite element modeling [41].

1. Thresholding creates a mask; a classification color consisting of the same range of HU in the processing image. Air has the lowest value while bone has the highest. Thresholding allows the specialist to choose one tissue type from the others, called masks.

2. Region growing selects certain parts from the selected mask and to get rid of floating pixels. This has do be done when the mask has been selected. Region growing helps with selecting between parts, even though the mask includes a lot of parts, region growing can select only one of them.

3. Mask Editing is for modifying the mask selected. It is possible to draw, erase and add to the mask by threshold selecting. It is possible to modify one slice at a time but also multiple. Mask editing includes drawing or erasing pixels from the masks formerly made. It is possible to add pixels e.g. if the model is to be solid, the specialist has to fill up some pores and gaps or erase from the mask if it's not supposed to be on the final model.

4. Morphology operations remove or add pixels to the boundary of the selected mask, this is also possible to do with multiple slices at once: erode removes pixels, dilate adds pixels, Open performes an erode followed by a dilate and Close performs a dilate followd by an open. The tools Open and close also come into good use when breaking small connections. Morphology operations help with adding or erasing e.g. one pixel out from each pixel in the previous mask.

5. Boolean operations offer combination of two masks by various methods: minus to subtract one from another, it is also possible to unite and intersect. Boolean operations can e.g. be used to subtract one mask from another or unite two masks.

6. Simulation is for cutting, repositioning, distracting, soft tissue simulation, merging, splitting, mirroring and so on. The simulation part is used to simulate operations, to get a pre and post operation or treatment view.

The toolbox is very large so described segmentation methods are only the ones used here. All these methods acquire good knowledge of the human anatomy for the models to be accurate. If the models are inaccurate the doctor can't use them and the purpose reverses, causing time to be wasted or even possibly harm to the patient. In the software view the images are visible in sagittal, coronal, transversal view and the 4th window is for the 3D model, as shown in figure 19.
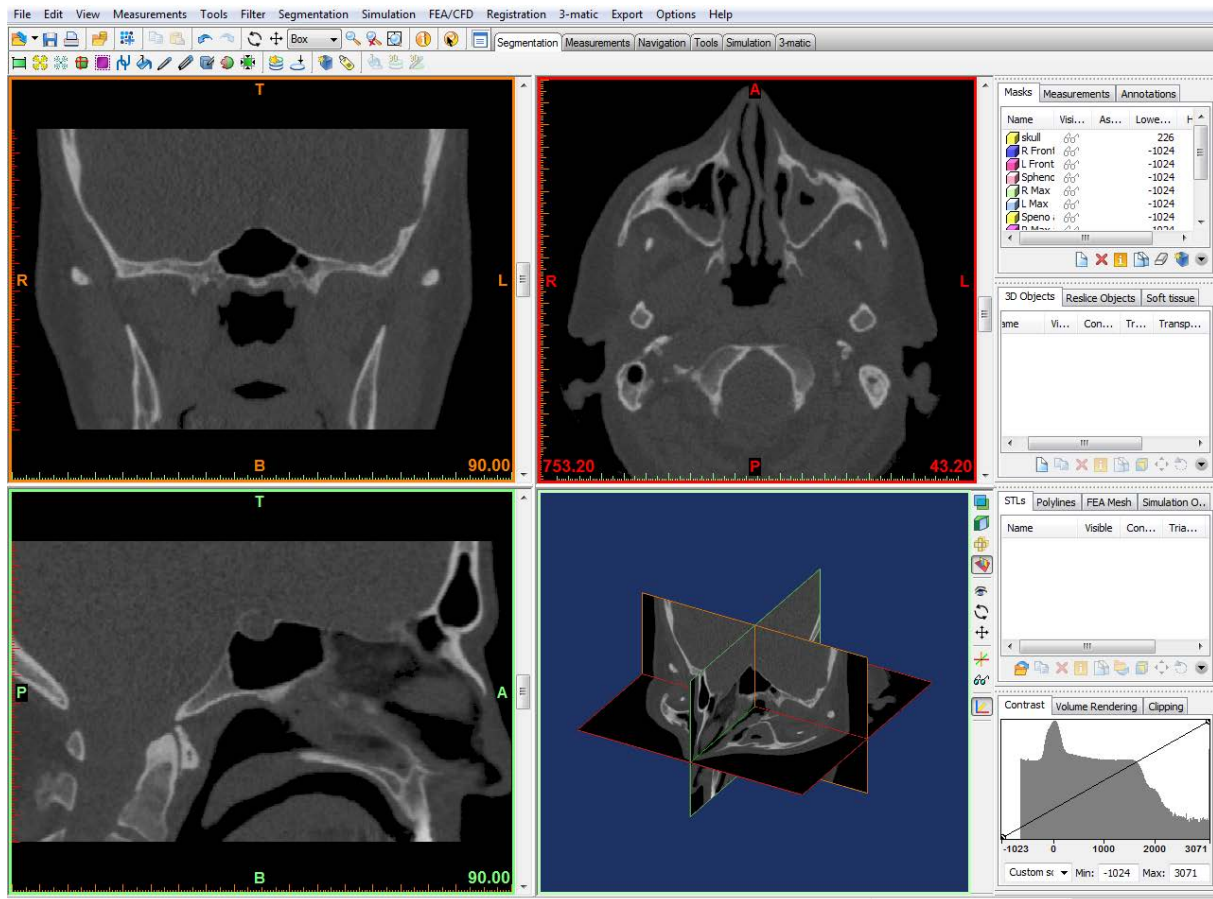
Figure 19: MIMICS views, processing of the patients

2.2.3. Segmentation process

The images of the 30 patients were used to calculate volumes in the sinuses. The segmentation process included a lot of the methods described in previous chapter, the axial view of the slides are used because it is the easiest way for this type of segmentation. The first operation when an image has been imported, the threshold for air is selected, in this case HU from -1024 to -20, as shown in figure 20:
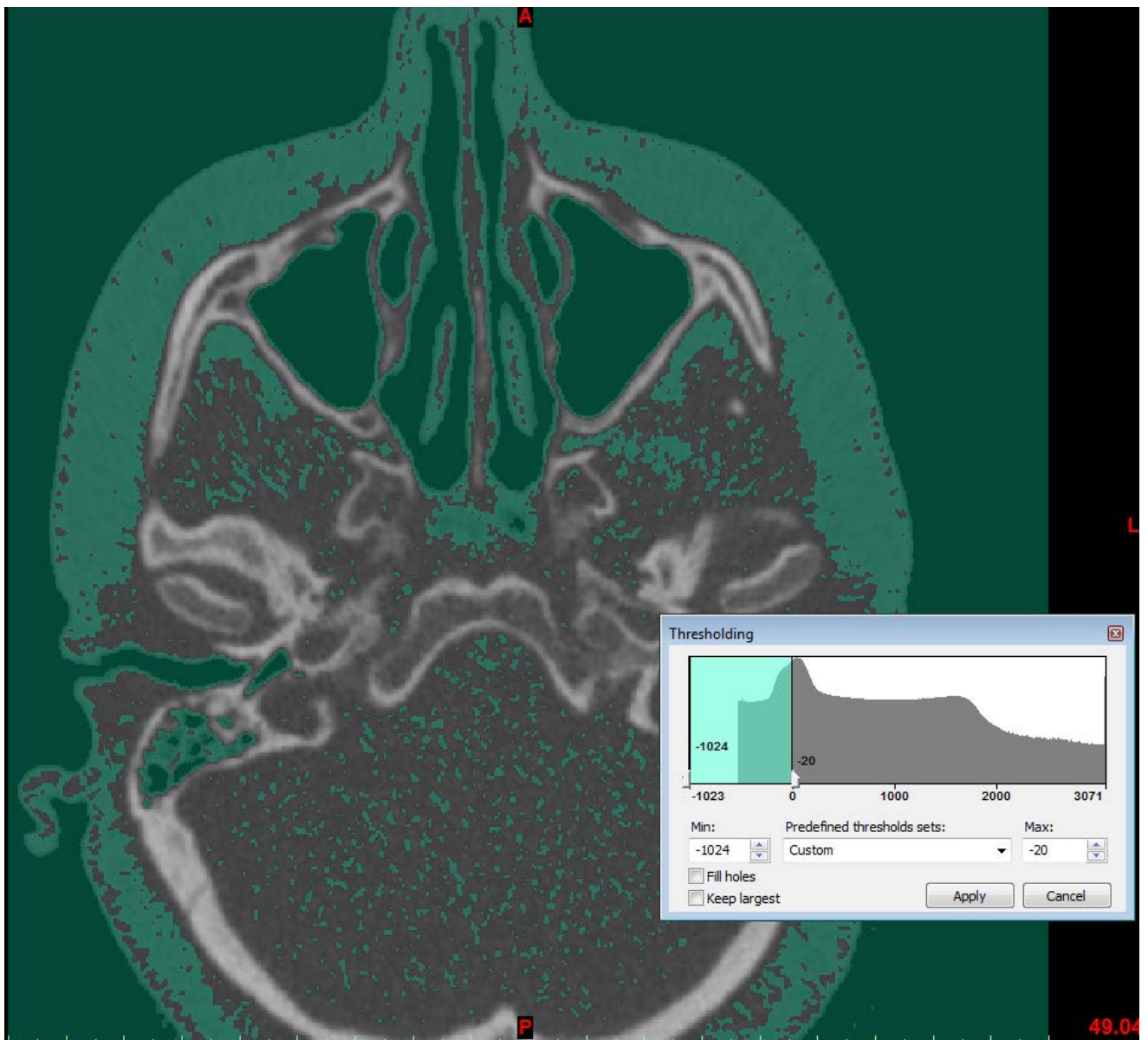
Figure 20: Threshold selected, mask made

Because of connections of the air to the surroundings, pixels need to be erased with mask editing so the field of view can be excluded from the surroundings. When all the connections are broken, new pixels are added inside the volume for the whole volume to be measured. Figure 21 shows erasing and adding of pixels.
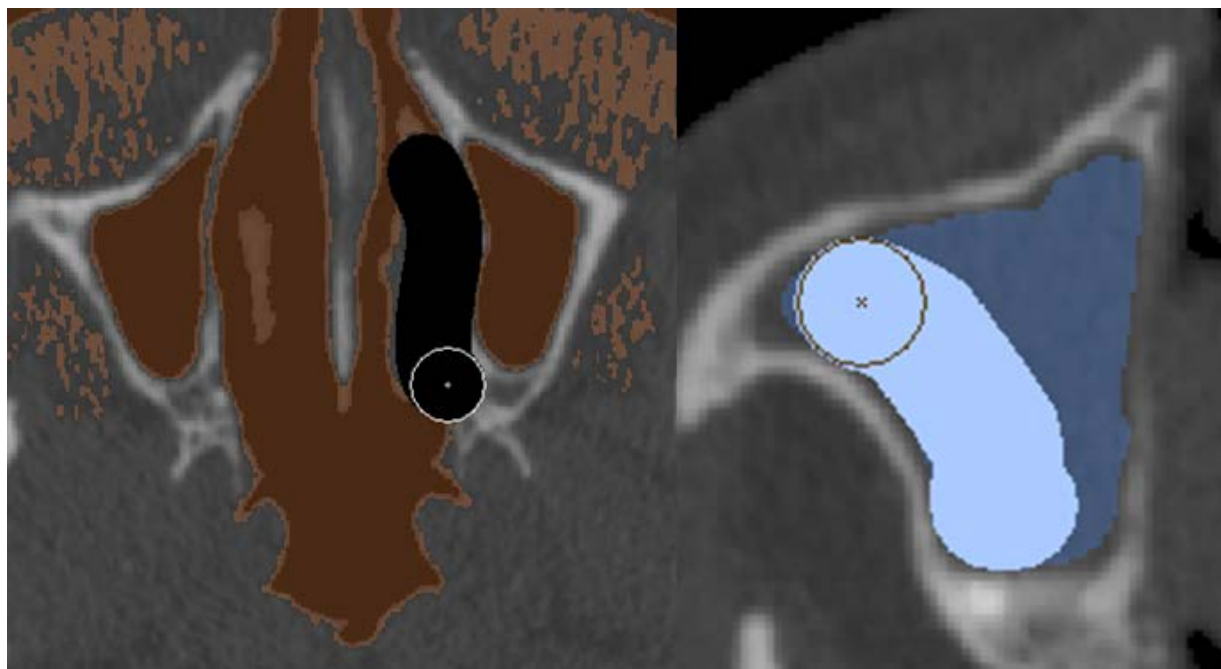
Figure 21: Pixels erased on left, added on right

When the sinus is air filled the segmentation process is easy. The only procedure needed is selecting the mask by thresholding air and then use the tool dilate for 2-3 pixels, shown in figure 22 to fill out the volume.
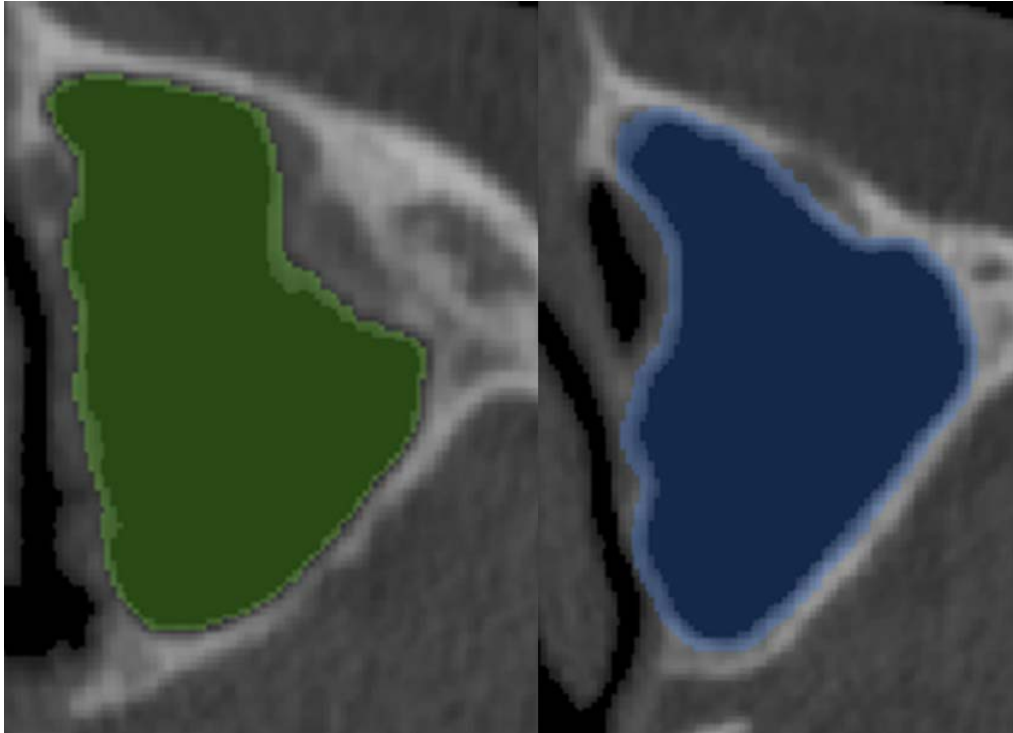
Figure 22: Left is before dilate and right after.These CT slides are not the same.

Figure 23 shows the selected area with both air and tissue, a whole volume.
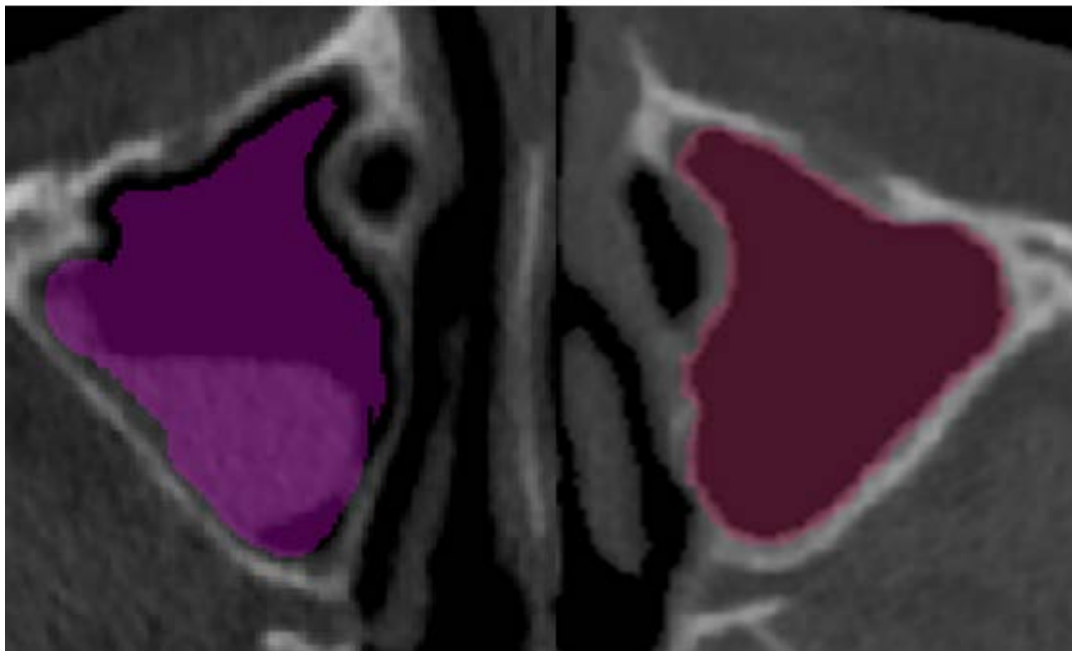
Figure 23: Whole Maxillary volume selected no matter the tissue type, axial view

2.2.4. Volume calculation

The volume in a 3D file can be generally obtained through the voxel size and number of voxels in the 3D object. In biological tissues this is more complicated and there are additional issues to consider. The image that results from the assumption that a voxel within a data set is occupied by one single material is an approximation of the reality because of real dimensions involved in biological tissue. The voxel represents measured value that is a mean attenuation value for different materials or tissue types, called partial volume effects. This will be the case especially for the voxels lying at the border of the object or voxels covering objects thinner than the voxel's dimensions. This lack of resolution can be somewhat overcome by assigning mean values to these voxels and then using interpolation algorithms.

Mimics has two different algorithms that can be used to compensate partial volume effects, contour interpolation and gray value interpolation, shown in figure 24. The latter is more accurate but tends to deliver noisy 3D models, which makes it less useable for medical images. Table 3 shows the difference in volume between algorithms. The contour interpolation value always gives greater value than the gray value interpolation.
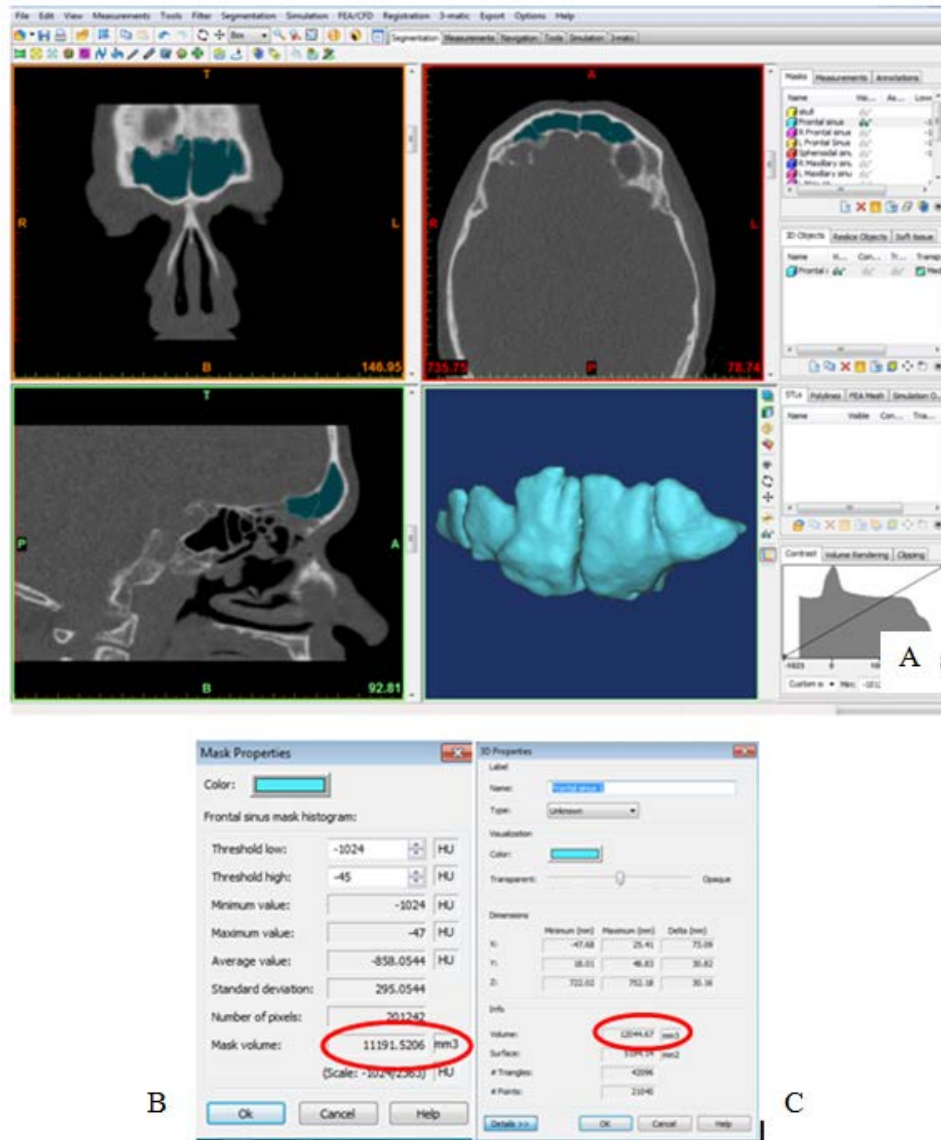
Figure 24: comparison between volumes algorithms calculated with MIMICS for subject 3: A shows the four views of MIMICS, B volume measurements in 2D, mask calculation, C volume measurements on the 3D object

Table 3: Comparison between gray value interpolation and contour interpolation

Sinus	Frontal sinus		Shenoid sinus		Maxillary sinus	
Interpolation	Gray value	Contour	Gray value	Contour	Gray value	Contour
Subject 3	11191	12045	14402	15208	45727	46222
Subject 8	1824	1985	8870	9280	23797	25034
Subject 17	1050	1178	10268	10820	32687	374212
Subject 25	3681	3715	4858	4920	24194	24436

Incorporating partial volume effect compensation greatly improves 3D model rendering accuracy. In this work the contour interpolation algorithm is used to visualize the 3D model of

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sinus cavity and the grey value interpolation algorithm to calculate and measure the sinus volume. A comparison has to be made out from the one and the same method because it isn't reliable if a different approach is used to retrieve data. Table 4 shows what kind of data is retrieved along with the ratio of tissue and air from the whole volume that is usable for making graphs for comparison. Figure 25 gives an example of the resulting 3D model for analyzing; Frontal sinuses are blue, Sphenoid sinus is pink and Maxillary sinuses are green. The colored sinuses are masks that volumes are easily extracted from.

Table 4: Shows the results doctors get from measurements, example from subject 3

Volume	Right frontal sinus	Left frontal sinus	Sphenoid sinus	Right Maxillary sinus	Left Maxillary sinus
Tissue	1704	947	2709	16484	19410
Air	3826	4715	11693	1081	5050
Whole sinus	5530	5661	14402	21267	24459
Ratio of air	69%	83%	81%	31%	21%
Ratio of tissue	31%	17%	19%	69%	79%
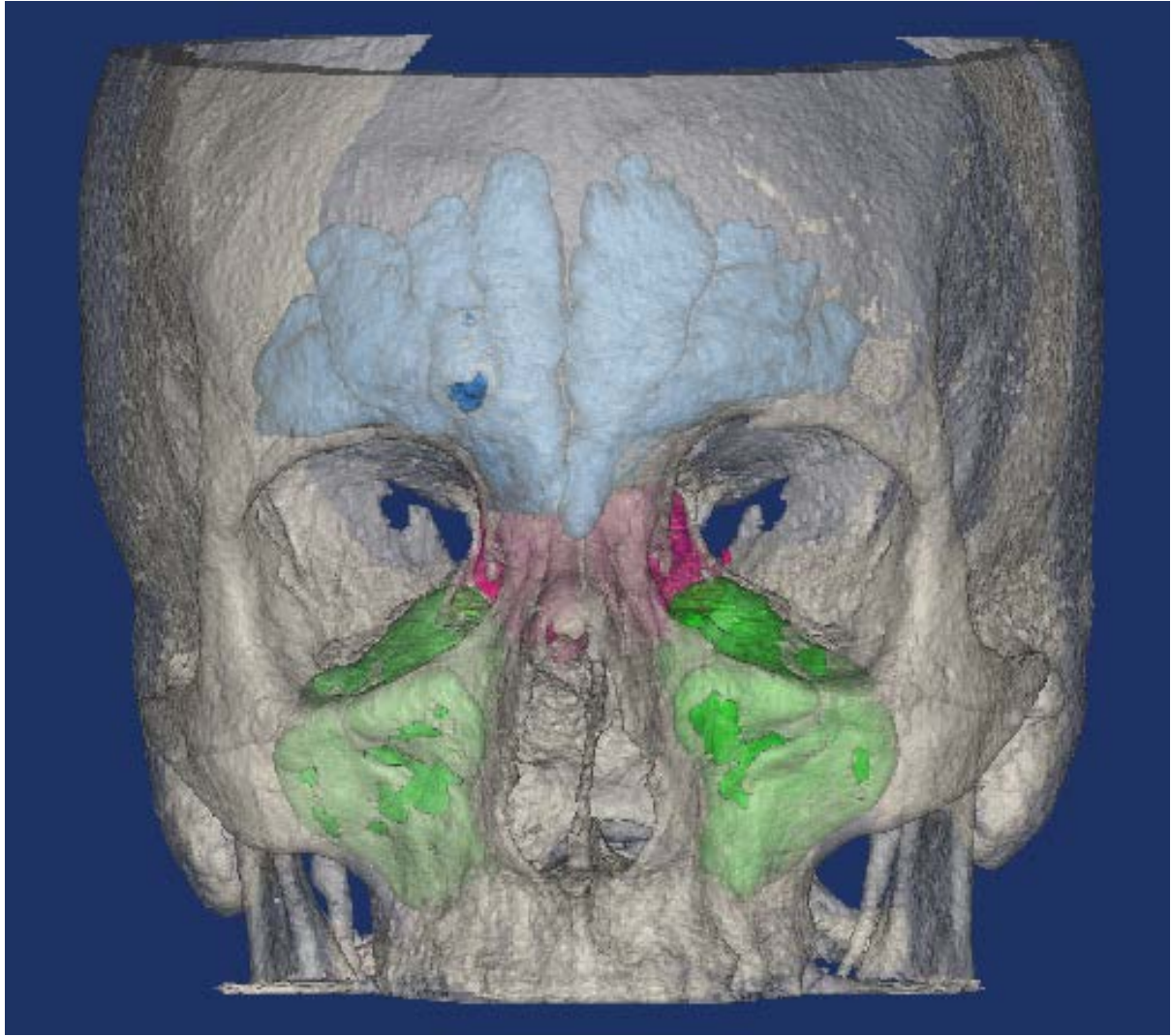
Figure 25: Processed volume of all sinuses

3.   Database design for the Rapid Prototyping service at Landspitali

The RP service at LSH is a rapidly growing department and needs a database to collect all the data regarding its cases. Figure 26 lists up the protocol needed for the service like they are described in chapter 1.3. The service has 3DP machine called ZPrinter® 450 from ZCorp. The database is a tool to gather data for this service and to make it easy for doctors to order models through it instead of ordering via email [42].

Figure 26: An introduction poster for doctors

A database is needed for the service to gather all the information that comes in regarding cases and for easy access for all parties, the engineers and the medical staff. It allows for calculations both for data analyzing and for the model cost. A database provides shelter for data, data analysis and an overview; all in one place instead of being in many places and in many excel files on various computers. This way, all parties can access up to date data. Figure 27 describes the workflow that is necessary for creating a database. First the tables are formed and a decision made on the structure of the database. From that decision relationships are formed. The service decides what information they want to extract so queries and forms are

created. When the user mode is designed, macros are inevitable to make buttons for actions required.
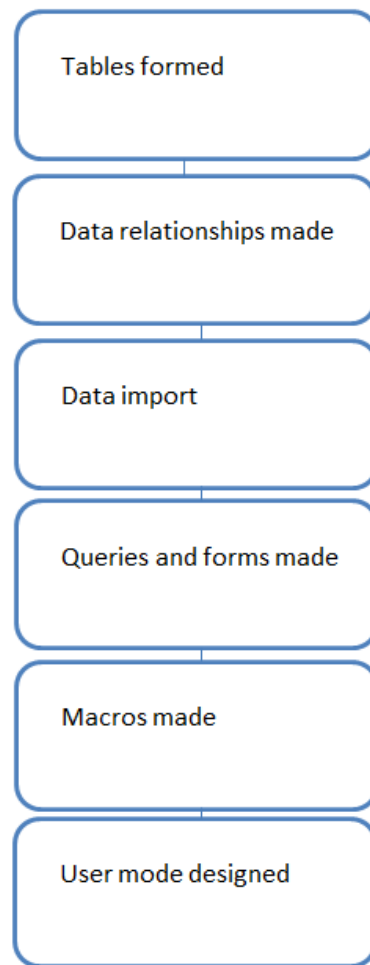
Figure 27: Workflow for the data mining process

3.1. Database architecture

A database is used to gather data from different projects and keep it in one place. The database should be stored onto the LSH server on a secure spot for all parties to access. Patient information, image protocols, measurements and everything that needs to be kept together should be kept in the database. Each department should be kept as a subfolder under the RP services hat. In each department folder, are different case types, with a subfolder for each patient that has undergone that treatment/surgery. For the different cases there is a need for comparison and of course the possibility of adding new patients. To get the overview that

is needed Microsoft©Access 2010 is used. A database is a software system used for cataloging, retrieving and running required data. It manages incoming data, organizes it and provides ways for modifying or extracting the data. A database is designed to store a lot of data in complex ways that the everyday user does not have to understand. The database has to offer data safety, therefore it has to be on the LSH server that is protected for losses of data and is maintained properly. A database offers multiple users to use it at the same time and the need for a database rises from the number of people working with the same material. A database schema is the overall structure that specifies data, relationships, semantics and consistency constraints on the data. The database model is based on collection of basic objects, called entities and the relationships between them. An object contains values stored in instance variables within the object. Methods are bodies of codes that operate on the object. An object catches data from another object by invoking a method. This is not visible externally. Each record has a fixed set of fields. The size of a database varies from few megabytes to gigabytes or even terabytes. A database schema is specified by a set of definitions expressed by a data definition language. Data directory is a set of information stored in a specific file that contains data about data that the average user never sees. A data definition expresses a set of definitions used to specify storage structures and access methods. Users can be allowed to read/look at the data but not manipulate it. The designer decides who can do what regarding data manipulation, meaning retrieving, insertion, deletion and modification of the data. A query is a statement requesting how the information is to be retrieved. The goal for the database is to keep all types of data according to the use.

At LSH a good database is a tool to connect engineers and physicists. A requested data can be accessible for everyone working on the case. A good database can provide time reduction and work efficiency because of data gathering, all data accessible in one place. The RP service

undergoes a lot of projects that have to be under control. The departments that ask for the service vary so all the data has to be reachable under one hat.

Database is made as an overview of the 3D service at LSH. The RP service is rapidly growing and the database created is supposed to ease the overview of all the projects assigned. The architecture of the database is decided beforehand. All relations have to be designed although it is possible to add more later on. Figure 28 shows relationships between data sets in the sinus project. This is not visible for the day to day user but is behind the scenes to manipulate how the data is connected. This way the data added are also connected the right way. By using this relationship, data will automatically be displayed the way the designer wants.
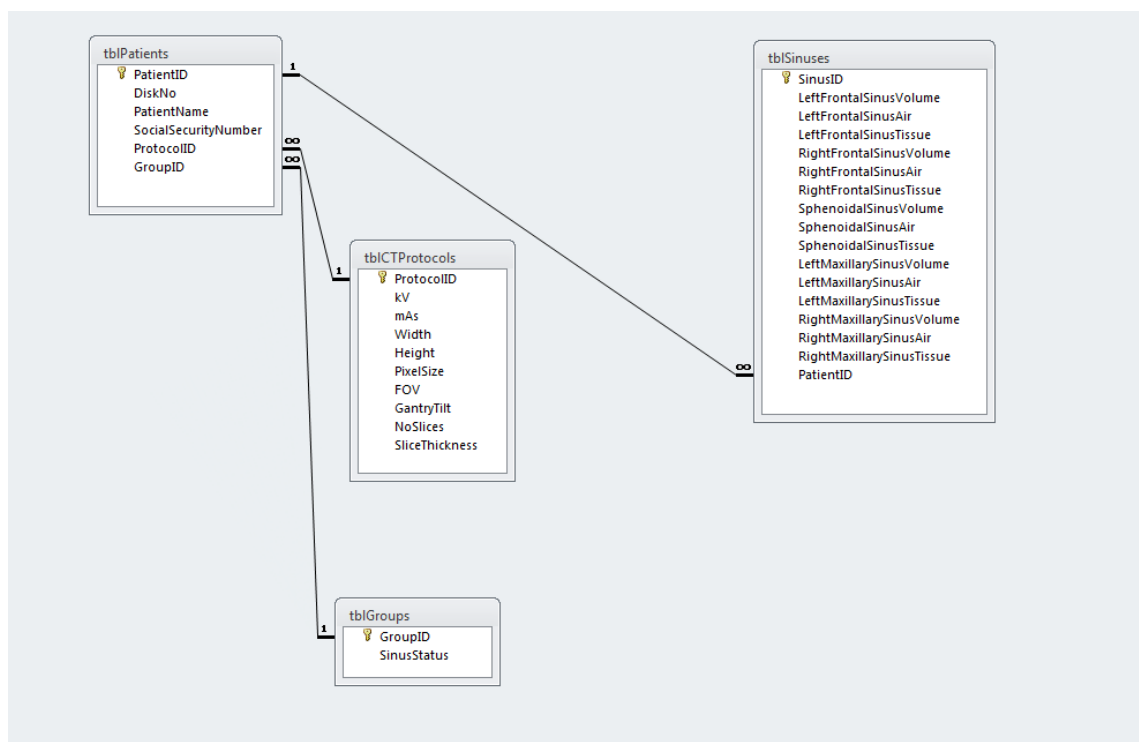
Figure 28: Relationships behind the sinus data

Relationships are very important, relationships are amongst objects. Each data has fixed set of fields and therefore it is called relational model database. It uses a collection of tables to present the data. When the tables are ready, similar to those made in excel, it is possible to get anything wanted from it in a form or a query that retrieves requested information. Forms are

an overview of wanted data also but the difference between queries and forms are that in queries it is possible to make calculations, use filters and choose how to pinpoint the data more accurately [43].

In the project information was extracted from excel files available but in the future the idea is to enter each data when it is available. Pages were made for each project and buttons/macros made accordingly.

3.1.1. Data base tree

The ideal database tree in figure 29 shows how the database should be built. The database has to hold together all information for all departments serviced but also the binder usage and all data that helps in calculating the cost of the models.
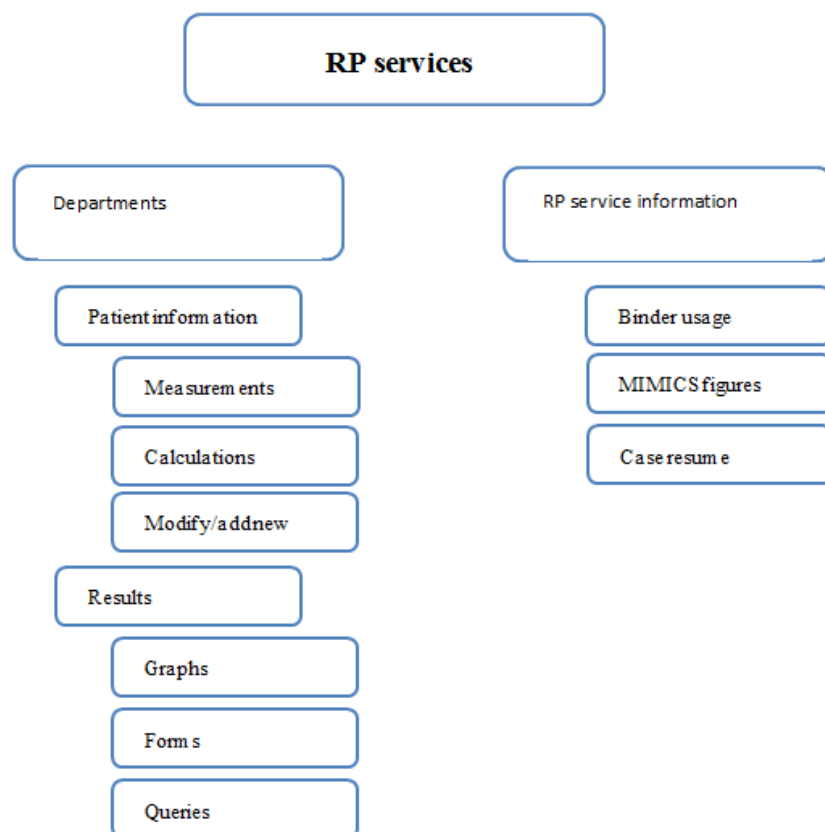
Figure 29: An ideal database tree

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4.   Results

4.1.   Analysis of sinus nasal volume

A method is developed to evaluate the anthropometry of sinus nasal cavities, based on the threshold definitions. Masks are made for all the sinuses of interest. The tools of MIMICS are used to select or deselect pixels for a good measurement. When the masks have been finalized with all wanted pixels, the program calculates volume of it. From that volume, a ratio is calculated with two equations:

$$ratio = \frac{volume\ of\ air}{whole\ sinus\ volume} * 100 \quad (1)$$

$$ratio = \frac{volume\ of\ tissue}{whole\ sinus\ volume} * 100 \quad (2)$$

The ratio is calculated between the air mask, equation (1), and tissue mask, equation (2), this ratio is put into a graph to show the status of the sinuses.

Ratio	Sinus status
Tissue 0% - 40%	Clear
Tissue 40% - 100%	full

Group 1 has all the sinuses clear, i.e. all tissue ratios are under 40%, patients are considered healthy. Figure 30 shows a patient in group 1.
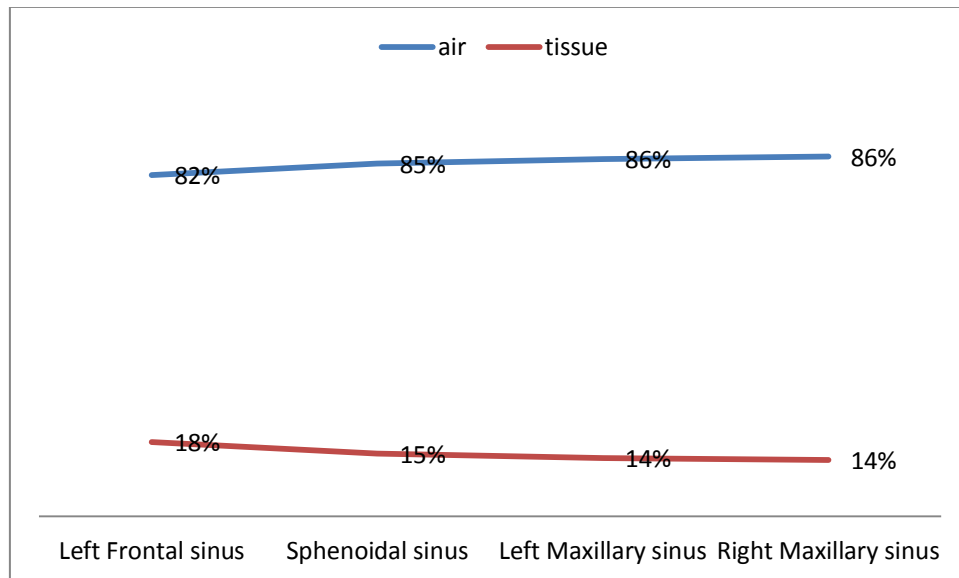
<div align="center">**Figure 30: Group 1 - all sinuses clear**</div>

Group 2 consists of patients that only have one sinus full, figure 31 show the Sphenoid sinus full but the others can also be singularly full without the other, e.g. the left maxillary sinus can be full even though the right one is clear.
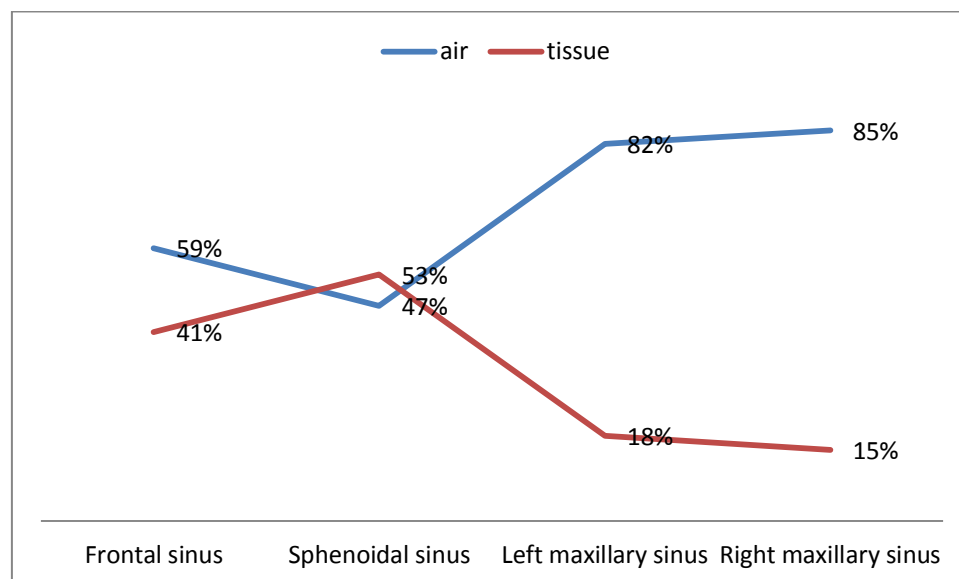
<div align="center">**Figure 31: Group 2 – One sinus full**</div>

Group 3 has both of the maxillary sinuses full, according to the data as is shown in figure 32.
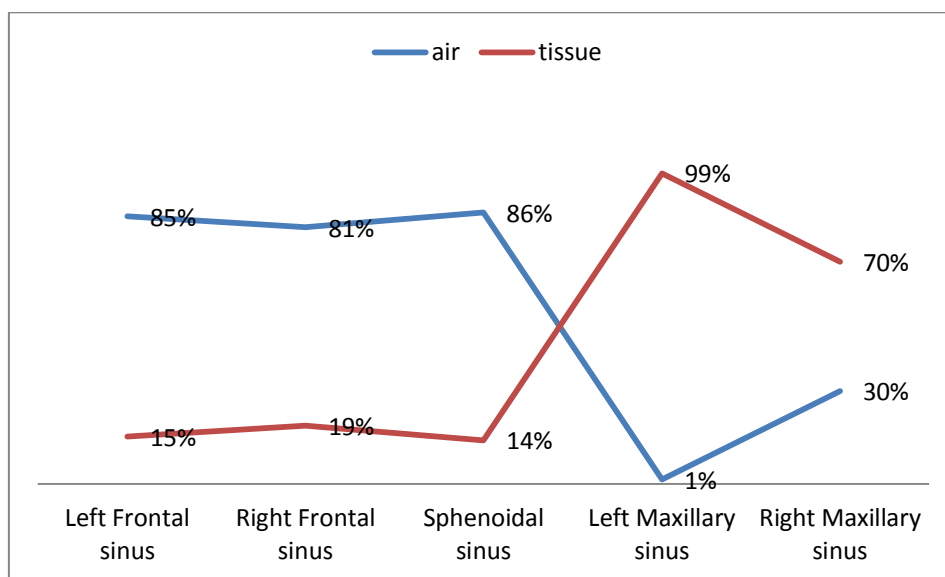
Figure 32: Group 3 - Both maxillary sinuses full

Group 4, this group classifies any two sinuses full, figure 33 shows the right frontal and the left maxillary sinuses full.
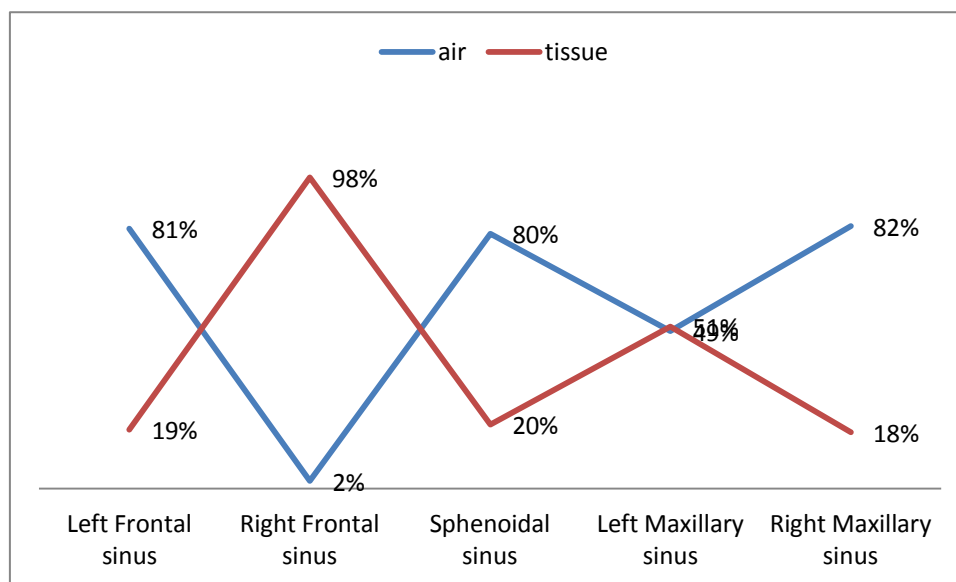
Figure 33: Group 4 - Two sinuses full

Group 5 is classified by three sinuses being full. Figure 34 shows how both of the frontal sinuses are full and also the left maxillary sinus.
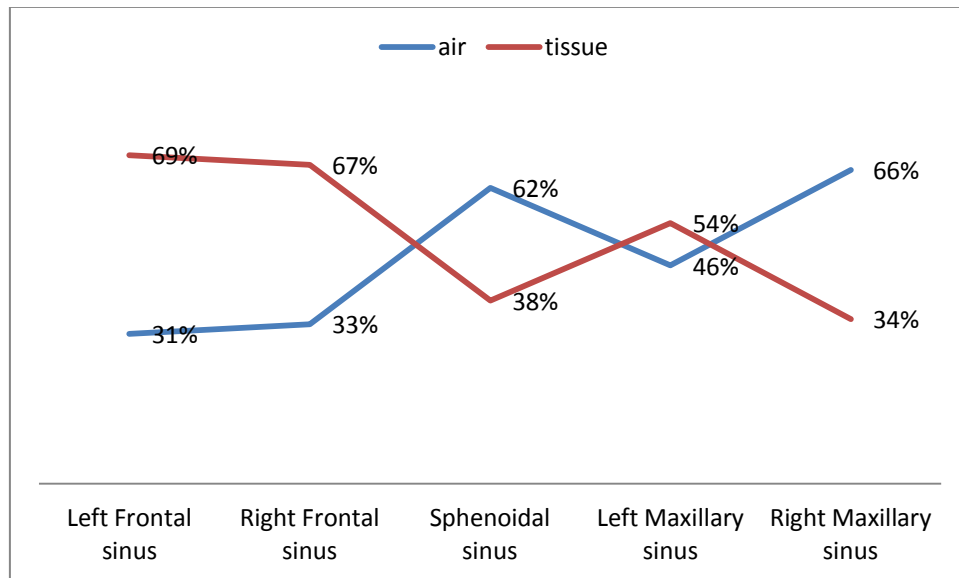
Figure 34: Group 5 - Three sinuses full

Group 6 consists of patients with all sinuses full. Figure 35 shows all the sinuses over 40%.
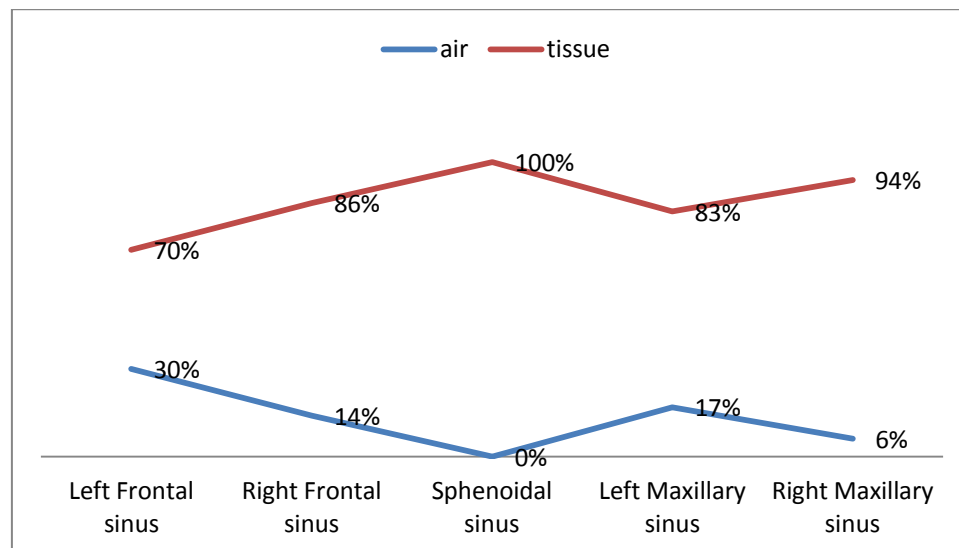
Figure 35: More than three sinuses full

The pie chart in figure 36 displays how many subjects are in each group and the percentage of the 30 subjects processed.
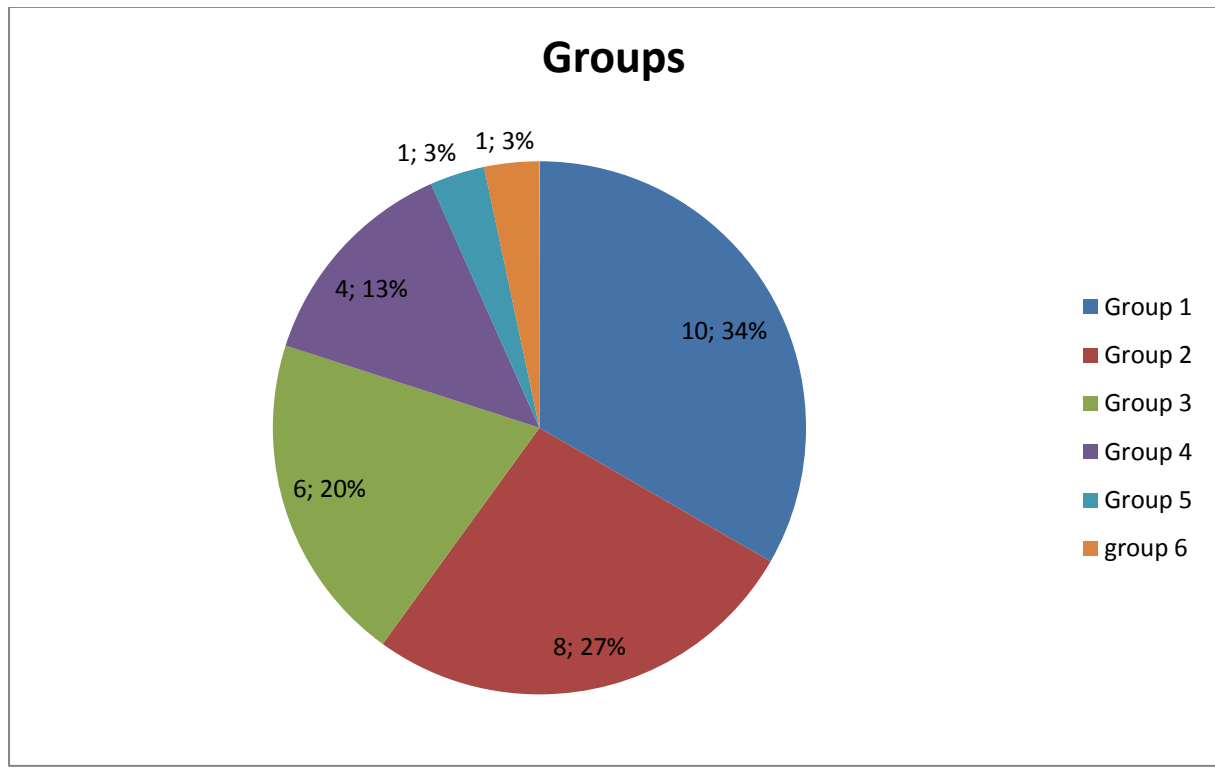
See all 30 graphs in Appendix A

4.2. Data mining for medical modeling and rapid prototyping service

The database built for the RP service at LSH is not the same as the ideal one in figure 29. The RP service has been working a lot with the ENT department, therefore it gets most of the space on the database for now even though the other departments are also available as shown in figure 37.
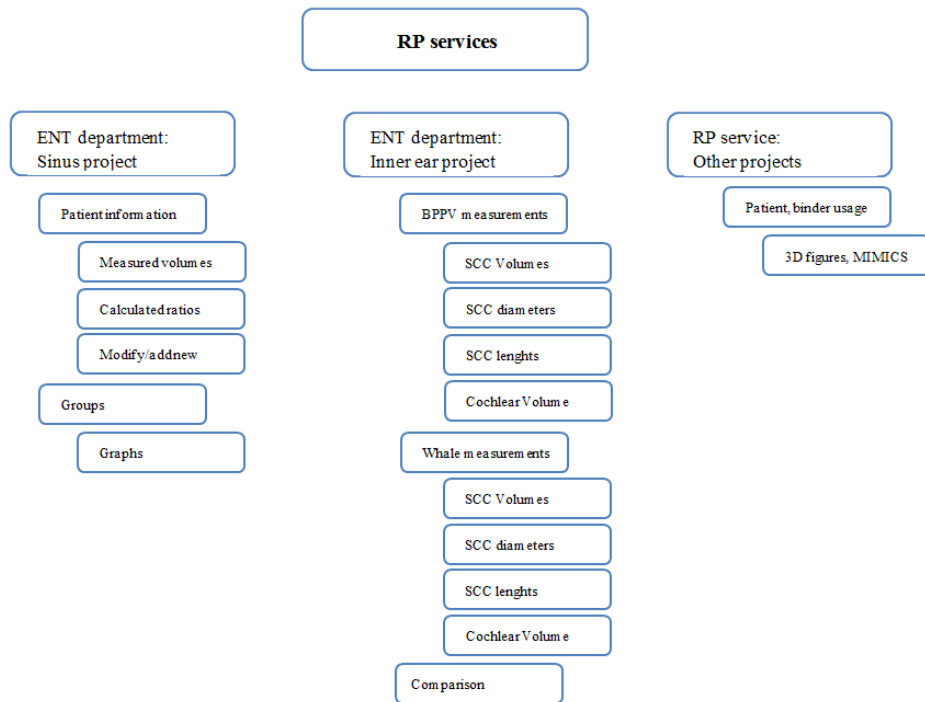
Figure 37: The database tree for the RP service at LSH

When data has been imported and organized the front page looks like figure 38, with buttons for each project.
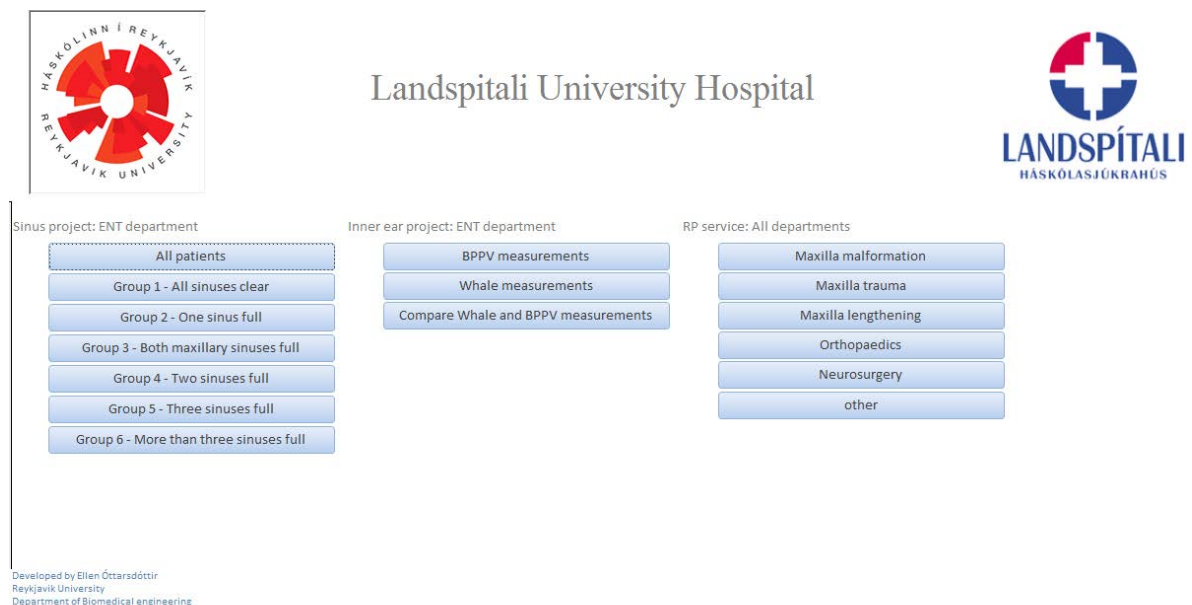
Figure 38: The front page of the Database

4.2.1. Sinus nasal project

The blue buttons in figure 38 lead to the pages described on the button, as shown in figure 39 when the All patients button is pressed.

Figure 39: A form that shows one patient and all the measurements related.

In a page like the one shown in figure 39 it is possible to view measurements, patient by patient or to add new measurements and to add a new patient.

A query helps with organizing the patients according to the group they consist of, in the view shown in figure 40, it is also possible to push buttons to see measured volumes, see calculated ratios between tissue types and to add a new patient. The home button sends the user back to the front page. This query only shows patients in group number 1, the ones with clear sinuses.

Figure 40: A query, gives a collection of data

If more patients are added afterwards, it is performed in Access. The structure of the database specifies data relationships and consistency. All the buttons are made by the designer. First there is the sinus project described above in Novel applications. Under "All patients" there is a list of all subjects sorted into groups of severity of inflammations. Under each group, there is a list of all subjects in that group and a possibility to press a button to go home, that is the front page. There is also a possibility to see graphs, as shown in figure 41.
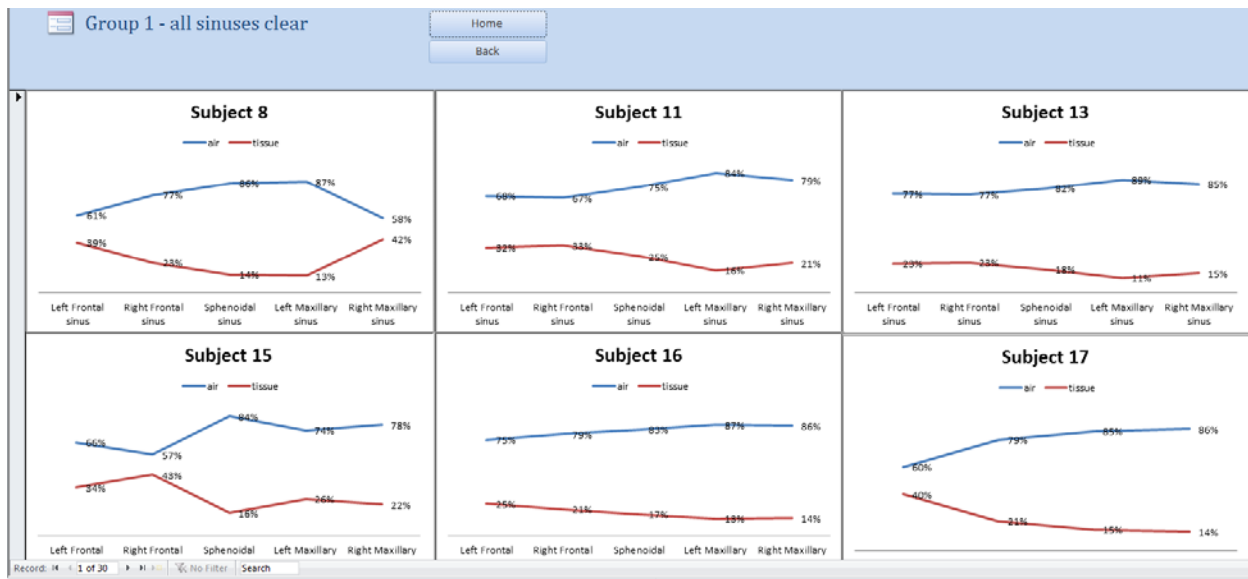
Figure 41: An example of graphs comparing one group - Group 1

In that view it is either possible to go home, i.e. the front page, or to go back one page.

5. Conclusion and discussion

5.1. The thesis

The sinus project gave good hands on training in the software MIMICS and can without a doubt help physicians in evaluating treatments with this non-invasive method. Of course it is possible for the physician to look at the CT scans alone without implementing them into MIMICS but the 3D process gives a possibility for calculations and tools to measure various tissue types. Both LSH and the patient benefit from this because of a better understanding of the case, and in some cases surgeries can be avoided, saving valuable resources and time. The method also gives results that are usable for minimizing antibiotics use. Information like this is also put on the database, by the doctor when ordering the processing work and the engineer to submit data to clinical staff. Referring to the results in the sinus nasal cavity project, a database like this can help both the engineer and the doctor to understand each other, it is a tool between them. The database created is a helpful tool to keep track on everything done by the RP service and helps in calculating cost. It is good to manage all the data in one place.

This is all possible in excel but each data in a different sheet so this makes viewing easier and an easy access because it is all in one place. It holds information together that otherwise would be in many different places with a number of people. There is no doubt that it is in everyone's best interest to gather the information in one place so it is accessible for all parties. The database is a good tool between engineers and clinical staff where the staff can enter information for engineer's evaluation and for the engineer to give an overview of his work and to show its results.

5.2. Future challenges

5.2.1. Brain Surgery

Brain surgeries can be very complicated in planning so medical modeling is a valuable tool to help doctors plan where the most suitable location is to enter the skull and also to realize whether or not the surgery is even possible.

Brain surgeons use a navigation system for these surgeries but even so the model can also help. At Landspitali University Hospital in Iceland they use StealthStation S7 from Medtronic that can be described as a GPS navigation system for surgeons. The system interacts with MRI, CT and more modalities. It has two navigation systems to choose from, an advanced optical surgical navigation camera or AxiEM™ electromagnetic system.

5.2.1.1. Segmentation

For segmentation of a brain tumor the best way is to combine MRI and CT images because of the different quality of different tissues. By using that method it is possible to get the best quality of both modalities. This makes it possible to segment the skull and the tumor for visualization of the tumor in reference to the skull, as shown in figure 42. The doctor can then create reference points on the model of the skull before the surgery is performed and even practice the entrance, shown in figure 43.
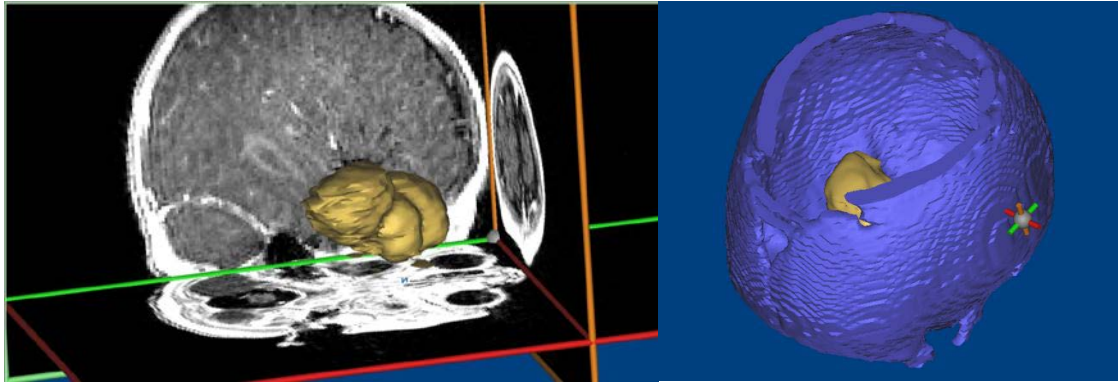
Figure 42: A brain tumor segmented in MIMICS

Figure 43: Model ready for practice, small tumor is pink in the bottom of the skull

5.2.2. The Future

The future for RP lies in more challenging anatomical cases, scaffold manufacturing and tissue engineering. The challenges are in discovering what materials are best to use for mimicking the microstructures of living materials. The scaffolds need to be accurate, with the right pour size and thickness of walls. Enormous findings have been developing in the organ manufacturing field today. Scaffolds are made and even organs printed out of some materials. A constant development is ongoing regarding this field and will hopefully give good results in the future. Problems are mostly trapped volumes. Materials picked have to offer results for conditions inside the body and it's crucial that the scaffold helps with cell regeneration. Materials have to be bioresorbable and offer the possibility of living tissue becoming one with the scaffold, even in some cases the scaffold has to dissolve in time when the tissue has grown into it. RP techniques are capable of using biological agents that are very useful when scaffolds are fabricated. 3D printing is mostly used in scaffold manufacturing in this purpose to date because of many limitations in other techniques.

The most recent news are from a company called FASOTEC in Japan (www.fasotec.co.jp), which states that expectant parents can "print" out their fetus, as shown in figure 44. The mother undergoes MRI for imaging, the images are processed in a 3D software and printed out in a 3D printer using clear resin for the mothers body and white one for the fetus. This is called "Shape of an Angel" and costs around US $1230 for a 90x60x40mm model.
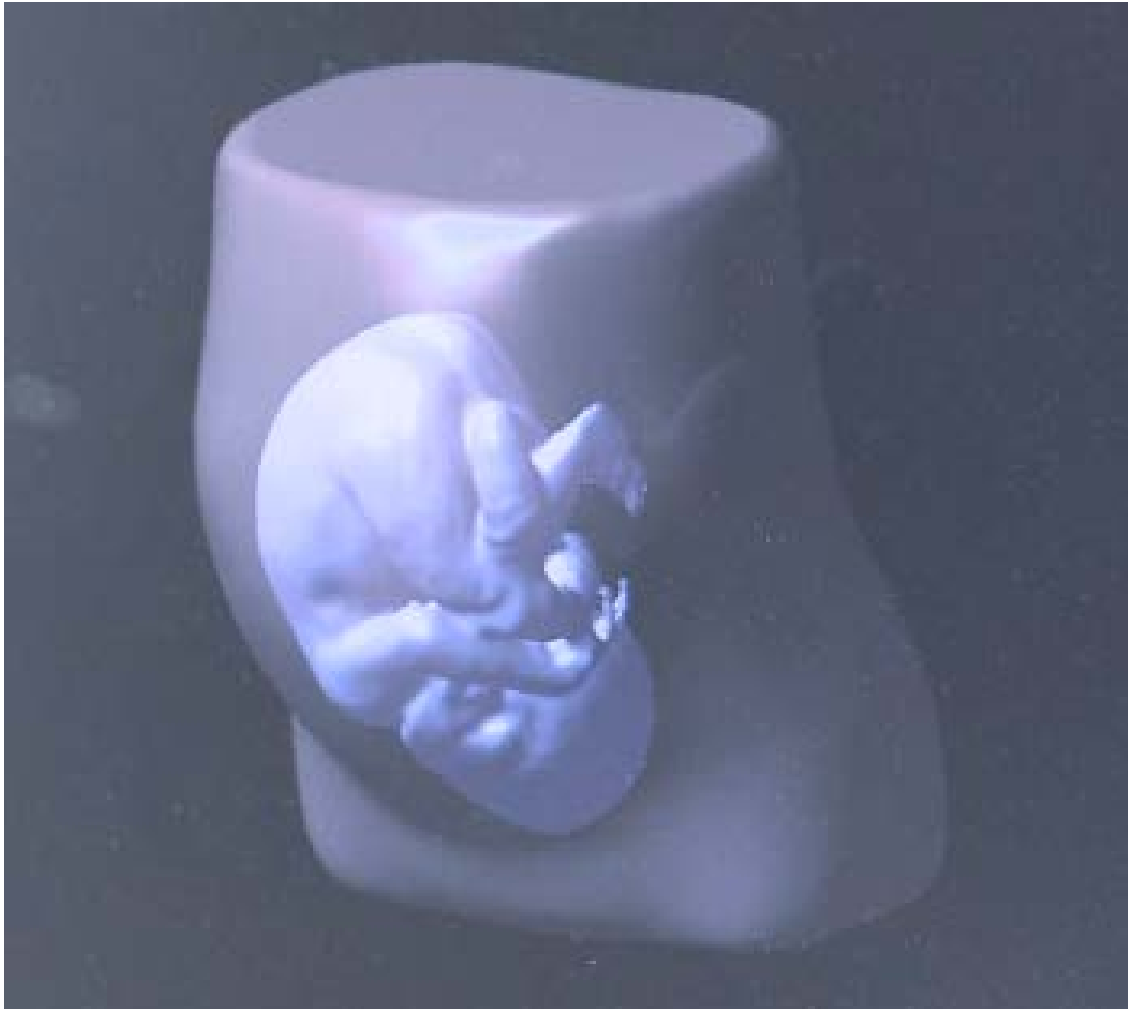
Figure 44: A 3D model of a fetus

Doctors are realizing more and more how priceless this method is, it is only a question of trying new things and figuring out what more is possible.

5.3.   Cost, organization and brake even in LSH

The service gives a new perspective on cases. Cases are very different and the possibilities are endless. Medical modeling provides a good noninvasive method for very difficult cases. The specialist who processes these models has to have a good knowledge of the human anatomy. This technique is constantly under development so the difficult problems specialists are facing today will probably be easily processed in the future. Changes and new tools are being added to these 3D processing softwares rapidly. If specialists and doctors work together this can be much more widely used for assessment of clinical cases and preparation of surgeries. In some cases models have stopped unnecessary surgeries and minimized surgery time, lowering the risk of infections and blood clots. This is not only used for preparing surgeries/treatments but doctors can also use these models for displaying it to co-workers in demanding cases.

The time and cost savings differ between cases. In calculating the time savings in surgeries from 3D modeling, there are a lot of factors that cannot be calculated precisely because of missing parameters. A break-even analysis calculates when the 3D modeling is profitable. Helga H. Bjarnadóttir from economical/statistics department of Landspitali University Hospital collected numbers necessary for calculations, especially surgery and equipment costs. A number of doctors at the hospital gave away time reduction. Break-even calculations are then performed as follows:

$$Break - Even = \frac{f_c + (vc * t)}{vs * t}$$

Where

F_c = fixed costs

v_c = variable costs/surgery

v_s = variable savings/surgery

t = number of surgeries

A break-even of <1 represents a saving for each following surgery – there the savings are larger than the costs.

The break-even is 33 surgeries when cost is compared to savings, table 5, for each surgery. After 33 surgeries the procedure is profitable for the hospital. This number lowers though when factors come into account, like: patients not staying as long at the hospital, each day in recovery cost around 83000 ISK, material cost lowers with 3D modeling preparation and in some cases a second surgery is prevented.

Table 5: Saving-cost comparison and break-even analysis

costs						
Operation type	segmentation + printing model [kr/surgery]	extra preparation time	office cost [kr/year]	software cost (use 7 years) [kr/year]	software-updates [kr/year]	printer (use 7 years) [kr/year]
Maxilla lengthening/Tibia fracture	25.000	-*	5.430.000	463.500	650.000	714.285

savings**				calculation		
Operation type	Operation cost [kr/minute]	savings [kr/surgery]		fixed costs	7.257.785	kr
Maxilla lengthening surgery	4179	around 250.740kr		variable costs/surgery	25.000	kr
Tibia surgery	4012	around 240.720kr		variable savings/surgery	245.730	kr
				break-even point:	33	surgeries/year

Some factors have to be considered when reducing the model cost itself. The Binder usage is given in the printing process but out from that calculation for powder usage has to be performed but it is not possible to do that precisely without knowing how the model is built: are there trapped volumes for example. The process time has to be included into calculations along with the imaging modality, does the specialist need CT images or MRI or even both? The view of interest has to be clear to save on materials. If the specialist has knowledge of specifications to minimize the cost without risking the accuracy of the model it has to be

performed. It is difficult to minimize costs in calculations because of the many non-quantifying factors.

Doctors interviewed were Dr. Ingvar Hákon Ólafsson, Dr. Guðmundur Björnsson, Dr. Halldór Jónsson Jr. They have all been using this service for some time now. It would be better if the service would be less time consuming. Hopefully, the method will work faster in the future. In acute cases they can't wait for the time needed for this modeling work to be done. Also because the service at the hospital only offers 3D printing it is not possible to take the model into the operating room, because it is not possible to sterilize them.

3D modeling at LSH is a very useful tool for treatment/surgery planning and for simulation. It does not always lower expenses but can increase the safety of the patient and their quality of life after surgery. If the surgeon has prepared for the surgery it most certainly benefits the patient, resulting in shortened recovery time, less chance of infections and lowered cost.

Even though numbers are given doctors agree on one thing: if these models save one life it is priceless!

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Appendix A

Shows all graphs from the 30 patients, randomly selected and measured in the Anthropometry for sinus nasal cavity, evaluation.

Subject 3

air — tissue

	Left Frontal sinus	Right Frontal sinus	Sphenoidal sinus	Left Maxillary sinus	Right Maxillary sinus
air	83%	69%	81%	21%	31%
tissue	17%	31%	19%	79%	69%

Subject 4

air — tissue

	Left Frontal sinus	Right Frontal sinus	Sphenoidal sinus	Left Maxillary sinus	Right Maxillary sinus
air	30%	14%	0%	17%	6%
tissue	70%	86%	100%	83%	94%

Subject 5

air — tissue

	Left Frontal sinus	Right Frontal sinus	Sphenoidal sinus	Left Maxillary sinus	Right Maxillary sinus
air	81%	2%	80%	51%	82%
tissue	19%	98%	20%	49%	18%

Subject 6

air — tissue

	Left Frontal sinus	Right Frontal sinus	Sphenoidal sinus	Left Maxillary sinus	Right Maxillary sinus
air	64%	0%	68%	78%	3%
tissue	36%	100%	32%	22%	97%

Subject 7

air — tissue

	Left Frontal sinus	Right Frontal sinus	Sphenoidal sinus	Left Maxillary sinus	Right Maxillary sinus
air	75%	72%	72%	35%	27%
tissue	25%	28%	28%	65%	73%

Subject 8

air — tissue

	Left Frontal sinus	Right Frontal sinus	Sphenoidal sinus	Left Maxillary sinus	Right Maxillary sinus
air	61%	77%	86%	87%	58%
tissue	39%	23%	14%	13%	42%

Subject 9

air — tissue

	Left Frontal sinus	Sphenoidal sinus	Left Maxillary sinus	Right Maxillary sinus
air	63%	64%	27%	31%
tissue	37%	36%	73%	69%

Subject 10

air — tissue

	Left Frontal sinus	Right Frontal sinus	Sphenoidal sinus	Left Maxillary sinus	Right Maxillary sinus
air	50%	45%	6%	28%	6%
tissue	50%	55%	94%	72%	94%

Subject 11

air — tissue

	Left Frontal sinus	Right Frontal sinus	Sphenoidal sinus	Left Maxillary sinus	Right Maxillary sinus
air	68%	67%	75%	84%	79%
tissue	32%	33%	25%	16%	21%

Subject 12

air — tissue

	Left Frontal sinus	Right Frontal sinus	Sphenoidal sinus	Left Maxillary sinus	Right Maxillary sinus
air	74%	77%	83%	93%	29%
tissue	26%	23%	17%	7%	71%

Subject 13

air — tissue

	Left Frontal sinus	Right Frontal sinus	Sphenoidal sinus	Left Maxillary sinus	Right Maxillary sinus
air	77%	77%	82%	89%	85%
tissue	23%	23%	18%	11%	15%

Subject 14

air — tissue

	Left Frontal sinus	Right Frontal sinus	Sphenoidal sinus	Left Maxillary sinus	Right Maxillary sinus
air	31%	33%	62%	46%	66%
tissue	69%	67%	38%	54%	34%

Subject 15

air — tissue

	Left Frontal sinus	Right Frontal sinus	Sphenoidal sinus	Left Maxillary sinus	Right Maxillary sinus
air	66%	57%	84%	74%	78%
tissue	34%	43%	16%	26%	22%

Subject 16

air — tissue

	Left Frontal sinus	Right Frontal sinus	Sphenoidal sinus	Left Maxillary sinus	Right Maxillary sinus
air	75%	79%	83%	87%	86%
tissue	25%	21%	17%	13%	14%

Subject 17

air — tissue

	Frontal sinus	Sphenoidal sinus	Left Maxillary sinus	Right Maxillary sinus
air	60%	79%	85%	86%
tissue	40%	21%	15%	14%

Subject 18

air — tissue

	Left Frontal sinus	Right Frontal sinus	Sphenoidal sinus	Left Maxillary sinus	Right Maxillary sinus
air	80%	71%	79%	8%	44%
tissue	20%	29%	21%	92%	56%

Subject 19

air — tissue

	Left Frontal sinus	Right Frontal sinus	Sphenoidal sinus	Left Maxillary sinus	Right Maxillary sinus
air	76%	67%	75%	81%	84%
tissue	24%	33%	25%	19%	16%

Subject 20

air — tissue

	Left Frontal sinus	Right Frontal sinus	Sphenoidal sinus	Left Maxillary sinus	Right Maxillary sinus
air	68%	56%	78%	83%	82%
tissue	32%	44%	22%	17%	18%

Subject 21

air — tissue

	Left Frontal sinus	Right Frontal sinus	Sphenoidal sinus	Left Maxillary sinus	Right Maxillary sinus
air	75%	53%	77%	85%	85%
tissue	25%	47%	23%	15%	15%

Subject 22

air — tissue

	Left Frontal sinus	Right Frontal sinus	Sphenoidal sinus	Left Maxillary sinus	Right Maxillary sinus
air	77%	76%	84%	72%	76%
tissue	23%	24%	16%	28%	24%

Subject 23

air — tissue

	Left Frontal sinus	Right Frontal sinus	Sphenoidal sinus	Left Maxillary sinus	Right Maxillary sinus
air	68%	75%	82%	88%	86%
tissue	32%	25%	18%	12%	14%

Subject 24

— air — tissue

61%	71%	79%	83%	51%/49%
39%	29%	21%	17%	

Left Frontal sinus | Right Frontal sinus | Sphenoidal sinus | Left Maxillary sinus | Right Maxillary sinus

Subject 25

— air — tissue

68%	72%	81%	80%
32%	28%	19%	20%

Frontal sinus | Sphenoidal sinus | Left Maxillary sinus | Right Maxillary sinus

Subject 26

— air — tissue

69%	72%	79%	89%	80%
31%	28%	21%	11%	20%

Left Frontal sinus | Right Frontal sinus | Sphenoidal sinus | Left Maxillary sinus | Right Maxillary sinus

Subject 27

— air — tissue

77% 71% 80% 84% 84%

23% 29% 20% 16% 16%

Left Frontal sinus | Right Frontal sinus | Sphenoidal sinus | Left Maxillary sinus | Right Maxillary sinus

Subject 28

— air — tissue

86% 68% 53% 64%

14% 32% 47% 36%

Left Frontal sinus | Sphenoidal sinus | Left Maxillary sinus | Right Maxillary sinus

Subject 29

— air — tissue

67% 86% 80% 83%

33% 14% 20% 17%

Left Frontal sinus | Sphenoidal sinus | Left Maxillary sinus | Right Maxillary sinus

Subject 30

air   tissue

82%	85%	86%	86%
18%	15%	14%	14%

Left Frontal sinus   Sphenoidal sinus   Left Maxillary sinus   Right Maxillary sinus