Universidade do Minho
Escola de Engenharia

Luis Filipe Pereira Gonçalves

Photorealistic modelling and rendering of 3D human anatomy for medical training

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Abstract

Biomedical simulation makes use of three-dimensional (3D) models as a virtual representation of the human anatomy. Although current computer-based training and education systems have used such models, most of them fail to reproduce authentic anatomy, in terms of morphology, texturing and functional behaviour. The production of 3D organic models with a level of realism able to deceive medical professionals is still a challenge. In this dissertation work, our main purpose is to design and implement solutions to reach the highest level of organic realism allowed by current hardware and software graphics performance. Real-time or interactive rendering is out-of-scope of this work, since all the production will be made offline, with special emphasis on anatomy correctness, realistic illumination and texturing. We propose a generic pipeline to accurately reconstruct and render human anatomy, mainly focusing on hard tissues. A case study is presented in the field of Odontology. Using this pipeline we successfully created a 3D model representing a human mouth (teeth, mandible and maxilla) for realistic and detailed medical animations, as required by dentists. This virtual model was subject to an evaluation process, where a group of dentists believe that the model as enough quality to fulfil their requirements.

Resumo

Simulações biomédicas utilizam modelos tridimensionais (3D) como representações virtuais da anatomia humana. Existem actualmente muitos sistemas de “*e-learning*”, para ensino e treino que já usam estes modelos. Contudo, uma grande maioria é incapaz de recriar autenticamente anatomia ao nível de morfologia, de texturas e comportamento funcional. A produção de modelos 3D orgânicos com realismo e detalhe suficiente para conseguir iludir profissionais médicos é ainda um desafio. Nesta dissertação, temos como objectivo primordial desenhar e implementar soluções que alcancem o máximo de realismo orgânico permitido pela performance de hardware e software gráfico actual. Renderização interactiva ou em tempo real não está no âmbito deste trabalho, visto que toda a produção vai ser realizada em modo *offline*, com ênfase em exactidão anatómica, iluminação e texturas realistas. Propomos um *pipeline* genérico que facilite a reconstrução e renderização de anatomia humana, focando nos tecidos duros. É apresentado um caso de estudo em Odontologia. Usando este *pipeline*, desenvolvemos com sucesso um modelo 3D representando a boca humana (dentes, mandíbula e maxilar) para animações médicas realistas e detalhadas, tal como solicitado pelos dentistas. Este modelo virtual foi sujeito a um processo de avaliação, onde um grupo de dentistas acredita que o modelo tem qualidade suficiente para satisfazer os seus requisitos.

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1. INTRODUCTION

1.1. Motivation

Surgical techniques and clinical protocols that surround all medicine disciplines are constantly evolving. This evolution creates the need for medical education and training of physicians, allowing them to learn and apply new techniques.

Understanding the anatomy relevant to a surgical operation is important to good surgical planning and to avoid errors. This knowledge of anatomy means knowing not only the names and locations of various organs and anatomical parts but also the relationships between these parts [1].

Multimedia material describing surgeries are a great asset for medical education. Several types of educational material can be used, such as videos, images, medical scans, textbook diagrams, etc. Videos can either be real surgery recordings or computer generated 3D animations, which include virtual models of human anatomy. In terms of realism, there is no doubt that video recordings are far ahead from others in representing surgeries. On the other hand, animations can provide better didactic content. Spatial relations between anatomical structures can be observed from several viewpoints that are difficult or even impossible to achieve in real situations. Animations also allow highlighting a certain teaching point by focusing only on the necessary structures and eliminating the unnecessary ones. For instance, the surgical instruments and patient bleeding during an operation can sometimes obstruct the observation of crucial anatomical or interventional details. Furthermore, they can also be used to represent anatomical evolution, the growth of a disease in an organ, etc.

This is by no means a discussion to prove that 3D animations are the best resource for surgery teaching purposes. Although animations may represent an important role in education, they are insufficient to provide all the essential knowledge a doctor needs. Hence, animations should be used together with other teaching materials and methods.

Clinical applications for diagnosis and treatment simulation, as well as surgery planning, use models that need to be efficiently created and visualized. Although these applications need to present an acceptable quality to aid the professionals, they exhibit some flaws in terms of realism and correctness. Computer-based training and education systems contain models and animations with reduced realism, failing to reproduce authentic anatomy. Some medical professionals who use this kind of systems complain that the current available models in the market do not meet their requirements. The production of three-dimensional organic models that are anatomically correct and well formed is therefore an important challenge.

1.2. Objective

This thesis work was realised within an industry project that served as its implementation basis. The main idea behind the project is to generate a multimedia application that supports video playback for medical training. The videos within this application contain 3D animations, which resemble real surgical techniques and methods. Health professionals will use this application for surgery teaching and demonstration. For instance, it can be used to exhibit new techniques in conferences or conventions, as well as patient elucidation about a certain procedure.

The animations need to fulfil certain requirements in order to be realistic and easily understandable, such as anatomy correctness, realistic illumination and texturing. One goal of this project is to produce a generic pipeline that enables us to accurately reconstruct any human anatomy part, mainly focusing on hard tissues, like bones.

We needed to investigate how to obtain models of human anatomy and, above all, how to guarantee correct and valid morphological appearance and good spatial relationship. The health professionals will use these models as didactic resource.

In the following section the related work is presented. Section 3 describes the general concepts and methods used to obtain a 3D model. The results achieved are presented in section 4 and then are subject to an evaluation and validation by medical experts. The summary of this non-formal study can also be found in section 4. The discussion and conclusion takes place in section 5.

2. 3D RECONSTRUCTION IN MEDICAL CONTEXT

Human anatomical 3D models can be developed through several approaches. This section covers the projects and work with focus in creating anatomy models.

Prior to develop a 3D model of human anatomy, it is necessary to understand and know its final purpose. The majority of medical applications involving 3D visualization of human anatomy require interaction and fast rendering times, whereas the quality of the models is not the most important goal. In these cases, there must be a compromise between quality and rendering time. Other applications, normally with educational purposes, require high quality renderings to depict anatomy. Usually, these applications do not provide interaction.

In [2], a 3D model of the human pelvis was generated from the Visible Human Project datasets. The automated segmentation methods were not reliable to separate muscles in the pelvis and had no precision. Thus, manual segmentation was applied. The 3D mesh is obtained through surface rendering. Afterwards, the model is textured in photographic quality with human tissue colour and can be interactively used to teach anatomy.

Sweet et al built an interactive virtual reality model of the organs encountered in a minimal invasive surgery to make the acquisition and maintenance of skills easier [3]. The goal was to achieve accuracy in anatomic relationships and variations, photorealistic appearance and realistic behaviour with real time interaction. High quality 3D geometry of each organ is reconstructed from CT (Computed Tomography) images with a program called Vitra. A low-resolution smooth mesh was created with artistic adjustments using Maya software. The models were mapped with photorealistic colour textures, which were obtained from real samples of tissue. ZBrush software was used for detail enhancement. To provide a sense of depth, bump maps were applied, and the final textures were generated and edited in Photoshop.

An approach to achieve the geometric anatomy of the human paranasal sinuses from CT images is presented in [4]. The purpose was the segmentation of relevant regions for 3D reconstruction, visualization and volumetry. The commercial software Amira was used to perform semi-automatic segmentation, either by following an image gradient or by growing region based on grey level of different anatomy parts. The reconstruction is used to create a finite element models for surgery simulations. Therefore, an exact knowledge of the geometry arrangement of the paranasal region is crucial. The 3D reconstruction accuracy relied deeply on the segmentation approach.

In 2007, an approach of 3D visualization of temporomandibular joint was developed based on MRI (Magnetic Resonance Imaging) images to aid in diagnosis. After an initial image processing, like Gaussian smoothing and contour filtering, the bones were semi-automatically segmented. The anatomy surface model was reconstructed using Amira built in surface reconstruction algorithm [5].

Zachow et al [6] present a pipeline for geometry reconstruction of individual anatomy parts. This sequence combines segmentation of medical images and surface reconstruction of 3D structures. This pipeline allows the creation of high quality meshes even when reconstructing complex anatomy parts. The results obtained were generated with Amira.

In the Yusop et al paper [7], a similar but detailed reconstruction pipeline for generating 3D models of *cancellous*[1] bone is introduced. Starting with medical images (CT or MRI) and using Amira software to apply noise filtering, image segmentation and boundary surface reconstruction to obtain a 3D representation of the bone (view an example result of this pipeline in Figure 2.1).

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[1] Cancellous bone is the spongy interior layer that protects the bone marrow.

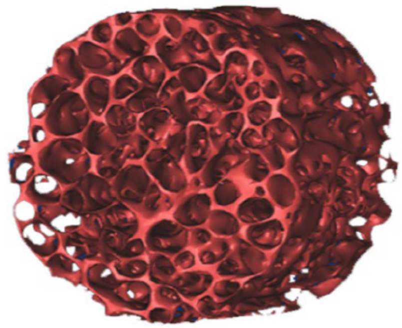


Figure 2.1 – 3D reconstruction of a cancellous bone

A method to achieve a digitized description of the human teeth and dental bridge geometry can be found in [8]. The project aimed to develop a system by integrating CT scanning, image processing, CAD, mesh generator, and finite element analysis (FEA). The CT scans provides a high accuracy of cross-sectional geometry and speed of acquisition. The geometric model of the tooth has some errors since it is composed by a set of curved surfaces that diverge in a complex way. Thus, some adjustments of the geometry are needed. This step is done by changing point by point, and is applied only when perfect tooth geometry is required, since it can be especially time consuming.

Several 3D models of teeth are available over the internet, such as *Zygot* (http://www.3dscience.com/), *Primal Pictures* (http://www.primalpictures.com/) , *Nucleus Medical Art* (www.nucleusinc.com), *3DSpecial* (www.anatomium.com), Argosy (http://www.visiblebody.com), *BioDigital* (http://www.biodigitalsystems.com/), *Hybrid Medical Animation* (http://www.hybridmedicalanimation.com/), etc. Nevertheless, the process that leads to the creation of these models is neither well described nor available.

Zygote, a 3D medical visualization company, provides 3D content for the Biomedical, Entertainment, and Professional markets. It has created quality 3D models of human anatomy, like the teeth and heart. The 3D teeth model presented in Figure 2.2 derivates from a digitized cast of a real skeleton, and from the subsequent modelling of each structure. These models focus on the regions of the inner mouth, highlighting the human teeth anatomy [9]. Although the 3D teeth may appear to have reasonable quality for a non-expert, it does not satisfy the specialists in terms of anatomical correctness.

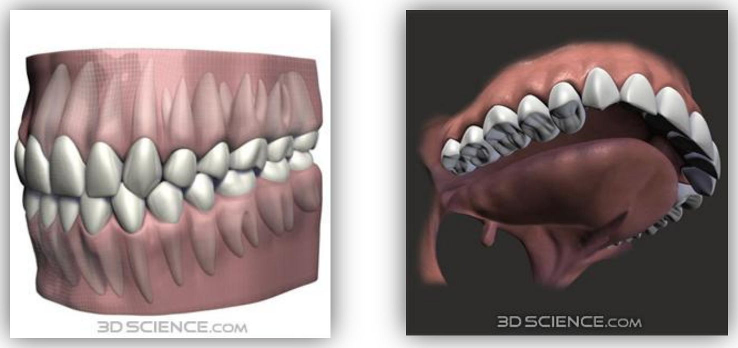


Figure 2.2 - Zygote 3D model of teeth

The Zygote 3D human heart model (Figure 2.3) is based on MRI and CT data, and maintains true human-heart shape, with valves and vessels in accurate proportion and position. Map channels used are colour, bump and deformation. These texture maps are photo-realistic.

Figure 2.3 –The Zygote 3D Human Heart Model

According to [10], Zygote was pioneer in creating a 3D heart model by using MRI and CT scans as source material, making it the most accurate 3D heart ever (until today). The use of medical data allowed to precisely determining tissue thickness, valve placement and real human heart shape. The models were textured with real human photos.

3. OUR METHODOLOGY

In the present chapter the methods, stages and critical concepts behind our approach for developing a 3D model of any human anatomy structure are described.

As a case study, we are interested in the reconstruction of the maxilla, mandible, teeth and soft tissue surrounding these structures. This specific case will help to prove the effectiveness of our approach.

We have built a pipeline, shown in Figure 3.1, in order to enable the reconstruction of any 3D human structure. The first stage is responsible for acquiring medical data (such as X-ray or Computed Tomography images). Enhancement algorithms can be applied to improve image quality and to assist the subsequent steps. Relevant information, such as bones and soft tissues, are extracted from this data. For the later step we exploit Amira software capabilities, which allow applying image segmentation techniques. Afterwards, we use a surface reconstruction technique to obtain the surfaces of the structures (a 3D mesh usually composed by different objects).

At this moment we enter in the anatomy modelling stage for detail enhancement. The resulting surfaces need to be adjusted and refined to eliminate or reduce the imperfections. We utilize a modelling tool (Autodesk 3D Studio Max) to edit the mesh. This same tool is also used to apply textures to the objects.

The scene visualization stage is mainly in charge of employing global illumination techniques. Here photorealistic rendering is used to give the anatomy a better and realistic look.

It is important to work closely with health specialist to validate all results and, if necessary, manually adapt the virtual model accordingly to his opinion [11]. Hence, these last two stages are validated by a specialist, which must possess profound anatomy knowledge about the desired anatomy parts to reconstruct. This stage guarantees the correctness of the resulting 3D model. The model is validated in terms of spatial relationships, morphology and colour appearance. The corrections of the specialist can move the process back to the anatomy modelling or scene visualization stages. The process ends when the specialist feels that the models fulfil his quality requirements. These requirements may diverge depending on the purpose of the project/model.

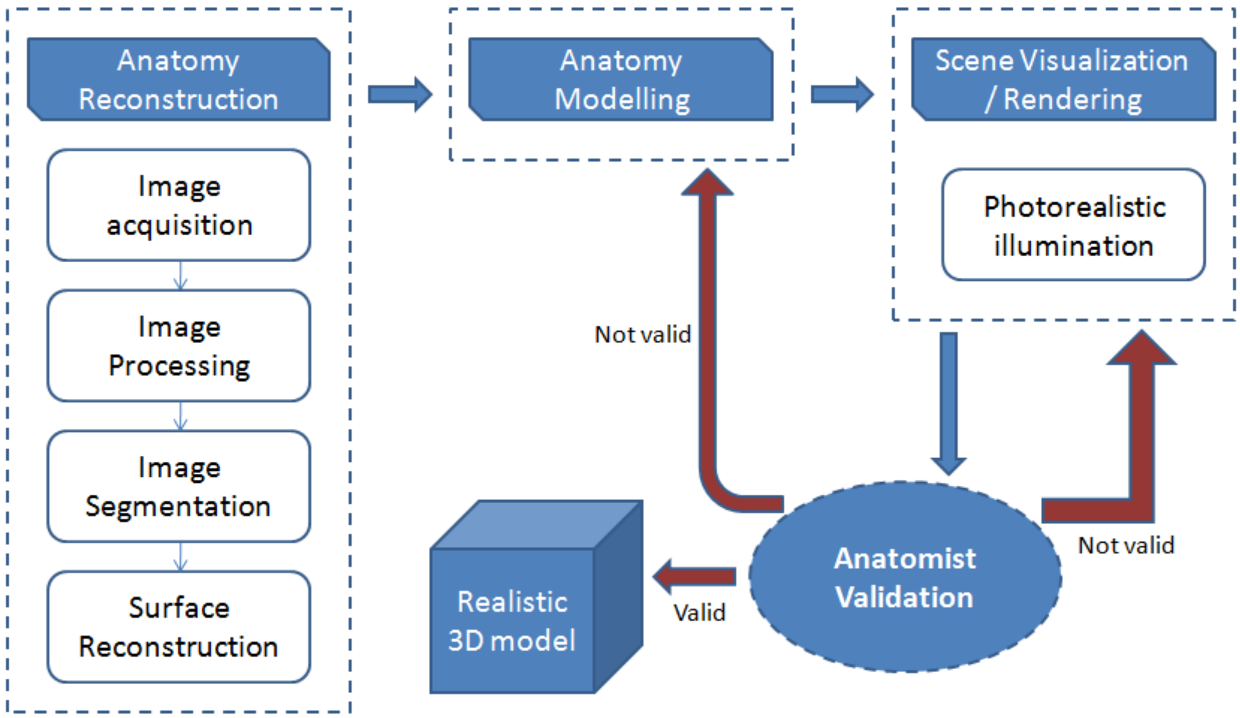


Figure 3.1 - Reconstruction Pipeline

3.1. Anatomy Reconstruction

To obtain realistic models, two distinct approaches can be taken. An **artistic approach**, usually based on references such as real photographs, videos and physical objects, tries to replicate the models using points, polygons and splines, sectioning the 3D object. Achieving a high level of detail and realism with this approach can be a very laborious task.

As an alternative, the **scientific approach** involves image analysis, image processing and medical visualization. Here, a medical image dataset (Section 3.1.1 below) is acquired, analyzed, processed, visualized and explored.

Compared with the first approach, where the model is created from scratch, the use of real data can guarantee better and more accurate results [8, 12]. Like the majority of anatomy education and surgical education systems, we will use medical volume data and derived information, mostly segmentation information.

In this stage, the main challenge is how to recover the 3D shapes of the desired anatomical parts from medical images with high accuracy, and to convert them into geometry.

3.1.1. Medical Image Data

Medical image data is normally a set of continuous images slices. Each slice corresponds to a thin cut of the scanned body part at regular intervals. The pixels (picture elements) that compose a slice have a scalar value, which represents an intensity value. The intensity value measures the material property of the scanned part in a certain position, relative to the value of the x-ray absorption of the tissue present in that position. Areas possessing similar intensity values usually denote anatomical structures, whilst accented gradients correspond to tissue boundaries.

Volumetric data aggregates the image slices forming a three-dimensional image stack, representing an approximation of the anatomical structures three-dimensional shape. The image space is now a 3D grid composed by voxels (volume elements). The distance separating adjacent images is known as slice distance, and it depends on the sensor of the CT device and the parameters defined by the specialist during image acquisition.

3.1.2. Data Acquisition

Medical visualization methods and applications are based in data acquired by several different scanning devices. The most popular are X-ray, computed tomography (CT) and magnetic resonance imaging (MRI). Although there are alternative imaging modalities such as 3D ultrasound, positron emission tomography (PET) and single-photon emission computed tomography (SPECT), the use of CT and MRI prevails because of their high resolution and their good signal to noise ratio [13]. CT is also appropriate because it shows good global and local contrast, and is especially useful for bone like tissues visualization, taking into account that they are used for soft tissues visualization as well.

3.1.2.1. X-Ray

Wilhelm Röntgen discovered in 1895 the X-rays, the first medical image data allowing the visualization of internal parts of a body. Figure 3.2 presents in the left the first ever X-ray, taken by Röntgen, and in the right an example of a dental X-ray. Dentists still currently use these images to diagnose and treat their patient's teeth.

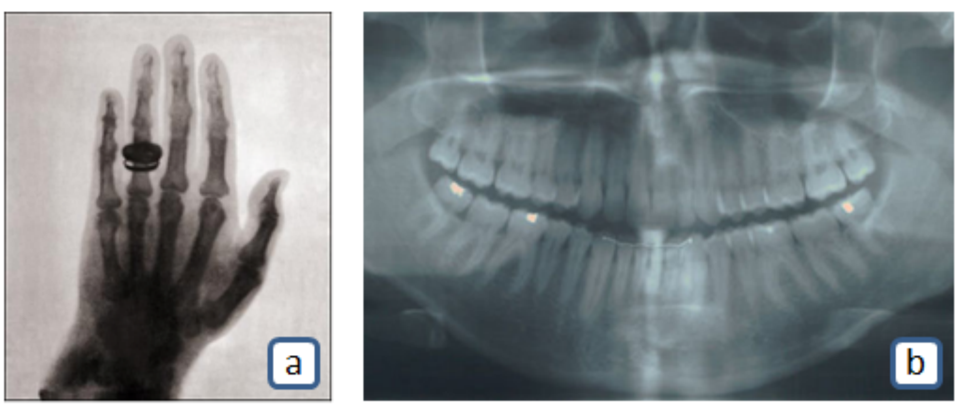


Figure 3.2: X-ray imaging: (a)[2] First X-ray (1895); (b)[3] Dental X-ray;

[2] Retrieved from http://www.worldsfamousphotos.com/2007/03
[3] Retrieved from http://www.sciencelearn.org.nz/contexts/see_through_body/sci_media/images/dental_x_ray

A single X-ray image merely allows perceiving the outline of structures. Basically, it is a 2D projection image of the structures. Hence, it is not viable to determine the accurate position of structures with solely one image. To overcome this problem, two X-ray images are frequently taken in different views (for instance: frontal and lateral view of the same body part). This way the spatial perception of the different objects is enhanced.

The radiation doses used to create X-rays can be a hazard to the patient involved in the process. Lowering the doses will decrease image quality, whilst high doses may harm the patient by growing a possible cancer. As a consequence, there must be a compromise between image quality and radiation doses. A lower dose creates image with lower signal to noise ratio and therefore both local and global contrast are severely affected. Moreover, lower doses require longer exposure times to overcome low signal to noise ratio problem. These longer exposure times are uncomfortable for the patient, which may move during treatment, thus generating invalid images.

3.1.2.2. Computer Tomography (CT)

Godfrey Hounsfield contributed in 1968 for an important breakthrough in medical imaging, through the introduction of X-ray Computer Tomography (CT). This new image device made possible the volumetric representation of structures. CT is based on X-ray, and calculates a volume dataset from a series of X-ray images acquired by an emitter/detector system rotating around the scanned body.

CT is able to accurately localize anatomical structures in depth. Unlike X-ray images, CT is able to detect different soft tissues such as liver and pancreas. However, the contrast between soft tissues is small with CT data. Whenever soft tissue is essential to be recognized, MRI images should be used because they offer a superior soft tissue contrast. CT is better for hard tissue identification, such as bones.

The number of slices, the number of pixels per each slice and the voxel distances characterize CT datasets. The number of pixels of a slice represents the image resolution (e.g. 256 x 256).

Imagine a dataset of 200 slices with a resolution of 256 x 256 composes a volume of 256 x 256 x 200 voxels. The voxel distance is divided in slice and pixel distance.

The noise that may be present in the data is affected by the resolution. Maintaining the radiation dose while the resolution is increased will result in noisier data. Thus, radiation dose must be taken in account when better image quality is necessary. Similarly to X-ray, in order to avoid putting in risk the patient health, there must be a trade-off between image quality and radiation dose.

3.1.2.3. Computer Tomography Image Dataset

The image dataset used in this project was acquired with a CT scanner. This imaging technique was chosen seeing that is the most appropriate to discriminate hard tissues like bone structures, producing detailed anatomic information. MRI data does not possess a good quality to distinguish skeletal structures. In the case study, the desired structures are the craniofacial bones: teeth, maxilla and mandible. Soft tissue is considered to be less important in this first stage, although it will be produced later without segmentation. It was important to obtain and represent the bones in a first stage, and develop and model soft tissues on top of the bones accordingly with their final anatomic appearance afterwards. This way, CT data were preferred over MRI data.

In order to cover sufficient mandible volume at adequate resolution for visualizing small structures like tooth roots we used a dataset of 166 image slices. This dataset composes an image volume of 512 x 512 x 166 volume elements (voxels). Some of these images are shown in Figure 3.3. The slice distance is 0.5 mm.

The images composing the dataset (Figure 3.3) were analysed and validated by two dentistry specialists. They concluded that the patient has good anatomy without any defect in the structures that will be reconstructed in the case study.

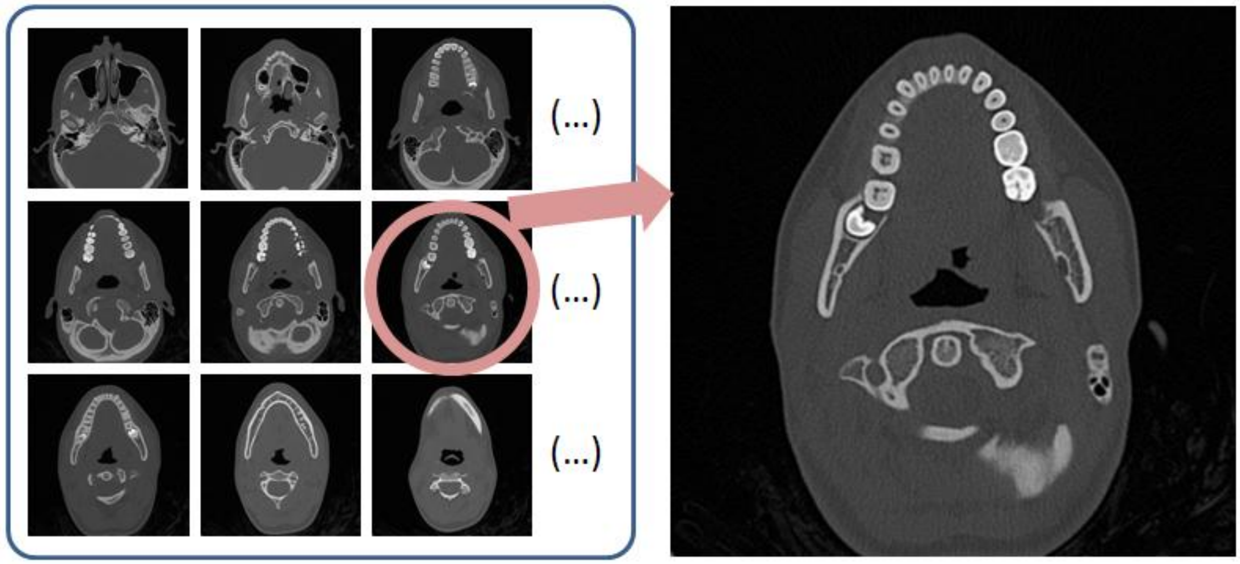


Figure 3.3 – Some of the CT images used

3.1.3. Image Processing

The quality of medical images is often affected by noise, caused by a variety of interference sources and other phenomena in image acquisition systems [14, 15]. Noise will reduce contrast and visibility of details. In order to diminish the presence of noise and increase the contrast of important structures, image enhancement algorithms can be applied. The main purpose of these algorithms is to improve the quality of the images and thus providing a clearer image for the observer, thus allowing him to better distinguish information contained in the image.

Image enhancement techniques also have some drawbacks that must be taken in consideration. Although noise is reduced, they might eliminate small details, edge sharpness, and may generate artefacts.

Amira provides a number of image filters that may be applied to the medical images. These filter help reduce image noise. We have tested and applied each filter to the case study image dataset without any significant image quality improvement.

The image dataset used in the case study does not have high level of noise and has enough contrast to allow the detection of meaningful structures in the subsequent step (image segmentation). Therefore, there is no need to apply any image enhancement techniques to the used dataset.

Image enhancement should be used carefully because of the undesired effects, like loss of small details or noise amplification. The diverse nature of medical images and each of their problems makes impossible to find a single technique that guarantees the enhancements of every kind of image. Each image dataset and their enhancement requirements must be examined and a set of techniques have to be tested. This will help discover the best enhancement technique for the dataset.

3.1.4. Medical Image Segmentation

In this subsection the attention is centred on image analysis techniques and methods that allow the extraction of relevant information from medical datasets. This information is essential to distinguish the anatomy structures and to correctly generate their geometric description.

Medical Image segmentation concerns with the segmentation of anatomic structures from medical images. Structures of interest may include organs, bones, vessels, etc. Although image segmentation involves any kind of images, it will be referred in this project in the context of medical imaging.

Image segmentation is the process of partitioning image data into meaningful structures providing an easier analysis and understanding of the data. Segmentation is used to recognize and outline objects. These objects are identified as a certain anatomic structure and their boundaries are delineated. An example of image segmentation can be found in Figure 3.4. More precisely, image segmentation attributes a label to each voxel in an image dataset to indicate it is part of a given structure. Normally a map of labels is created to determine which voxels compose a structure.

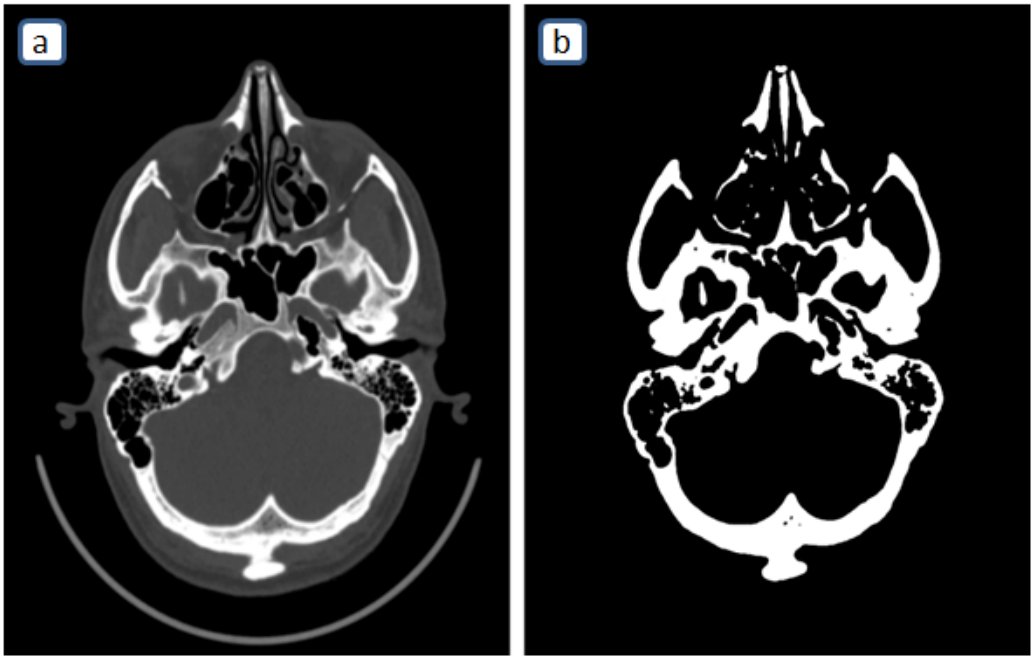


Figure 3.4 – Image Segmentation (a) Original Image; (b) Segmented image

There are three main categories of segmentation techniques: manual, semi-automatic and automatic. Automatic segmentation is a fully automated process that does not need any user interaction to be completed. Semi-automatic requires some user interaction to help identifying structures. Manual segmentation is a completely interactive task, where the boundaries delineation is always drawn by hand.

Generally, segmentation of small structures such as teeth is a difficult task because teeth come in different shapes and their arrangements vary substantially from one individual to another. The difficulty is aggravated when the teeth are misaligned, which is a common occurrence in clinical cases. Whereas clinical applications require fast segmentation and visualization, educational systems need essentially high-quality results [13]. Thus, the accurate segmentation of the teeth is an important component in Odontology training [16]. For clinically useful applications, it is a good strategy to attempt automatic solutions that produce acceptable results in the majority of the cases. These solutions should be complemented by more general semi-automatic solutions for the remaining cases [13]. At the moment, there are no automatic solutions that can grant reliable and accurate results. For teeth segmentation no automatic solution produces acceptable results for the purposes of the case study project.

3.1.4.1. Manual segmentation

This is the most general method for segmentation, which consists on manually drawing on each image slice. Normally, the user outlines or fills all regions of interest using mouse-based software.

This method is robust because it is always applicable and generally provides better results than other methods. However, it is very slow, arduous, irreproducible and imprecise, because the user delineation slightly differs from the real boundaries. Hence, manual segmentation is unsuited in clinical applications for diagnosis and surgery planning which require faster results. Despite these drawbacks, manual segmentation is applied very often, especially when different regions have low contrast intensities and unpredictable shape.

3.1.4.2. Region Growing

The process of region growing commences by selecting one or more seed points (pixels) that belong to each of the structures (regions) to be segmented. According to an inclusion criterion, the adjacent pixels are evaluated in order to determine if they should be considered part of the structure. If so, the pixels are added to the region and the process carries on until the criterion is not fulfilled.

One common inclusion criterion is the evaluation of the pixel intensity value within a user-defined interval. Values of the lower and upper threshold must be provided. The process includes the pixels whose intensities lie inside the interval.

Figure 3.5 shows a practical example of this technique. Figure 3.5a is a part of the original scan image, where the desired object to be segmented is the tooth bone. The outcome of selecting a seed point (picture b) is visible in picture c, where the area to segment is automatically filled.

Normally, the threshold interval is established based on heuristic method. The segmentation begins with a specific interval that is adjusted until the desired result is obtained.

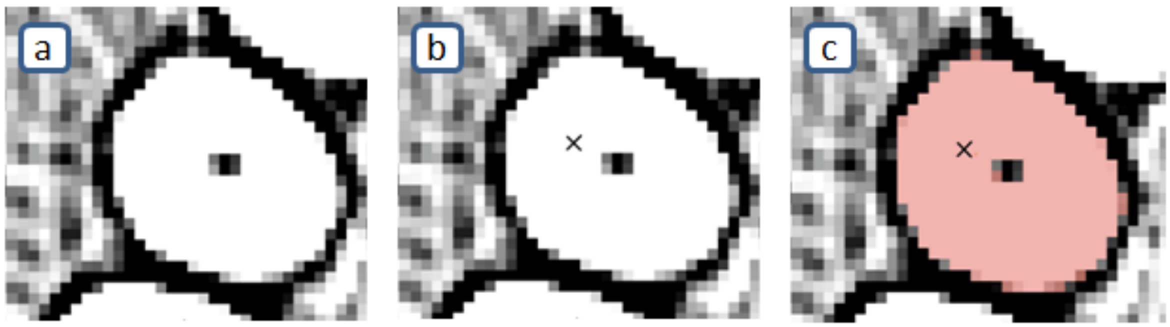


Figure 3.5 –Region Growing Segmentation example

3.1.4.3. Amira

Amira is an interactive system used to visualize, manipulate and analyse medical data. It is very useful and easy to use, not only for image segmentation but also for surface reconstruction. Several recent projects use this software due to its capabilities [5, 6, 7]. High quality 3D geometry can be created even when complex anatomical shapes of different materials are encountered [6]. This was the software chosen for the current pipeline stage.

This software provides a *Segmentation Editor* component, which contains a variety of tools for manual and semi-automatic segmentation.

Region growing is provided through the *Magic Wand* tool, which allows the user to pick the seed point and to adapt the lower and upper value of the gray level interval. All the neighbouring pixels inside this interval are selected.

Often medical data has unpredictable structures and biological variability. This makes the region growing method inapplicable to certain images of this type. To solve this problem we must use other Amira features, either in conjunction or separately with the region growing tool.

Magic Wand also has a feature that lets the user define limit lines. This prevents unwanted pixels or regions from being included in the region growing process. Figure 3.6 illustrates one possible use for this feature. In this example we wanted to segment only the bottom structure (marked by an 'x'), but the region growing method selects also the adjacent structure (Figure a). This happens because there is no clear separation between structures. In the picture b, a line is drawn to correctly delineate the boundary of the structure.

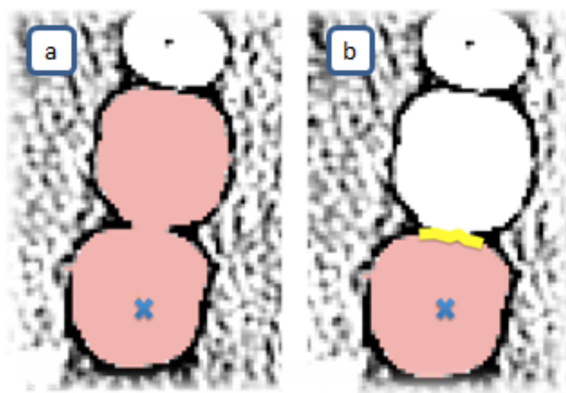


Figure 3.6 – (a) Region growing problem; (b) *Magic Wand* solution

Amira includes other useful tools for manual segmentation, for instance the *brush*, *lasso* and *thresholding*. The user defines regions by manually painting each voxel (*brush*), or by drawing a counter curve (*lasso*). The *lasso* tool can also perform live-wire segmentation, which allows the user to choose a start point on a boundary and then move the cursor approximately around it. This should automatically draw a counter line around the boundary. Sometimes it is necessary to pick additional boundary points.

3.1.5. Surface Reconstruction

In this step, the main goal is to reconstruct the 3D shape of the desired anatomy parts, by creating a polygonal surface. This surface is obtained using the segmented boundaries from the last step.

The 3D reconstruction and visualization of anatomy can be achieved by surface reconstruction or volume rendering. Volume rendering provides the visualization of the whole volume dataset and it does not require an intermediate geometrical representation and image segmentation. All the information available in the images, including the interior or unclear surfaces, within the data is used and can be visualized. However, it may be difficult to interpret the cloudy interiors and rendering time is increased when compared to surface extraction.

Moreover, there is an absent of tools for modelling the volume directly. Since we may have to modify this volume, and we are mostly interested in obtaining the surface of anatomical structures, volume rendering is not suitable for this project. Therefore, the geometry is created through surface extraction.

This technique consists in connecting the 2D contours, which resulted from segmentation, between adjacent slices in order to build a surface model (isosurface). There are several algorithms that implement surface reconstruction, where the most common is the Marching Cubes [17].

Basically, the Marching Cubes algorithm analyzes every individual volume cell and evaluates if the isosurface passes through it. If so, the triangulation is computed using a lookup table, which has all possible cases of triangulation. The use of this kind of table accelerates the process of triangulation.

The original Marching Cubes algorithm is not fail-safe because sometimes inconsistencies may arise, namely holes in the surface resulting from the triangulation.

Amira software provides a similar method to Marching Cubes. This new algorithm generates a polygonal surface without cracks and holes, and guarantees that triangles do not intersect each other, and that regions with different materials will be clearly apart and separated [18]. The drawback of this algorithm is the possible loss of minor details.

Figure 3.7 displays the result of applying the surface rendering algorithm on the segmented information. These surfaces are correctly generated without any inconsistency.

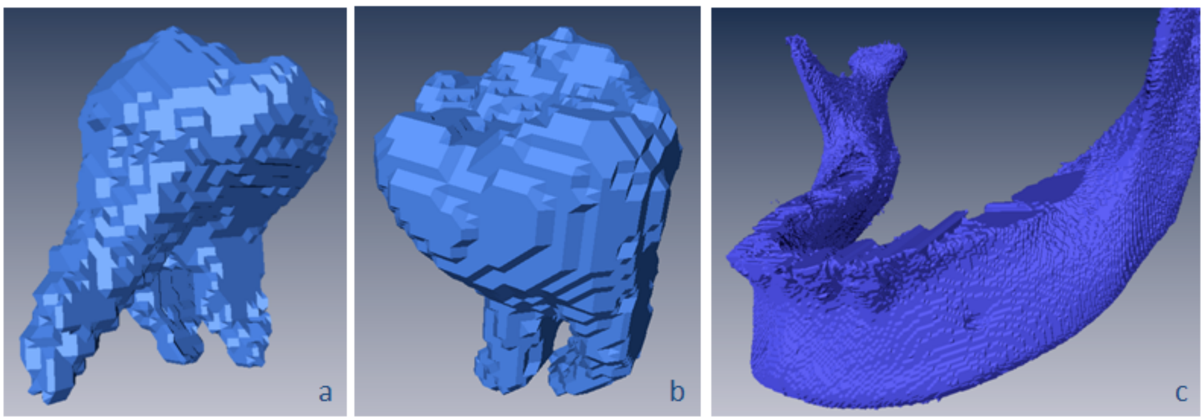


Figure 3.7 - Surface rendering results: (a) superior molar (b) inferior molar (c) Mandible

Anatomical structures often have complex morphology and show smooth transitions. When reconstructing anatomy surfaces it is important to preserve its original shape complexity and all significant details. Although the resulting surfaces do not have gaps, some artefacts are still visible. The surface's morphological appearance is very rough due to the presence of undesired noise and spatial resolution (voxel spacing). A possible source for this noise is the segmentation process [19]. The segmentation is performed manually or semi-automatically by a non expert in medical images. Sometimes the delineation of contours may be wrong and irregular, due to lack of knowledge or experience in interpreting and identifying the relevant structures in the images. The applied surface reconstruction algorithm can also cause the noise.

These artefacts can be solved through surface smoothing. We intend with this step to diminish the artefacts and obtain a surface more similar to the real one. This process will make the surface appear better looking.

We smooth the surface that resulted from surface reconstruction. This step is also done with Amira. Figure 3.8 shows the result of applying a smoothing process to the surfaces above illustrated (Figure 3.7). The original shape is preserved but is clearly smoother and regular, enhancing the perception of the anatomical morphology. Comparing with the structures obtained in the previous step (Figure 3.7), these structures have a more organic and natural appearance.

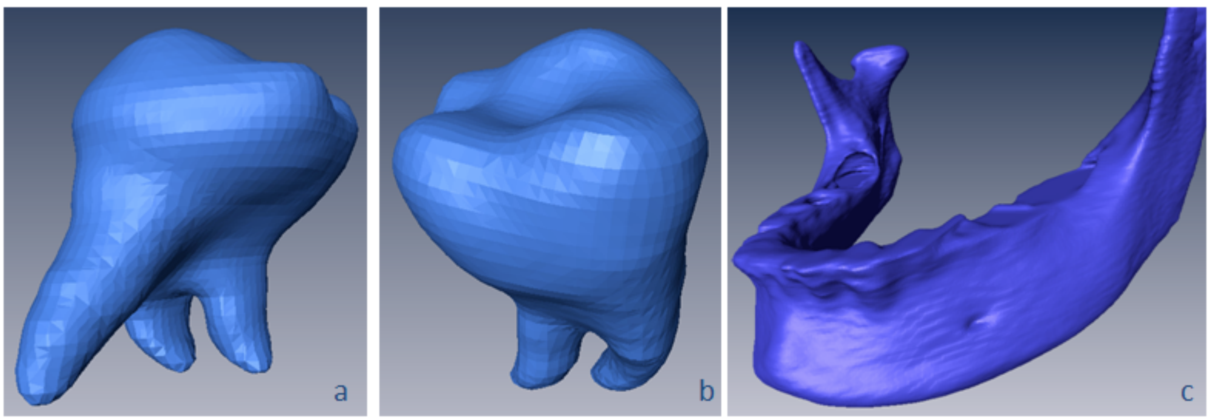


Figure 3.8 - Surface smoothing result: (a) superior molar (b) inferior molar (c) Mandible

3.2. Anatomy Modelling

Once the anatomy reconstruction stage is completed, we have a surface geometry that represents an approximation of the real 3D anatomy shape.

In section 3.1.5 we mention that the surfaces hold some irregularities (noise), which could have origin in the sub-stages from geometry reconstruction. In the Surface Reconstruction step (3.1.5) we reduced some of this noise, however some irregularities are still present. The noise resulting from manual segmentation makes the boundaries of structures irregular and consequently the surface shape will be poorly defined, loosing small details. The overall silhouette is reasonable but the morphology is sometimes partially incorrect. Therefore, we need to modify the existing geometry to obtain a surface that appears even more natural and correct.

In this step we used the commercial software, Autodesk 3Ds Max 2008. This is a tool for modelling, animating and rendering 3D objects.

Amira offers the possibility to export the surface geometry data to a Stereolitho (STL) file. STL is a CAD format normally used for rapid prototyping. It is a faceted surface representation, which contains a list of the triangular surfaces without adjacency information between them. This format is used for the data flow (depicted in Figure 3.9) because the chosen modelling tool supports it.

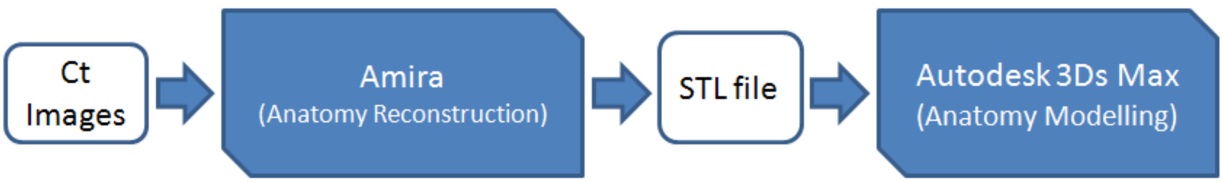


Figure 3.9 - Data flow in the pipeline

This STL file is imported to 3Ds Max. Here it is necessary to weld the vertices of the mesh because there is no connectivity associated with them. This way, the STL mesh will be imported as a contiguous surface, and not just a group of unattached polygons.

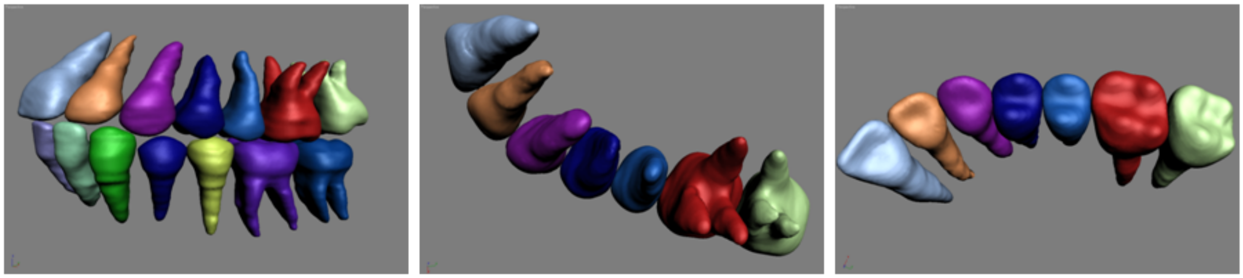


Figure 3.10 - Teeth model imported into modelling software

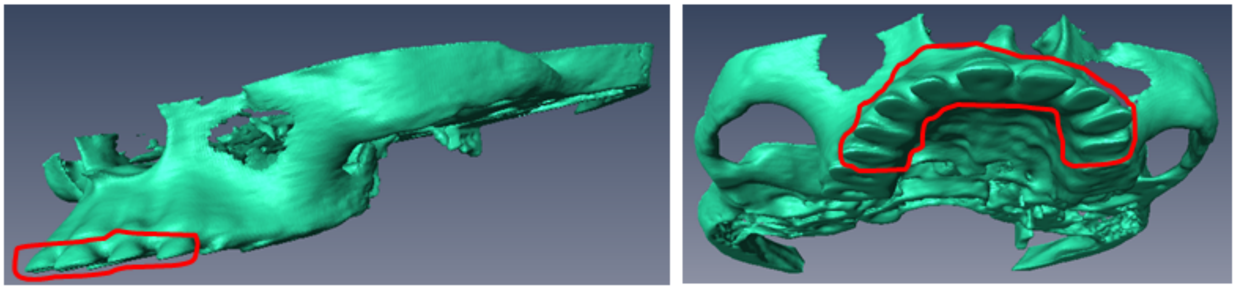


Figure 3.11 – Maxilla imported to modelling software with errors from segmentation step

The models in Figure 3.10 and Figure 3.11 were presented to dental specialist for a first validation and appreciation. He pointed out several irregularities in the teeth morphology, such as the roots (badly formed), the top of the crown from molars and premolars (not well "carved"), as well as the absence of the *amelocemental junction*, which separates the root from the crown. Figure 3.12 shows some minor modifications and corrections that the specialist considered being necessary to achieve correctness.

As it is visible in Figure 3.11, the maxilla surface was incorrectly segmented in Amira. The overall shape is correct, except for the highlighted part. The maxilla includes part of the superior teeth attached to it. We let the model pass to the modelling step like this because this problem is easy to solve and still preserve the maxilla original morphology. Once the teeth were validated, the mandible and maxilla were adapted in a way that the teeth would fit perfectly. According to the specialist, these modifications would make the teeth more believable to any person with minimal Odontology knowledge. Here believable means that these persons will consider the teeth's morphology correct and with a natural aspect, similarly to real teeth.

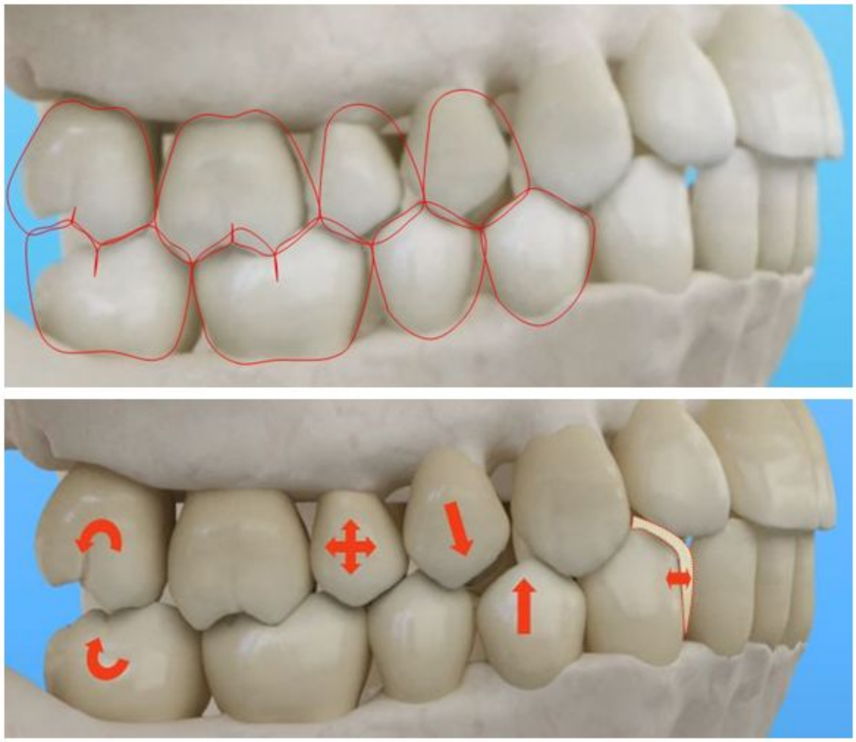


Figure 3.12 – Some corrections and modifications required by the dentistry specialist

The client company provided us some references (Figure 3.13) to aid in our modelling task. The pictures (a) (b) and (c) are photographs of an artificial model, whilst the (d) is from a real tooth (in this case a molar).

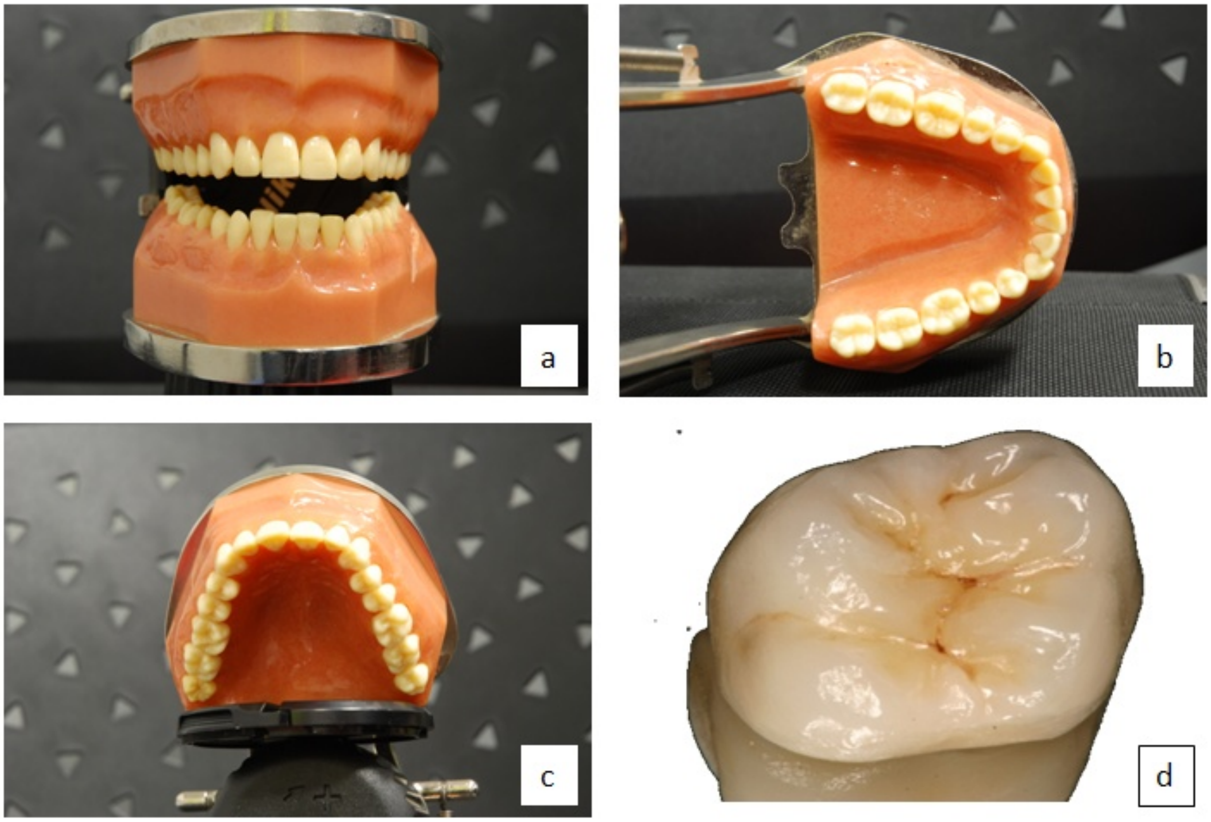


Figure 3.13 - Teeth references

The surface modifications and adjustments were made in the modelling software. Autodesk 3Ds Max has numerous tools to aid in this task. These tools can be used to refine the surface so that it looks more organic and natural.

One of such tools, named *Soft Selection,* can affect the translation, rotation and scale of any sub-object kind (vertex, edge, and polygon). *Soft Selection* selects all the sub-objects in the neighbourhood of a certain selection. When an action is applied to the selection it also affects, in a similar way, the neighbouring sub-objects. For example, if we select a polygon (Figure 3.14a) and then apply a translation of 4 units along its normal, then with *Soft Selection* (Figure 3.14c), the surrounding polygons inside a specified range are translated a distance of 2 (Figure 3.14d). This will result in a smoother transition than without *Soft Selection* (Figure 3.14b), thus very helpful in modelling organic surfaces.

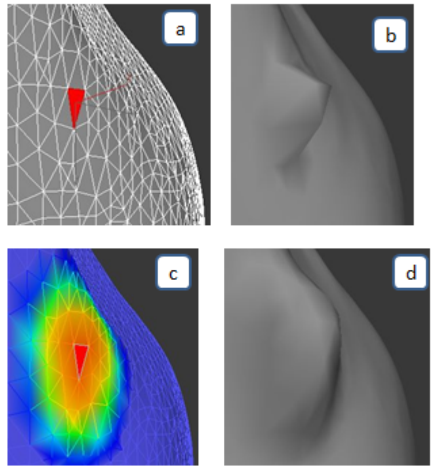


Figure 3.14 – (a, b) normal polygon selection and translation; (c, d) polygon selection and translation with Soft Selection;

The *Paint Deformation* tools (*push, pull and relax*) are very helpful and intuitive to add surface details. These tools allow doing something like "3D sculpting" in the surface.

During modelling, it is usual to have regions of the mesh that are tight or rough. Whenever this happens, a *Relax* operation can be applied. This operation smoothes the overall geometry by separating the vertices closer to an average distance.

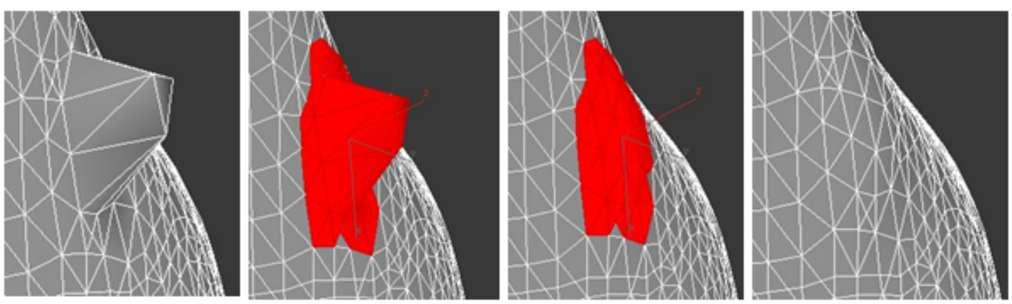


Figure 3.15 - Relax operation on several polygons to smooth out certain mesh irregularities

3.2.1. Results

The following pictures illustrate the final teeth morphology. The specialist positively evaluated these 3D models. In Figure 3.16, it is now visible and perceptible a junction separating the crown from the root. The roots were also refined to look sharper. In some roots it was necessary to add more volume.

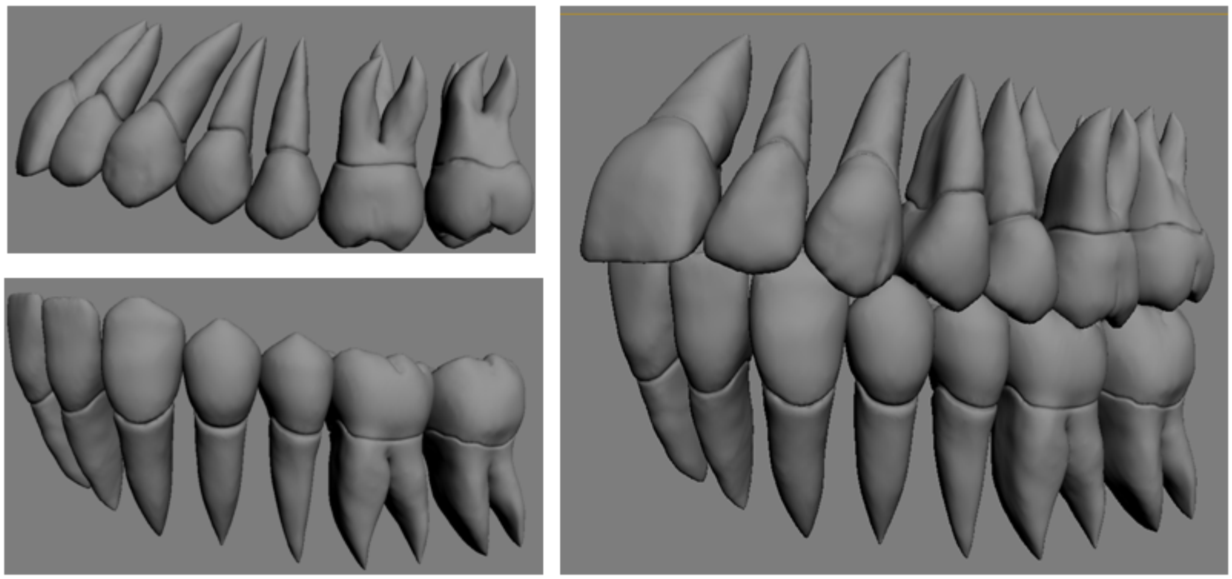


Figure 3.16 - Anatomy modelling final result - junction and root

Figure 3.17 and Figure 3.18 show the resulting appearance of the crowns. We added some detail to the crows of the premolars and molars. Comparing with the previous model without the last modifications, this 3D model has more resemblances to real crowns (like the one in Figure 3.13d). Figure 3.19 shows the virtual model superimposed to the physical model reference.

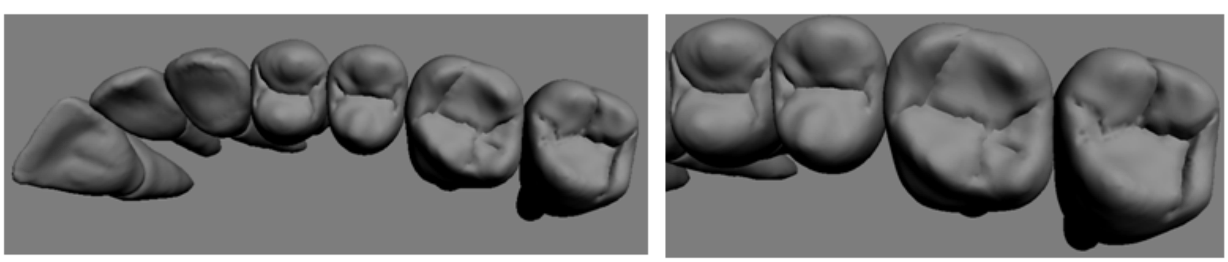


Figure 3.17 - Anatomy modelling final result - upper teeth crows

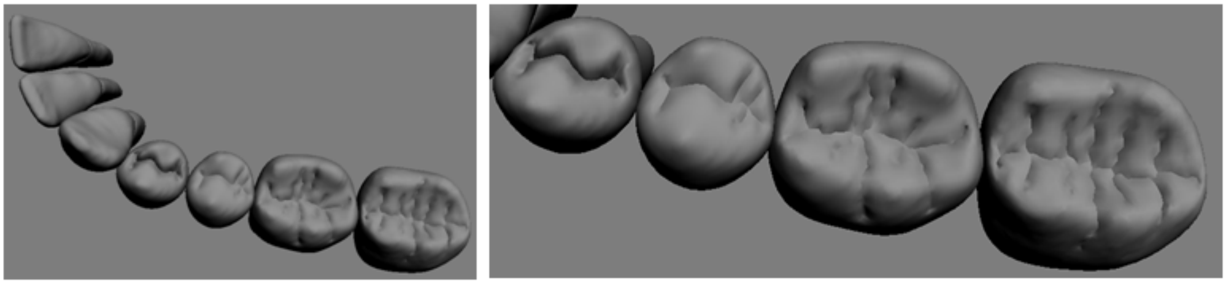


Figure 3.18 - Anatomy modelling final result - lower teeth crows

Figure 3.19 – 3D virtual model compared with photographs (coloured and desaturated) of physical model used as reference

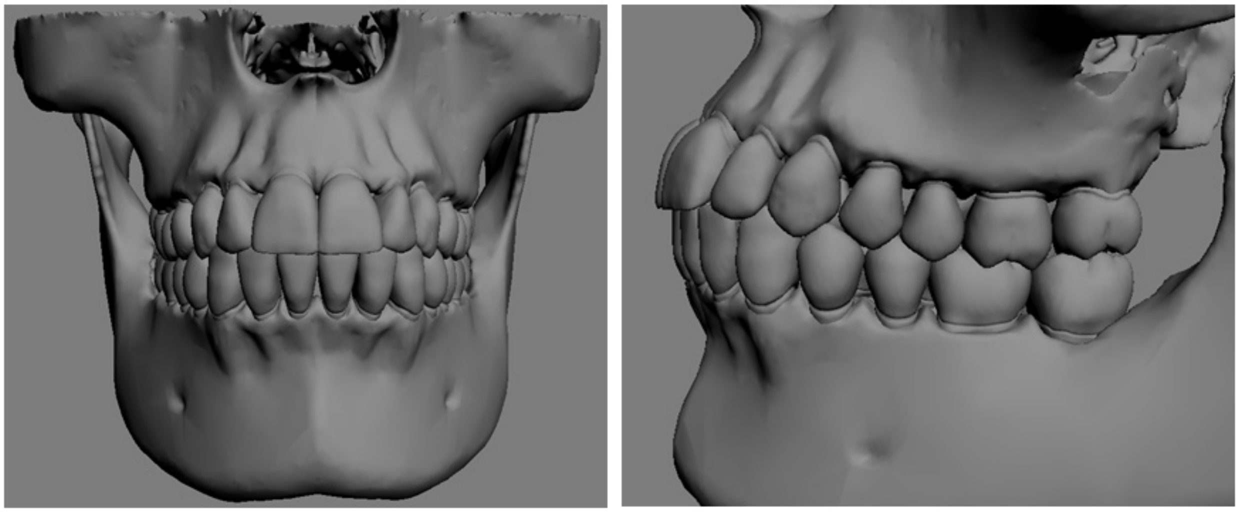


Figure 3.20 - Anatomy modelling final result - Maxilla, mandible and teeth

The teeth overall appearance is considerably closer to a real one. We must remember that teeth shape will diverge from person to person, thus there is not a predefined universal correct shape and size. The morphology obtained here may differ from the references' ones, and still be a valid representation of teeth. We want to achieve a 3D model that gives the most natural and organic appearance as possible, in such a way that an observer will not perceive it is a virtual representation.

3.3. Scene Visualization and Rendering

This section describes the process of scene visualization to reach a realistic and organic look of the anatomy, mainly focusing on texturing, lighting and photorealistic rendering through global illumination techniques.

In the current stage we used V-Ray, a commercial rendering plugin for 3D Studio Max. It supports the standard 3Ds Max lights, materials and maps. Additionally V-Ray includes its own optimized plugins to decrease rendering times. This was the rendering engine used in the project.

3.3.1. Texture Mapping

Once we obtain the anatomy surface we apply materials, that is, apply colours and textures to define the look of the object. Mapping defines how a texture (image) is projected onto the objects surface.

Texture mapping adds variation and detail to a surface, in a deeper level of detail than the modelled geometry. This is a process that changes the surface appearance at each position usually through an image. Texturing an object will increase its overall appearance significantly [20].

UVW mapping is a mathematical technique for coordinate mapping, often used to apply a 2D image (a texture) to a 3D object. "UVW", similarly to the Cartesian coordinate system, has three dimensions; the third dimension lets texture maps to wrap in complex ways onto irregular surfaces. Each point in a UVW map corresponds to a point on the surface of the object. A map must be created and its points are assigned to (XYZ) points on the desired surface. This UVW map is then wrapped back onto the object, thus projecting the image in a more flexible and advanced way than simpler texture mapping (like planar projection). UVW mapping is frequently applied for texturing objects with irregular shapes.

The *UVW Map* and *Unwrap UVW* modifiers from Autodesk 3Ds Max 2008 were used to apply textures onto the model.

UVW Map modifier allows the user to apply the mapping coordinates to mesh objects. The *Unwrap UVW modifier* lets a user to assign mapping coordinates to sub-object selections, and to change existing UVW coordinates of an object (unwrapping). Maps can be adjusted to perfectly fit on a mesh or polygon.

The overall basic colour appearance of every tooth in the model is mainly defined by the texture applied using *UVW Map modifier*. Cylindrical projection (Figure 3.21b) was used to project the map (Figure 3.21a) and to fit correctly on the tooth. This texture was created using V-Ray material capabilities, which allows to combine, in several manners, different textures. Figure 3.21c is the tooth viewed within the modelling software and Figure 3.21d is the rendered tooth, which depicts its final appearance.

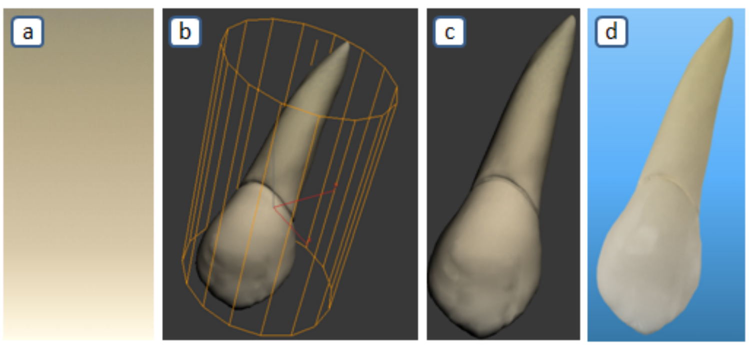


Figure 3.21 - Basic teeth texture process

To precisely texture the teeth crowns we applied the *Unwrap UVW modifier*, on top of the above described map. Figure 3.22a represents the upper premolar teeth before texturing. The UVW coordinates were edited to fit the crown salience (seen as red line in Figure 3.22b). Then we rendered a UV template (Figure 3.22c) with the same software. Afterwards this image is edited using software for image edition (in this case, Adobe Photoshop) where the final texture is created (Figure 3.22d). Finally, the texture is added to the teeth material to fit perfectly as seen in (Figure 3.22e).

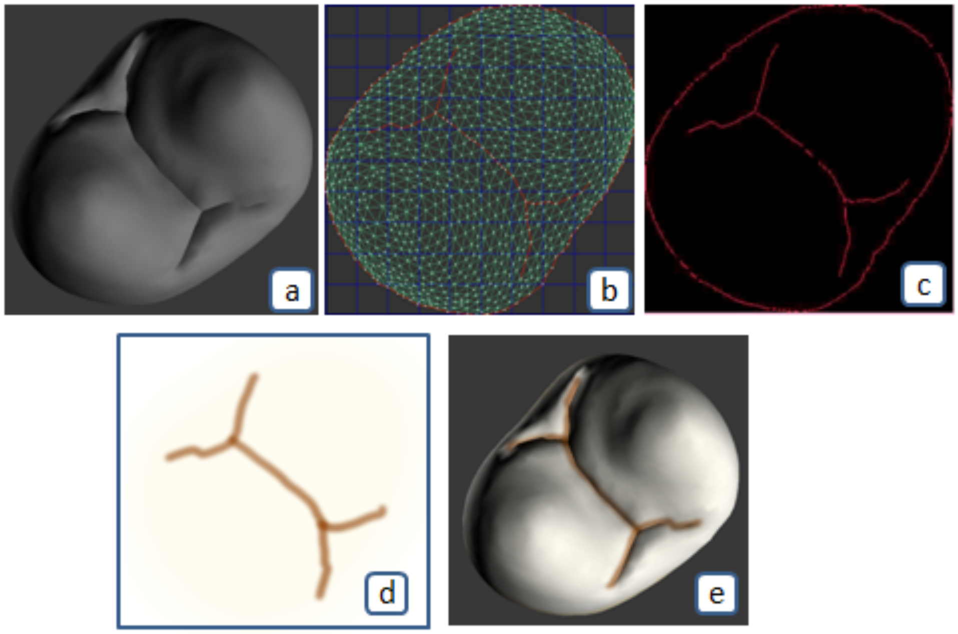


Figure 3.22 - Crown texture mapping process

3.3.2. Scene Lighting

One possible way to illuminate a 3D scene is through an ambient light. It illuminates the whole scene uniformly, as opposed to a real world light. However, a better approach to obtain realistic results is to use fill lights, which provides secondary lighting that works slightly like real ambient light [21].

We use the conventional three-point lighting technique (Figure 3.23), which is often used in Computer Graphics because it helps stand out 3D shapes and forms within a scene using light [21, 22].

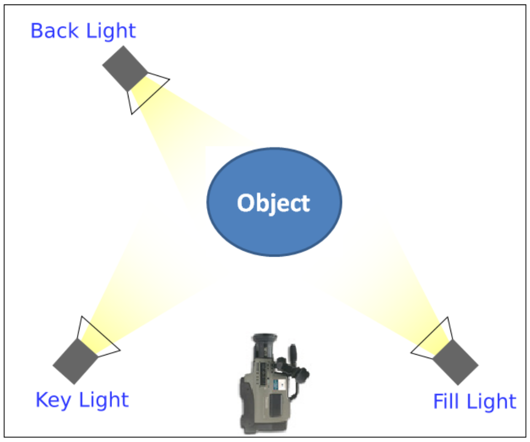


Figure 3.23[4] – Standard three point lighting scheme

Figure 3.23 illustrates this technique, which implies the use of at least three lights. Each light has different roles: key, fill and back light. The lights placement is based on the camera position. For this description we assume that the camera is positioned in front of the object. The key light is responsible for providing the primary illumination of the desired object. Normally, it is the brightest light in the scene, producing the darkest and most noticeable shadows. This light is placed in front of the object, but positioned slightly off to one side. The shadows casted from this light will increase the depth of the shot. The fill light placed in front of the object and off to the opposite side of the key light, acts as secondary illumination within the shadows. This light provides form and shadow fill, reducing the dark area caused by the key light. The back light is positioned behind the object to provide dimension and highlights, giving it a sharp outline.

The difference between using only one light and the technique can be seen in Figure 3.24. The three point lighting enhances the visualization of the entire scene.

[4] Image retrieved from http://en.wikipedia.org/wiki/Three-point_lighting

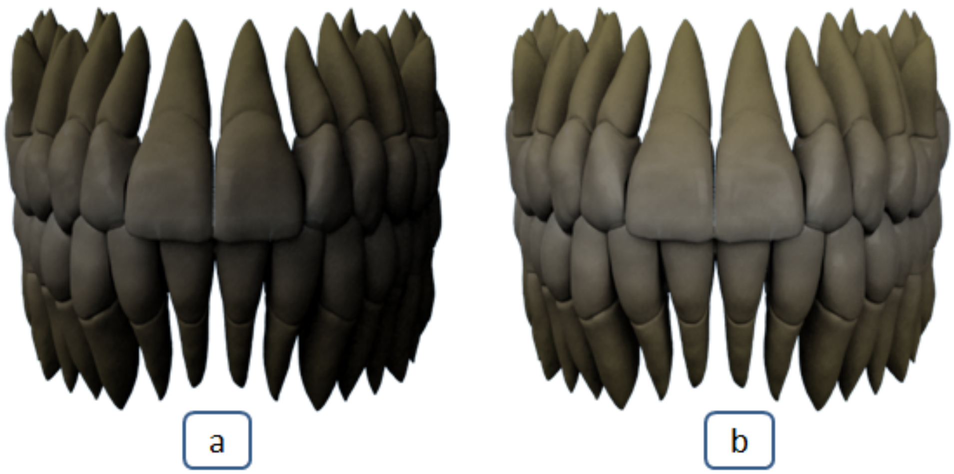


Figure 3.24 – Illumination results with: (a) One light only; (b) Three point lighting applied

3.3.3. Photorealistic rendering

Rendering is the process of synthesizing images from descriptions of scenes containing geometry, materials, lights and cameras.

This is the main last step in the pipeline, and it is responsible for assigning the final appearance to the models and animations.

Photorealistic rendering is a rendering style that aims to generate images as realistic as possible, such that they are indistinguishable from real photos. To achieve this goal the behaviour of light must be correctly modelled and simulated.

Modelling illumination and shading phenomena, like shadows and reflections, with precision and accuracy enhances the observer's understanding of spatial arrangement [18].

Creating photorealistic images to achieve visual realism is a serious challenge in computer graphics and as greatly encouraged research in this field.

Non-photorealistic rendering (also known as NPR) is a common alternative to the photorealistic method. NPR algorithms try to represent expressive styles, such as watercolour paintings, penand-ink drawings, cartoon-style drawings, technical illustrations, etc. These methods do not intend to simulate processes of nature, but instead they want to recreate an artificial style.

Concerning the execution time there are two distinct types of rendering in Computer Graphics: offline and real-time. Offline rendering is a computationally heavy task that usually achieves high quality images, whereas real-time tries to generate images at interactive rates, which can be used for instance in 3D video games. Photorealistic rendering can be performed in both real-time and offline. Offline rendering provides higher quality results.

Since the client requirements were to achieve high quality and realistic images and animations, we adopted the photorealistic approach. Given that the 3D models were going to be used in animations without any user interaction, there is no need for real-time rendering.

3.3.4. Global Illumination

In real life, the lights are normally reflected or refracted numerous times by object surfaces before reaching our eyes. Global illumination refers to any method that tries to realistically simulate light propagation inside a virtual scene. These methods can mimic a variety of visual phenomena, such as refractions (Figure 3.25b and c), caustics (Figure 3.25d and c), glossy reflections (Figure 3.25c) and diffuse inter-reflections (Figure 3.25a). Global illumination is normally used to achieve photorealistic renderings [13].

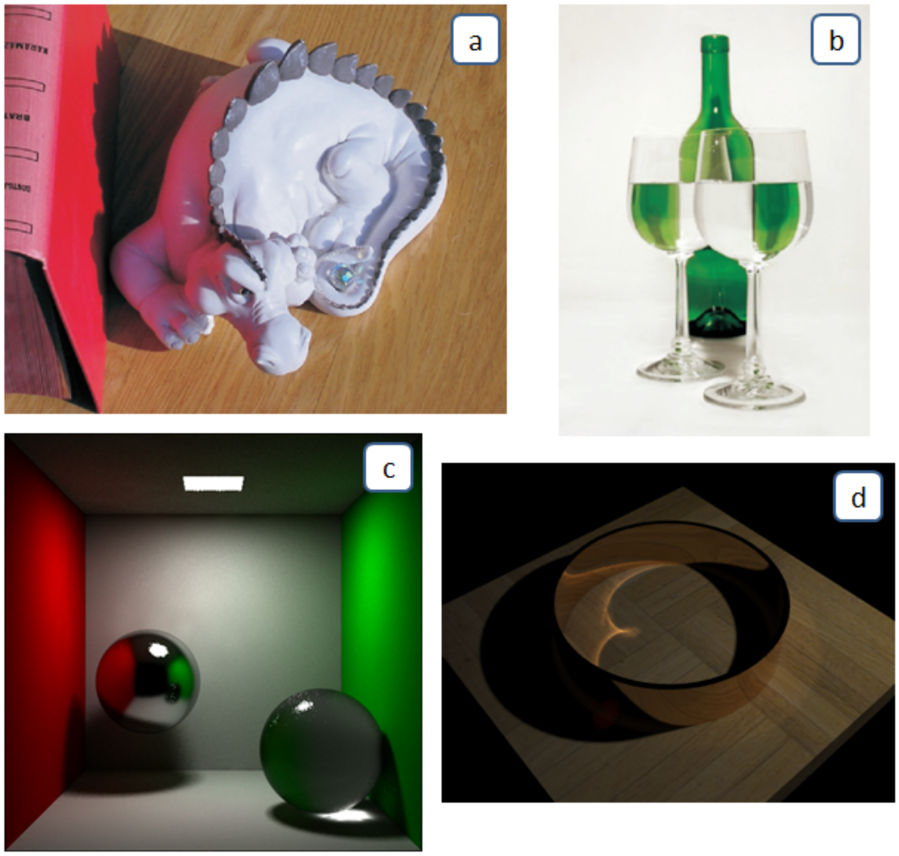


Figure 3.25[5] - Global Illumination effects

Global illumination calculates the light that comes directly from a light source (direct illumination), as well as the succeeding light rays that are reflected off other surfaces in the scene (indirect illumination). Images generated with global illumination will appear more photorealistic than just using direct illumination.

Radiosity, Ray Tracing, Beam Tracing, Cone Tracing, Path Tracing, quasi-Monte Carlo, Monte Carlo, Metropolis Light Transport, Ambient Occlusion, Photon Mapping and Irradiance Caching are examples of global illumination methods. Combining some of these algorithms can reduce the computational cost and still maintain good results.

[5] Images retrieved from Practical Global Illumination book and
from the website http://graphics.ucsd.edu/courses/rendering/2007/abarany/

Global Illumination can be computed through exact (unbiased), approximated (biased) or hybrid methods. The quality/time ratio and generated artefacts distinguish them. Numerous methods have been implemented to solve each approach.

The exact methods, like *Monte Carlo*, *quasi-Monte Carlo* or *Path Tracing*, achieve high quality and accurate images. To avoid the presence of noise in the resulting images the rendering times will be extremely high. Another disadvantage is that the global illumination computation of each image is not available for reuse.

With approximated methods it is possible to obtain good quality images in considerably less time than the exact methods. Usually, the global illumination computation can be saved for reuse. The noise problem disappears, but stains or mistakes may appear when rendering the image. Even though these methods are not completely accurate, the errors can be reduced to a point that they are unnoticeable. Among these methods are the *Photon Mapping, Irradiance Caching* and *Radiosity*.

Hybrid methods are a more flexible approach because they combine exact and approximated methods to calculate global illumination. When correctly coupled, it is possible to obtain the best of each approach and to reduce the overall problems. The main idea is to combine the speed from the approximated methods and quality from the others. This hybrid approach can be more complex to implement.

All these methods can be either view dependent or independent. They are view dependent when the global illumination is computed only for the visible parts of a scene. Sparing objects or areas of a scene from rendering can reduce the rendering time of an image. However, if the view changes (i.e. the virtual camera moves) it is required to compute again the global illumination, like on a fly-through animation, where the scene is static and only the camera moves. The view independent methods calculate the global illumination in the entire scene, even in the places that are not visible through the current camera view point. This is very handy to fly-through animations. The quality obtained with this kind of method may be lower. Accurate and detailed results are achievable at the cost of increasing the rendering time.

Ray Tracing and *Radiosity* were the first two algorithms for global illumination. In *Ray Tracing, the visibility of objects is calculated through the use of rays.* Basically this technique comprehends shooting rays from the eye (camera) through a pixel and into the scene, followed by recursively creating reflected and refracted rays until a diffuse surface is hit or stopping criteria is reached. From the intersection point of a ray with an object, another ray (shadow ray) can be shot to each light of the scene in order to determine if the point is illuminated or in shadow (view Figure 3.26). Other rays can be also traced from the intersection point, for example a ray created in the reflection direction of a shiny object. This ray obtains the colour of the first object intersected. Shadow rays are then used to test the visibility of the resulting intersection point.

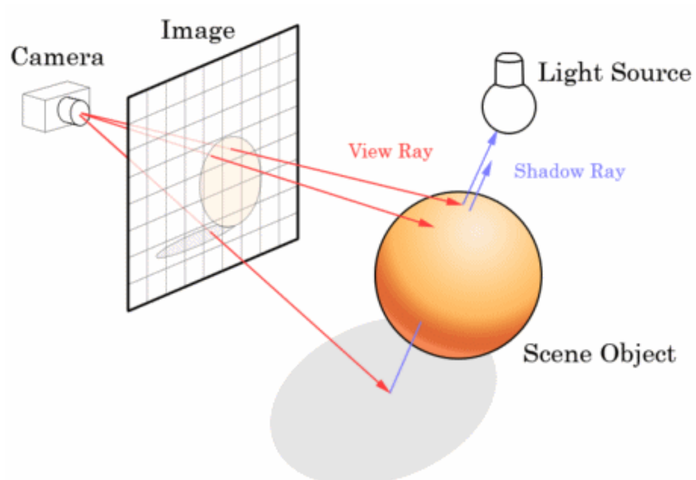


Figure 3.26[6] - Ray Tracing mechanism

The first version of *Ray Tracing* algorithm (commonly known as classical ray tracing) only calculates direct illumination and mirror reflections and refractions. The limitation is the inability to calculate some effects such as glossy and diffuse interreflections [23, 24]. To overcome these problems, the algorithm was later expanded with Monte Carlo methods, which applies a stochastic approach in the distribution of rays. The drawback of Monte Carlo ray

6 Image retrieve from http://en.wikipedia.org/wiki/Ray_tracing_(graphics)

tracing methods is the presence of variance, perceived as noise in the synthesized images. To eliminate this noise is necessary to greatly increase the number of used rays. Some improved methods appeared to solve the noise problem more efficiently, such as bidirectional Monte Carlo ray tracing, where the rays are sampled from camera and light at the same time. These Monte Carlo methods are completely exact (unbiased), hence their execution time is still excessive.

Radiosity is a finite-element method, which was developed as an alternative to ray-tracing methods. *Radiosity* is a view independent method, whereas Ray Tracing is view dependent. This aspect makes this method ideal for fly-through animations. Light distribution is computed by subdividing the scene in surface elements, and for each element the proper radiometric[7] value is calculated. The first version of this method was restricted to diffuse surfaces.

James T. Kajiya introduced in 1986 the rendering equation, which describes the distribution of light in a scene. The same author suggested the *Path Tracing* method to render an image using his equation. *Path Tracing* is an extension of Ray Tracing and is able to compute effects like caustics, reflections and colour bleeding. This view dependent method is very slow because it needs high number of rays to achieve enough quality and noise free images.

To overcome the problems usually noticed in exact methods, different methods have been developed, such as the approximate methods *Photon Mapping* and *Irradiance Caching*. These methods are normally used in offline renderings and to generate extremely realistic images [23].

[7] Radiometry is the field that studies the measurement of electromagnetic radiation, including visible light

3.3.4.1. Photon Mapping

The *Photon Mapping* motivation is to provide a global illumination method that accomplishes high quality renderings of complex scenes more efficiently than the previously described methods.

Photon Mapping method can be divided into two phases: the first shoots the photons from the light sources to the scene, and the second gathers the photons to generate an image.

The illumination is stored in a data structure called *photon map*, rather than being attached to the geometry. The map is built from photons (particles) emitted from the light sources and traced throughout the scene, resembling the way that *Path Tracing* follows paths from the camera. When a photon hits a diffuse surface, the hit position and the photon energy is saved in the *photon map*. When the first phase is finished, the *photon map* holds a representation of global illumination in the scene, containing information about all photon hits.

The use of such a separate independent map leads to a simpler representation and to efficiently simulate global illumination effects in complex scenes [24]. Among these effects are caustics, diffuse interreflections and participating media (e.g., clouds or smoke).

Ray Tracing can be used in conjunction with *Photon Mapping*, and is normally applied in the second phase, known as the *final gathering*, where rays are shot from each rendered location to gather indirect illumination (from *photon maps*) and direct illumination (from the light sources).

3.3.4.2. Irradiance Caching

This is a technique based in *Ray-Tracing* for computing global illumination on diffuse surfaces, which main purpose is to accelerate this computation. The core idea is to calculate indirect illumination only at determined regions in the scene, save the results in a cache and reuse these values for other uncalculated points through interpolation.

Irradiance Caching is frequently used for rendering high-quality images in a reasonable amount of time [25, 26].

This technique focuses on calculation of diffuse interreflections, which produces the colour bleeding effect (Figure 3.25a), where one diffuse surface obtains the colour from another surface. These interreflections are responsible for smooth gradual illumination [27]. *Irradiance Caching* does not address any global illumination effects concerning specular surfaces.

Irradiance Caching can be useful in generating high quality animations because it makes use of temporal coherence of indirect lighting to enhance the computation performance of global illumination and thus reducing rendering time [28, 29].

The *final gathering* phase of *Photon Mapping* method is slow. Irradiance *Caching* can replace Ray-Tracing in the final phase in order to accelerate rendering [27].

3.3.5. V-Ray Global Illumination Methods

As said before, V-Ray was the rendering engine used in the project. Similarly to others rendering engines, it is based on *Kaijya's* rendering equation, which describes how light travels in an environment. V-Ray has available several methods to calculate the global illumination, such as *quasi-Monte Carlo* (also known as brute force or direct computation), *irradiance map*, *photon map*, *and light cache*.

The four available V-Ray methods are based on the novel methods that have been presented in previous sections. The *quasi-Monte Carlo* method refers to the same method. V-Ray's *photon map* method corresponds to *Photon Mapping*, whilst *irradiance map* represents *Irradiance Caching*. The *light cache* is very similar to *photon map* (also based on *Photon Mapping*), which was created specifically for V-Ray.

The computation of global illumination in V-Ray is divided in two stages: *Primary bounces* and *Secondary bounces*. The *Primary bounces* address the computation of direct illumination (light that comes directly from a light source). Once the rays, representing the light travelling in the scene, hit an object several phenomena can succeed: diffusion, refraction, reflection, among others.

The *Secondary bounces* engine deals with the indirect illumination. It continues to compute the path of light flow after the rays (originated in the light sources) hit an object once.

A method can be associated to each of these stages. For this first stage it is possible to choose from all methods, while in the second only *irradiance map is not* available.

3.3.5.1. Irradiance Map

The foundation of this method is *Irradiance Caching* (described in section 3.3.4.2). The global illumination is calculated with accuracy only in the most important points of the scene, and interpolated for the rest of them. The critical points are usually located in areas where more attention is required, for instance on detailed geometrical shapes. V-Ray allows the user to define the number of points to be used, how to find them and also which interpolation method to apply. Properly configuring the settings of the Irradiance Map can lead to high-quality results in a short amount of time [30].

Irradiance map is actually a set of points in 3D space and each point has the information about the global illumination. Figure 3.27a presents a synthesized image from an example scene. In Figure 3.27b is shown the irradiance map (3D map formed by points) for that scene. The samples (points) used by the method to compute the global illumination are visible as white dots (Figure 3.27b). In the black regions the global illumination is determined by interpolating nearby samples. The number of samples is higher in areas that require more attention, like zones with high colour contrasts or brightness variations. After the location of every sample is determined, each sample shoots a particular number of rays to determine the global illumination value.

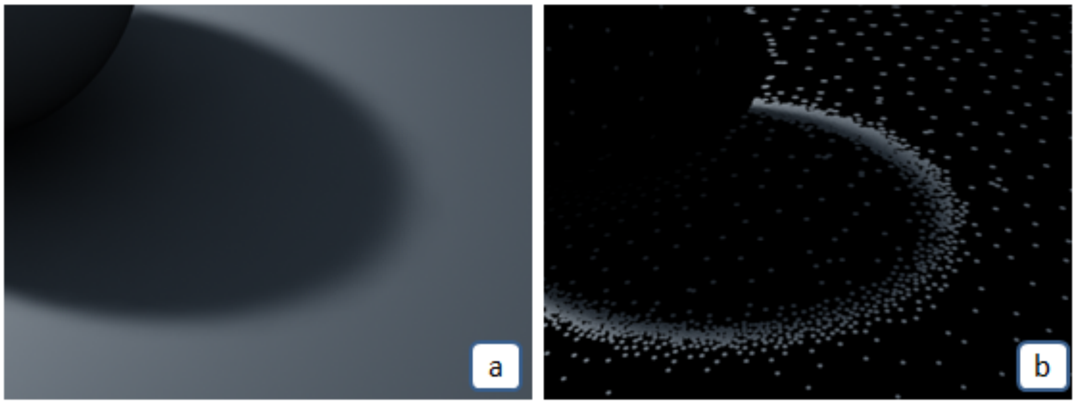


Figure 3.27[8] – (a) Rendered image; (b) Irradiance Map samples

This is a very fast method, since only a part of the scene points are considered for computing global illumination. The calculated data can be saved in a file for later use, thus saving time when rendering the same scene in different views and on fly-through animations. The noise problem present in other methods is practically absent.

Some details in the illumination may be incorrectly rendered due to the interpolation. Also, the use of low settings (like reduced number of samples) could cause flickering when producing animations. Another problem happens when motion-blurred objects are used in animations. Although this defect causes some noise, it is generally imperceptible and does not influences global animation quality.

3.3.5.2. Light Cache

This global illumination method provided by V-Ray is based on *Photon Mapping*. *Light Cache* aims to approximately compute global illumination to produce high quality renderings in the shortest time possible. It has the strong features of *Photon Mapping* and solves some of its weaknesses.

[8] Images retrieved from http://www.spot3d.com/vray/help/150R1/render_examples_advancedimap.htm

A map (light map) is constructed by emitting rays from the camera in the direction of the scene. Each hit point stores the calculated illumination from the rest of the succeeding rays in a 3D structure, in a similar way as *Photon Mapping*.

Light Cache solution can be applied in V-Ray for computing direct and indirect illumination. The setup of this method is simple and only requires defining the number of rays to shoot from the camera. Whereas in Photon Mapping the rays are shot from the light sources and each source may need different setup. Moreover the *Photon Mapping* usually works incorrectly in corners and small objects making these regions darker or brighter. This flaw has been solved in *Light Cache*.

Similarly to *Irradiance Map*, the *Light Cache* is view dependent, thus computing the global illumination only for the points visible by the camera. *Light Cache* does not work perfectly when bump maps are used.

3.3.5.3. Combining methods for Primary and Secondary Bounces

Using our model, we have created a sample animation (100 frames) for testing purposes. The rendered 3D scene (Figure 3.28) was composed by the lower teeth and the mandible, along with a surgical tool. This instrument is animated to simulate a teeth implant operation. The rendering time was measured for different combinations of V-Ray methods. The results obtained are presented in Table 3.1. For each proposed combination the rendering time is measured three times, but the only the minimum value is presented. These tests were all performed on a machine equipped with an Intel Core 2Duo processor (2.4GHz), 2Gb RAM and a NVIDIA GeForce 8600M GT.

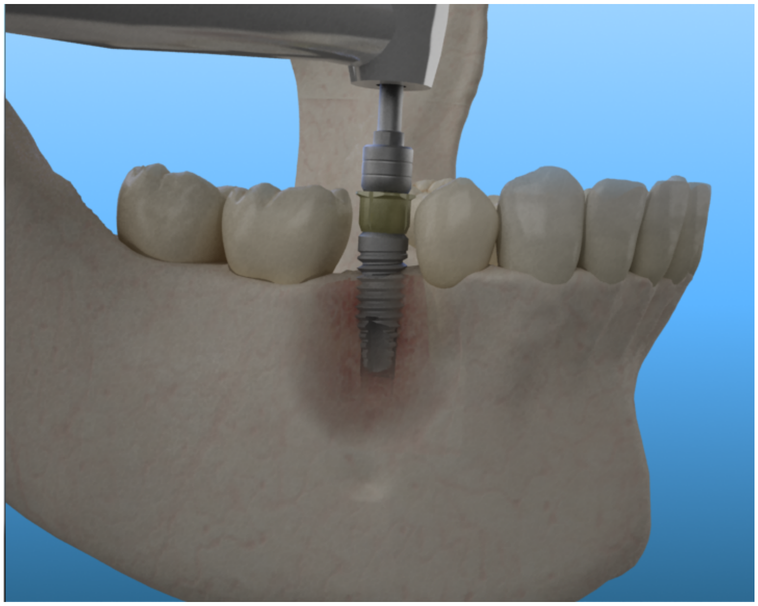


Figure 3.28 - A frame from the test animation

The *Irradiance Map* (IM) and *Light Cache* (LC) methods were chosen for *Primary bounces* (direct illumination) and for *Secondary bounces* (indirect illumination), respectively. This combination (number 1 in Table 3.1) is the best solution in terms of quality/time ratio. The solution is fast, provides good precision, correct illumination with only a few artefacts and some flickering in the animations. The illumination can be stored for reuse and, since these two methods are unbiased, the noise is never present or perceptible.

These two methods are often used together because of its high quality and particularly low rendering time [30]. It is possible to customize both methods either for fast rendering or for more accurate and precise results.

Rendering the sample animation (100 frames) with combination number 1 (IM + LC) we obtained approximately a speedup of 1.7x relatively to the two following combinations (QMC + LC and IM + QMC). This speed up represents an improvement of roughly 3 hours. Regarding the last combination (QMC + QMC), the speedup is 13x (improved 55h30min).

	Method Combination	Animation Rendering Time (100 Frames)	Rendering Time per Frame	Results
1	Irradiance Map (IM) + Light Cache (LC)	16213 s	162 s/frame	Fast, precise, very few artefacts, flickering is unnoticeable
2	quasi-Monte Carlo (QMC) + Light Cache (LC)	27664 s	277 s/frame	Precise, noisier images (which can be reduced by increasing number of rays shot in QMC, thus increasing rendering time)
3	Irradiance Map (IM) + quasi-Monte Carlo (QMC)	28201 s	282 s/frame	Very similar results when comparing with IM+LC, decent precision, few artefacts, flickering is unnoticeable, although slower)
4	quasi-Monte Carlo (QMC) + quasi-Monte Carlo (QMC)	216005 s	2160 s/frame	Slow, very precise, good quality, with a small amount of noise

Table 3.1 - Rendering animation time with different GI combinations

A real animation, which presents a surgical procedure, may have a higher number of frames. We estimate in Table 3.2 the required time to render an animation with 5000 frames. The effective rendering time may slightly differ from the estimated time. This table purpose is to provide an overall idea of the required time to render the final animations. We assumed that the rendering time per frame would remain equal when increasing the number of frames to render.

	Method Combination	Rendering Time per Frame	Estimated Animation Rendering Time* (5000 frames)
1	IM + LC	162 s/frame	225 hours
2	QMC + LC	277 s/frame	385 hours
3	IM + QMC	282 s/frame	392 hours
4	QMC + QMC	2160 s/frame	3000 hours

* Scaled from the 100 frame measurement

Table 3.2 - Estimated rendering time for a 5000 frame animation using different GI combinations

The major limitation of the chosen combination (IM + LC) is the presence of flickering in the rendered animations. This problem is caused by subtle variations in lighting between contiguous frames in regions, which are difficult for global illumination computation, like edges or small surfaces. In the *Irradiance Map* method, a particular number of adjacent frames (*interpolation frames*) can be used together to reduce flickering. When rendering an animation, V-Ray interpolates the maps from consecutive frames to smooth out the light variations between frames, and thus making flickering less noticeable. We managed to produce an animation without noticeable flicker.

4. RESULTS AND EVALUATION

4.1. Case Study – Final Results

The images shown in the present section are the final results of the developed work in the case study. The intermediate results obtained throughout the initial pipeline stages are presented in the previous section, thus not showed here.

The final images (Figure 4.1, Figure 4.2 and Figure 4.3) are renderings of virtual 3D models of the mandible, maxilla and teeth that we have created through the use of the proposed reconstruction pipeline. After obtaining the models presented in Anatomy Modelling section (page 25), we performed the last stage of the pipeline (Scene Visualization and Rendering). The result of rendering the scene after applying textures, setting the lights and global illumination methods can be viewed in these final pictures.

Figure 4.1 – 3D complete final model (teeth, mandible and maxilla)

Figure 4.2 - 3D teeth final model

Figure 4.3 - 3D teeth final model (focus on the crowns); Left: maxilla; Right: mandible

4.2. Evaluation and Validation

A survey was prepared to retrieve dentistry specialist's evaluation concerning the quality and realism of the resulting 3D models.

The survey (available in Appendix A) contains several images and an evaluation form. The images represent rendering snapshots from different viewpoints of the virtual 3D teeth models we have modelled. The form contained different criterion for evaluation: clarity of visualization; spatial relations between anatomic structures; morphological appearance of teeth, mandible and maxilla; teeth colouring appearance. A group of four dentists were asked to rate each criterion from 1(unsatisfactory) to 4(excellent). All these individuals are specialists in Dentistry with more than 14 years of work experience, except one with only 4 years. The results from the survey are presented in Table 4.1.

Rating Criteria	Clearness of appearance	Spatial relations	Root morphology	Root colour and texture	Crown morphology	Crown colour and texture	Junction morphology	Teeth overall colour and texture	Maxilla morphology	Mandible morphology	Overall morphology	Usefulness for teeh anatomy teaching	Usefulness for teaching surgery techniques	
	1	2	3	4	5	6	7	8	9	10	11	12	13	
Dentist 1 Rate	4	4	3	4	3	4	3	4	3	3	3	4	3	
Dentist 2 Rate	4	4	3	4	3	3	2	3	4	4	4	4	4	
Dentist 3 Rate	3	3	3	2	2	3	3	3	3	3	3	4	4	Overal Average Rating:
Dentist 4 Rate	4	4	3	4	3	3	2	3	3	3	4	2	4	
Average Rating	3,75	3,75	3	3,5	2,75	3,25	2,5	3,25	3,25	3,25	3,5	3,5	3,75	3,31

Table 4.1 - Evaluation Survey results

The 3D model achieved an overall average rating of 3.31, close to the excellence value (4). Particularly, these dentists considered, with an average rating of 3.75, that the 3D model provides a clear understanding of all the depicted anatomical structures. They also believe that the spatial relationships between structures are correct, i.e. possessing good positioning and orientation. This criterion obtained the same average rating as the previous one (3.75).

The overall morphology of the model was positively evaluated (3.5 average rating in column 11 of Table 4.1). The dentists rated the shape of the teeth roots with 3 and suggested that the root tips could be improved to be rounder, instead of being so sharp. The morphology of the crowns and the junctions were the worst rated (2.75 and 2.5 respectively), yet with a positive value. They commented that the junction should not be so pronounced. The maxilla and mandible are anatomically correct, except for some minor flaws (e.g. *palatine bone*[9] and fissure is not present).

In terms of texture and colours, the model is well rated (3.25). Generally the dentists mentioned that the textures should have more roughness.

Lastly, the dentists believe in the usefulness of this 3D model for anatomy teaching and for depicting surgery techniques and methods related with Dentistry.

[9] Located at the back part of the nasal cavity near the maxilla

5. CONCLUSIONS

In this project we proposed a generic pipeline to produce realistic virtual models of human anatomy. These are very detailed models that will be mainly used in non interactive animations. The primary target public of these animations are health professionals, thus necessary to achieve such level of detail. We successfully confirmed its effectiveness by presenting a case study in Dentistry area.

This is a robust pipeline, which will work with a great diversity of cases. The methods applied in each step of the process ultimately intend to reach photorealistic results with the highest accuracy and quality possible. Although we were not concerned with time issues, we sometimes used techniques that provided excellent quality/time ratio but that would guarantee correct and accurate results.

The case study consisted in constructing a 3D model of the human mouth, focusing on the teeth, mandible and maxilla. The generated model will be part of medical animations for depicting dental surgical procedures to dentists and other related professionals. With this model 3D animations and still images can be produced to improve presentations.

To achieve realistic and anatomically correct 3D representations it was indeed very helpful the support of a dentist specialist. He provided his opinion and validation reviews throughout the entire process. Evaluation, through informal observation, is essential to verify the quality of the adopted approaches. It helps discovering imperfections and inaccuracies in the reconstruction pipeline. With this information we can go back to a particular pipeline stage and make the necessary improvements. Only an expert in anatomy would notice and indicate the majority of flaws in the model. This insight is essential since the target public of the teeth model is the dentistry professionals.

The 3D model was afterwards positively evaluated by a group of experienced dentists through a survey (Appendix A). These subjects carefully examined the images rendered from different viewpoints. This survey is composed by several criteria to be rated. By analysing the survey results (Table 4.1 in page 55), we conclude that the produced virtual model has good quality in terms of clearness, morphology, texture, colour and usefulness. The dentists believe that the virtual model could be used for anatomy teaching and for producing virtual surgery procedures and techniques. However, some minor flaws are present, which could be easily solved over time. The level of quality and accuracy obtained is enough to prove the value and correctness of the proposed reconstruction pipeline.

More research is necessary to improve and enhance the speed of the segmentation step in this pipeline. Automatic segmentation of medical images would be optimal, but at this moment is still unrealistic. Furthermore, if the quality of the dataset resulting from image acquisition was higher, the segmentation in reconstruction stage should become simpler. The illumination setup for this model is proposed considering that it will be used in 3D animations. However, once the 3D model and animations are finished, some parameters of the illumination step may need to be adjusted.

As future work and as continuation of the case study project, we should develop the soft tissues on top of the validated virtual model of teeth. Later this complete model will be used in animations to describe medical procedures. These future steps also need to be evaluated and validated by a specialist.

6. REFERENCES

[1] P. Dev, "Imaging and visualization in medical education," *Computer Graphics and Applications, IEEE*, vol. 19, no. 3, pp. 21–31, May/Jun 1999.

[2] J. Venuti, C. Imielinska, and P. Molholt, "New views of pelvic anatomy: Role of computer-generated 3d images," *Clinical Anatomy 17, 3*, pp. 261–271, 2004.

[3] R. Sweet, D. Burke, Y. Shen, N. Zhang, and T. Reihsen, "Photorealistic 3-d virtual reality model of the abdomen and retroperitoneum," *Video presentation, American Urological Association annual meeting, Chicago, IL*, 2009.

[4] J. M. R. Tavares and R. N. Jorge, *Advances in Computational Vision and Medical Image Processing: Methods and Applications*. Springer Publishing Company, Incorporated, 2008.

[5] C. Kober, G. K. Yoshihiko Hayakawa and, L. Gallo, M. Otonari-Yamamoto, and T. S. R. A. Sader, "3d-visualization of the temporomandibular joint with focus on the articular disc based on clinical t1-, t2-, and proton density weighted mr images," *International Journal of Computer Assisted Radiology and Surgery*, vol. 2, no. 3-4, pp. 203–210, December 2007.

[6] S. Zachow, M. Zilske, and H.-C. Hege, "3d reconstruction of individual anatomy from medical image data: Segmentation and geometry processing," in *25. ANSYS Conference & CADFEM Users' Meeting*, Dresden, 2007, proc. CD 2.12.15.

[7] Y. M. Yusop, H. Haron, and M. R. A. Kadir, "3d reconstruction and analysis of trabecular bone using visualization and modeling technique," in *Proceedings of the 4th IMT-GT Conference on Mathematics, Statistics and Applications (ICMSA)*, 2008.

[8] W. Li, M. V. Swain, Q. Li, and G. P. Steven, "Towards automated 3d finite element modeling of direct fiber reinforced composite dental bridge," *Journal of Biomedical Materials Research Part B: Applied Biomaterials*, vol. 74B, no. 1, pp. 520–528, 2005. [Online]. Available: http://dx.doi.org/10.1002/jbm.b.30233

[9] “Teeth 3d models,” Retrieved June 12, 2009, 2009, http://www.3dscience.com/3D_Models/Human_Anatomy/Teeth/index.php.

[10] J. Heller, “Zygote puts the “art” in heart,” Retrieved June 12, 2009, 2006, http://www10.dcccafe.com/nbc/articles/view_weekly.php?section=Magazine&articleid=244868.

[11] Y. Ito, P. Shum, A. Shih, B. Soni, and K. Nakahashi, “Robust generation of high-quality unstructured meshes on realistic biomedical geometry,” *International journal for numerical methods in engineering*, vol. 65, no. 6, pp. 943–973, 2006.

[12] A. Courtenay and H. I. Graham, “Virtual teeth for endodontics training and practice,” in *IV ’00: Proceedings of the International Conference on Information Visualisation*. Washington, DC, USA: IEEE Computer Society, 2000, p. 597.

[13] B. Preim and D. Bartz, *Visualization in Medicine: Theory, Algorithms, and Applications (The Morgan Kaufmann Series in Computer Graphics)*, 1st ed. Morgan Kaufmann, June 2007. [Online]. Available: http://www.amazon.ca/exec/obidos/redirect?tag=citeulike09-20&path=ASIN/0123705967

[14] I. N. Bankman, Ed., *Handbook of medical imaging: Processing and Analysis*, 1st ed. Orlando, FL, USA: Academic Press, Inc., 2000.

[15] P. Suetens, *Fundamentals of Medical Imaging*, 2nd ed. Cambridge University Press, 2009.

[16] T. Kondo, S. Ong, and K. Foong, “Tooth segmentation of dental study models using range images,” *Medical Imaging, IEEE Transactions on*, vol. 23, no. 3, pp. 350–362, March 2004.

[17] W. E. Lorensen and H. E. Cline, “Marching cubes: A high resolution 3d surface construction algorithm,” *SIGGRAPH Comput. Graph.*, vol. 21, no. 4, pp. 163–169, 1987.

[18] D. Stalling, M. Westerhoff, and H.-C. Hege, *The Visualization Handbook*, 2005, ch. Amira: A highly interactive system for visual data analysis, pp. 749–767.

[19] R. Bade, O. Konrad, and B. Preim, “Reducing artifacts in surface meshes extracted from binary volumes,” in *International Conference in Central Europe on Computer Graphics, Visualization and Computer Vision, University of West Bohemia, Campus-Bory Plzen, 29/01/07-01/02/07*, ser. Journal of WSCG, vol. 15, no. 1-3. http://www.zcu.cz/: University of West Bohemia, January 2007, pp. 67–74, iSSN 1213-6972, ISBN 978-80-86943-00-8. [Online]. Available: http://wscg.zcu.cz/WSCG2007/Papers_2007/journal/B29-full.pdf

[20] P. Ratner, *3-D Human Modeling and Animation*. New York, NY, USA: John Wiley & Sons, Inc., 2003.

[21] D. Brooker, *Essential CG Lighting Techniques with 3ds Max, Third Edition*. Focal Press, 2008.

[22] J. Birn, *Digital Lighting and Rendering*, G. Maestri, Ed. Thousand Oaks, CA, USA: New Riders Publishing, 2000.

[23] T. Akenine-Möller, E. Haines, and N. Hoffman, *Real-Time Rendering 3rd Edition*. Natick, MA, USA: A. K. Peters, Ltd., 2008.

[24] H. W. Jensen, *Realistic image synthesis using photon mapping*. Natick, MA, USA: A. K. Peters, Ltd., 2001.

[25] M. Smyk, S. Kinuwaki, R. Durikovic, and K. Myszkowski, “Temporally coherent irradiance caching for high quality animation rendering,” in *In Eurographics 2005*, vol. 24, 2005, pp. 401–412.

[26] P. Gautron, K. Bouatouch, and S. Pattanaik, “Temporal radiance caching,” in *SIGGRAPH ’08: ACM SIGGRAPH 2008 classes*. New York, NY, USA: ACM, 2008, pp. 1–49.

[27] J. Krivanek and P. Gautron, “Practical global illumination with irradiance caching,” *Synthesis Lectures on Computer Graphics and Animation*, vol. 4, no. 1, pp. 1–148, 2009. [Online]. Available: http://www.morganclaypool.com/doi/abs/10.2200/-S00180ED1V01Y200903CGR010

[28] K. Myszkowski, “Perception-based global illumination, rendering, and animation techniques,” in *SCCG ’02: Proceedings of the 18th spring conference on Computer graphics*. New York, NY, USA: ACM, 2002, pp. 13–24.

[29] P. Gautron, K. Bouatouch, and S. Pattanaik, “Temporal radiance caching,” IRISA, Rennes, France, Tech. Rep. 1796, 2006.

[30] F. Legrenzi, *VRay: The Complete Guide*, 2008.

Appendix A

The images you will see in the next pages are snapshots of virtual 3D models of mandible, maxilla and teeth we have modelled.

The main idea of the following survey is to retrieve specialist's appreciation/evaluation about the quality and realism of the resulting models.

SURVEY FOR EVALUATION OF *3D MODEL / WORK*

This is an anonymous survey.

Age ☐

Do you have knowledge in Odontology/Dentistry area? Yes ○ No ○

What is(are) your job(s)?

- ○ General Dentist
- ○ Dental Nurse
- ○ Dental Sales
- ○ Implantologist
- ○ Oral Surgeon
- Other(s): ____________________________________

How many years have you been in this area? ☐

Please take a few moments to **observe the images in Supplement A**. Pay particular attention to the anatomy quality (if the bones are well formed), visual quality (if the colours and textures look correct) and the teeth morphology (crowns, roots and *amelocemental* junction).

Once you have observed the images, you are kindly asked to fill the evaluation form in the **Supplement B**. Please rate each criterion from 1 to 4 (where 1 corresponds to unsatisfactory and 4 to excellence).

It is important to emphasize that the third molar is not presented, because it will not be necessary for the surgery procedures which will be implemented.

Supplement A – Images

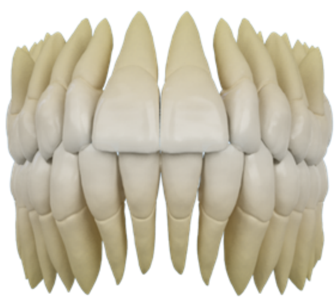
1

2

3

4

5



6

7

8

Inferior Teeth

8

9

10

11

12

Superior Teeth

13

14

15

16

17

Supplement B - Questions

		Rating 1–unsatisfactory 4-excellent				Comments[1] (optional)
1	Clearness of appearance (i.e. all parts of the model are clear and understandable?)	1	2	3	4	
2	Spatial relations between anatomic structures (i.e. the teeth, maxilla and mandible are well positioned and oriented?)	1	2	3	4	
3	Root morphological appearance (shape)	1	2	3	4	
4	Root colour and texture appearance	1	2	3	4	
5	Crown morphological appearance (shape)	1	2	3	4	
6	Crown colour and texture appearance	1	2	3	4	
7	Amelocemental junction morphological appearance (shape and position)	1	2	3	4	
8	Teeth overall colour and texture appearance	1	2	3	4	

[1] Fill the comment column whenever you feel the need to add explanation or to specify something relevant

		Rating 1–unsatisfactory 4-excellent	Comments[2] (optional)
9	Maxilla morphological appearance (shape)	① ② ③ ④	
10	Mandible morphological appearance (shape)	① ② ③ ④	
11	Overall morphological appearance (teeth, mandible, maxilla)	① ② ③ ④	
12	Do you think this model could be useful for teaching teeth related anatomy?	① ② ③ ④	
13	Do you think this model could be useful for teaching/showing surgery techniques and methods?	① ② ③ ④	

<u>Additional comments:</u>

[2] Fill the comment column whenever you feel the need to add explanation or to specify something relevant