TOOTH PARAMETER EXTRACTION BASED ON COMPUTED TOMOGRAPHY

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ABSTRACT

A new method to access external and internal dental parameters was developed to analyze ancient dental specimens, dated 2080±60 years, from the Highland Archeology Research Project in Pang Mapha, Mae Hongson province, northern Thailand. The objective of the study was to establish a fast and accurate method to extract dental parameters with minimal human interference without sample destruction. This method utilized Computed Tomography (CT) data and the image processing tool box of MATLAB®. The research consisted of a tooth type recognition process and morphometric process. In tooth type recognition, after segmentation, a neural network system, a computer process, played a big role in tooth classification procedure. For the morphometric process, image segmentation and measurement procedure techniques were used to assess enamel and dentin parameters. The tooth type recognition process can identify tooth type correctly for 71.79% of cases. Using morphometric process, measurement of enamel thickness and volume was satisfactory whereas the measurement of parameters for dentin needs some modification. Although a fast and accurate method was not achieved by the end of this study, at least this technique requires minimal human interference.

KEY WORDS : TOOTH PARAMETER EXTRACTION/ TOOTH RECOGNITION/ MORPHOMETRIC ODONTOLOGY/ CONE BEAM CT/ TOOTH TYPE/ HUMAN TOOTH/ IMAGE PROCESSING

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(TOOTH PARAMETER EXTRACTION BASED ON COMPUTED TOMOGRAPHY)

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บทคัดย่อ

แนวทางใหม่เพื่อศึกษาของลักษณะภายนอกและภายในของฟัน ได้ถูกพัฒนาขึ้นเพื่อใช้ในการวิเคราะห์ฟันมนุษย์โบราณที่มีอายุประมาณ 2080±60 ปี จากโครงการโบราณคดีบนพื้นที่สูงในอำเภอปางมะผ้า จังหวัดแม่ฮ่องสอน วัตถุประสงค์ของการศึกษาครั้งนี้เพื่อสร้างวิธีการที่รวดเร็วและแม่นยำสำหรับการวัดค่าตัวแปรของฟันโดยอัตโนมัติ ไม่ทำลายเนื้อฟันและใช้ความช่วยเหลือของมนุษย์น้อยที่สุด วิธีการนี้ใช้ข้อมูลจากเครื่องเอ็กซเรย์คอมพิวเตอร์ และเครื่องมือทางการประมวลผลรูปของแม็ทแล็บ (MATLAB®) ในการศึกษาประกอบด้วยกระบวนการรู้จำ และกระบวนการวัดค่า ในกระบวนการรู้จำนั้น ภายหลังจากการแยกฟันแล้ว ข้อมูลจะถูกส่งไปยังระบบเครือข่ายประสาท เพื่อแยกฟัน ในส่วนของการวัดฟันนั้น ข้อมูลฟันก็จะถูกแยกออกจากกันก่อน แล้วจึงจะผ่านไปยังกระบวนการวัดความหนาของเคลือบฟันและเนื้อฟัน จากการศึกษานี้ พบว่ากระบวนการจำแนกฟันนั้น สามารถทำได้ถูกต้องร้อยละ 71.79 ในกระบวนการวัดฟันนั้น ค่าของความหนาเคลือบฟันและปริมาตรของเคลือบฟันได้ผลเป็นที่น่าพอใจ ส่วนความหนาของเนื้อฟันนั้นยังคงต้องมีการปรับปรุงต่อไป แม้ว่าในส่วนของความเร็วและความแม่นยำนั้นจะยังไม่ได้ข้อสรุปในขั้นสุดท้าย แต่อย่างน้อยที่สุดวิธีที่ได้นำเสนอนี้ก็เป็นวิธีที่ใช้มนุษย์ให้มามีส่วนร่วมในการวัดฟันน้อยที่สุดวิธีหนึ่ง

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LIST OF ABBREVIATIONS

CT	Computed Tomography
GUI	Graphical User Interface
ISBME	International Symposium on Biomedical Engineering
2-D image	Two-dimensional image
3-D image	Three-dimensional image
CEJ	Cemento-Enamel Junction
X-ray CT	X-ray computed tomography
SPECT	Single Photon Emission Computed Tomography
CCD	Charge Coupled Device
ART	Algebraic Reconstruction Techniques
IRR	Iterative Reconstruction Re-projection
MRI	Magnetic Resonance Imaging
RF	Radio Frequency
HMH	Half Maximum Height
mm.	millimeter
cm.	centimeter
kV	kilo-Volt
mA	milliAmpere
sec.	second
DICOM	Digital Imaging and Communications in Medicine
NEMA	National Electrical Manufacturers Association
uint8	unsigned integer 8 bit
uint16	unsigned integer 16 bit
FOV	Field Of View
HA	Hydroxyapatite
MTEC	National Metal and Materials Technology Center

CHAPTER I
INTRODUCTION

1.1 Background

The Archaeology Research Project in Pang Mapha, Mae Hongson province, has discovered numerous individual teeth dated 2080±60 years from log coffin caves. The project requires a methodology to study both external and internal tooth structures in order to assess age of the individual, tooth wear pattern and dental pulp reaction to environment. With recent medical technology, Computed Tomography (CT) was proposed as a method of choice in assessing dental parameters without destruction of these valuable specimens.

1.2 Problem Statement

Tooth morphologic parameters provide important fundamental information for dental operations. This information may be applied in various dentistry divisions. For example, the virtual esthetic procedure requires the correct shape and dimension of a tooth for its best functionality. Similarly, these parameters are also the key to achieving full satisfaction from dental substitution in a patient. Some morphometric data are widely utilized in orthodontic treatment plans. This information is used in cases of teeth-size and arch-size discrepancies [Moyer analysis], crowding and spacing, tooth size discrepancies between arches [Bolton analysis], overbite and overjet and for good occlusion. They also give benefits in tooth selection for extraction in orthodontic treatment. Although tooth morphologic information (such as shape, size, diameter, length and thickness of structures) is very useful, there are only a few researches that focus on this parameter extraction method because of two main disadvantages; two-dimensional measurement and manual approach. For two-dimensional measurement, the distance between two points characterizes the values of each parameter. In the manual approach, this procedure is time consuming and requires trained personal interference. Multidisciplinary researches such as tooth based population classification may also be conducted based on the same set of parameters. The recent medical technology in Computed Tomography (CT) makes it possible to obtain all necessary parameters without destroying invaluable samples. From its exceptional feature, CT is mainly used to reveal the internal structures of teeth. The result can be visualized in three-dimensional representation. Even though tooth morphology information is important, few applications have been developed due to the highly complex processing schemes which mostly require human assistance, interference to obtain acceptable accuracy level, high expense and high radiation involvement.

1.3 Challenges

The extraction of tooth parameters is a major challenge. Ideally, the procedure for parameters extraction requires a fast and accurate method. Generally, high accuracy methods require a long procedure whereas fast methods result in low accuracy. Normally, a device requires a period of time for image extraction. A fast procedure may result in an incomplete image. Different data sets and different view for measurement from different scanning protocol could increase the extraction error. The scanning protocol is responsible for pixel size, which is referred to as image resolution. Small pixel size produces a better result than large pixel size. The dissimilar data set may also lead to inaccuracy because the varying data are operated by different formula. Lastly, the view of the assessment could bring about false morphometric information.

To solve this problem, the tooth measuring methodology must be well established.

1.4 Goals of the Thesis

A 3-D tooth measuring programme is currently being developed at the Biomedical Engineering Program, Faculty of Engineering, Mahidol University. The tooth parameters can be determined accurately and efficiently with minimum human interference. Objectives of this research study are demonstrated as follows.

1. To develop a new methodology for external and internal three-dimensional tooth measurement specific for ancient tooth specimens using CT information. This methodology consists of
   a. Tooth type recognition (eg. incisors, canines, premolars and molars) using morphological data.
   b. Dental parameter measurement.
2. A proposed approach will require least human interference in the computation.

1.5 Research Outcomes

This project provides several outcomes; a new technique for parameter extraction of a human tooth as well as an automatic tooth measurement programme for 3D Computed Tomography (CT) data. For a developed programming product, it is represented in a set of libraries. The set of computer commands, known as libraries, has been defined into two significant issues; the developed approach in morphologic classification and in morphometric odontology. At the end of this project, it is expected the graphical user interface (GUI) of these command sets will provide a user friendly method. Moreover, there is an expectation to be able to assess the tooth parameters from three-dimensional tooth information more precisely.

Another anticipated outcome is conference papers. Some significant outcomes and image processing algorithms of this project will be submitted to famous conferences in the biomedical engineering society in order to publish the results and obtain valuable feedback from the research society. Before conducting the final defense seminar, the outcome of this project was submitted to an International Symposium on Biomedical Engineering (ISBME) 2004 on November 16-18, 2004 at Rama Garden Hotel, Bangkok, Thailand. (Appendix 2)

Finally, this method is a promising approach to gather tooth parameter information from digital Computerized Tomography data in the same manner as the previously mentioned method does. The applied approaches can offer benefits for dental anthropology application. After the experimental process, not only the methodology but also the results can be utilized as guidance for researchers who are interested in this research field and attempt to develop the new techniques for measuring a human tooth.

1.6 Thesis Organization

This thesis is organized as follows:

- Chapter I: *Introduction* states the background and problem leading to conducting this research. The challenges and the goal are demonstrated in this chapter also.
- Chapter II: *Literature Review* provides brief introduction and background in dental parameters and related CT technologies and an overview of the studies associated with this research.
- Chapter III: *Materials and Methods* present the tooth measurement system and the operational phases that are performed in each procedure.
- Chapter IV: *Experimental Results* give the information of both tooth type identification and morphometric measurement in this study.
- Chapter V: *Discussion* comments on the significant results and relevant suggestions.
- Chapter VI: *Conclusion* summarizes this research and suggested future research is proposed.

CHAPTER II
LITERTURE REVIEW

In this chapter, a brief introduction to dental parameters, CT technology and three dimensional reconstruction methods are presented. The mathematical models of image reconstruction and its advantages and disadvantages are also discussed. The development of morphometric studies of previous researches is summarized. The last part of this revision gives the information for the image processing toolbox in MATLAB®, which was involved in this study.

2.1 Tooth measurement

2.1.1 Definition

Before starting the morphometric study, some dental terminologies must first be defined. The terminologies concern parts of a tooth. The tooth can be externally divided into two parts; crown portion and root portion. The crown is defined as the upper part of a tooth covered with the hardest tissue, enamel, whereas the root is the lower part of a tooth that is impacted in the jawbone. Root trunk and trunk base, only observed in multiroot teeth, are part of the root of either a molar or two-rooted premolar near the cervical line. The tip of the root is called the apex of the root (Figure 2.1).

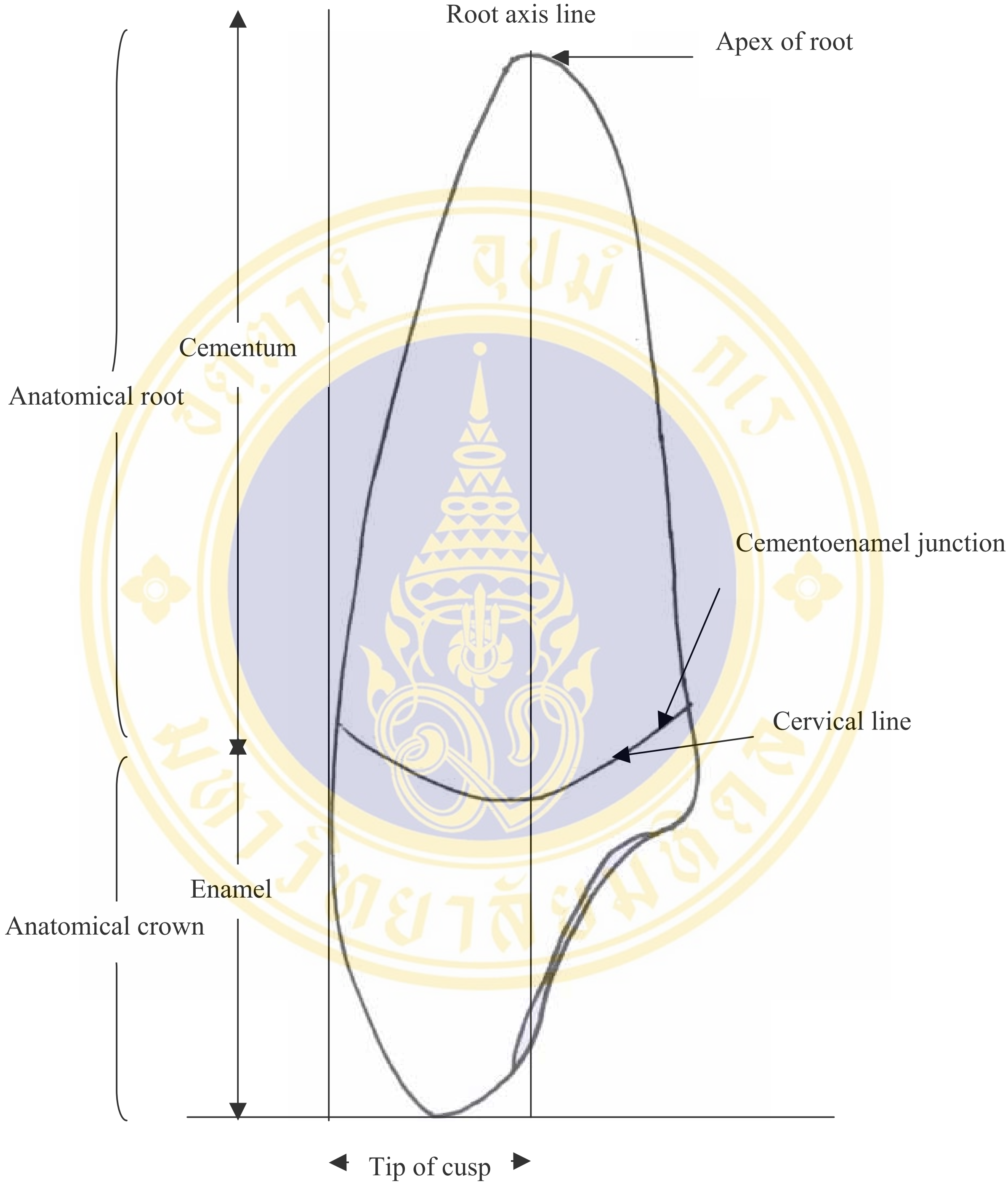


Figure 2.1 Parts of a tooth
(adapted from Dental Anatomy 2nd edition)

Internally, a tooth consists of three major layers; enamel, dentin and pulp cavity. The external tooth surface, composed of a much more inorganic component (i.e.Calcium) than others, is enamel. For this reason, enamel is the hardest tissue in the body [1]. Once crown formation is completed, enamel cannot be recreated. Different from enamel, dentin, the layer beneath the enamel surface, is mostly made up of organic components. It can reproduce and remodel when a surrounding stimulator activates. The internal structure is pulp cavity containing the blood and nerve supply to the tooth. Cells in this layer are also important. It continuously reproduces dentin according to external stimulation. Cementum in the root portion covers the root surface similar to enamel covering the crown portion. Cementum has the same physical strength as dentin, although the composition is slightly different. However, radiographic imaging cannot distinguish between the two. Periodontal ligament is the attachment connecting cementum to the bone therefore holding the tooth in its socket. The border where enamel and cementum meet each other is called the cemento-Enamel Junction (CEJ) or cervical line. CEJ is the important anatomical-reference to separate crown portion from root portion.

There are technical terms for each tooth surface. The facial surface is the outer surface of a tooth in the mouth resting against or next to the cheeks or lips. Another name for the facial surface of the posterior teeth is the buccal surface. Similarly, the labial surface is another name for the facial surface of the anterior teeth. The lingual surface is the surface of the mandibular teeth nearest the tongue. In the maxillary teeth, the nearest surface to the palate is commonly called the palatal surface. The mesial surface is the surface of the tooth nearest the dental arch midline. In contrast, the distal surface is the surface of the tooth farthest from the midline of the dental arch midline. The occlusal surface is the chewing surface of posterior teeth. Incisal edge is the cutting edge, ridge or surface of anterior teeth [1]. (Figure 2.2)

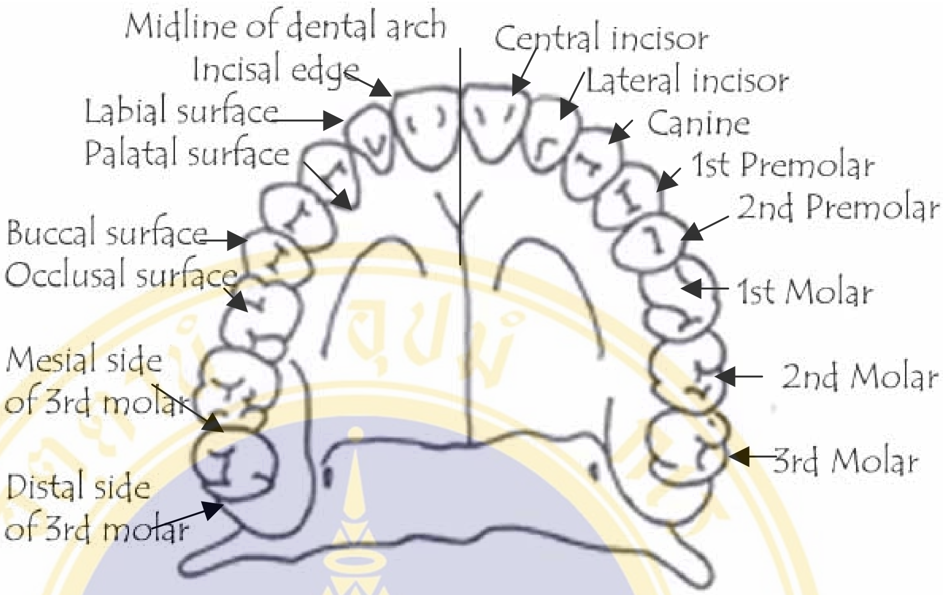


Figure 2.2 Terminologies of tooth surface
(adapted from Dental Anatomy 2nd edition)

There are a few terms about points of reference. Medial means toward the central line of the body. The proximal surface (approximal surface) is the surface or side of a tooth that is next to an adjacent tooth either the mesial or the distal surface. The contact area or contact point is the small spot or area on the mesial and distal surfaces of a tooth, which touches the adjacent tooth in the same arch, in teeth with good alignment. All of these terminologies are important for identification in tooth measurements.

2.1.2 Tooth parameters

Dental characteristics are species-specific including tooth types [2] (i.e. incisor, canine, premolar, molar) (Table 2.1) and morphology (i.e. tooth size [3], tooth shape, number of cusps, slope of incline plain, prominence of cingulum, etc.). Human’s tooth characteristic is non-prominant canine, dull first premolar, no inter-tooth space [4] and two-cuspid in premolar [5]. Odontometry is utilized to obtain the necessary data detailing the differences. Odontometry is a measurement method using the distance between assigned points to detail these differences both in the same and different species. Odontometry can be done both for internal and external tooth structures.

Table 2.1 Number of teeth in Human, Dog and Pig .(adapted from Provet pet health information at www.provet.co.uk)

		Incisor	Canine	Premolar	Molar
Human	maxilla	4	2	4	6
	mandible	4	2	4	6
Dog	maxilla	6	2	8	4
	mandible	6	2	8	6
Pig	maxilla	6	2	8	6
	mandible	6	2	8	6

2.1.2.1 External parameters

In previous research studies, a tooth was usually assessed in terms of its physical characteristics. Three dominant measurements are as follows [6].

1. Mesiodistal crown width

This is the greatest mesiodistal dimension taken parallel to the occlusal and the facial surface. The mesiodistal width of a tooth gradually changes during its lifetime because the tooth moves individually, therefore, the proximal sides of the tooth (contact points) rub each other causing proximal wear. Because this value is taken from the distance between mesial and distal contact points, a tooth that has any pathological change such as caries or fractures in the proximal part will be excluded from the study.

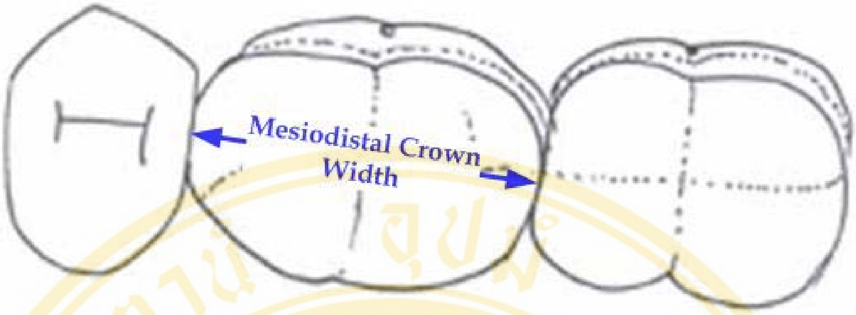


Figure 2.3 Mesiodistal crown width.

2. Buccolingual crown width

This measurement is the greatest distance between the facial and the lingual surfaces of the crown. It is taken at right angles to the plane of the mesiodistal diameter. Buccolingual diameters are normally unaffected because the buccal and lingual sides of the tooth are adjacent to the soft tissue. However, the buccolingual diameter may be affected in the case of severe attrition.

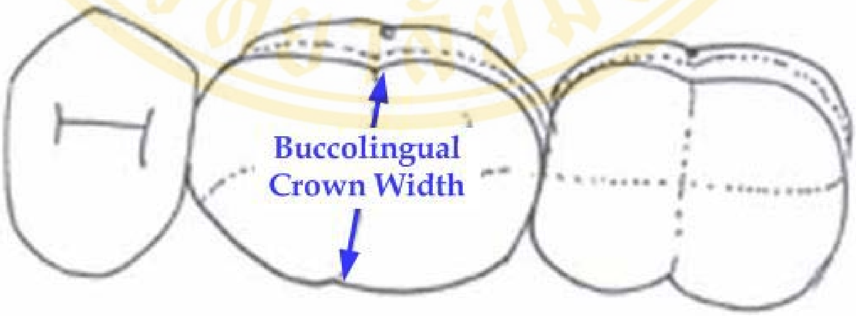


Figure 2.4 Buccolingual crown width

3. Crown height

This is defined as the distance from the tip of the highest cusp to the cervical line on the buccal side in posterior teeth while it is referred to the distance from incisal edge to the cervical line on the facial side of anterior teeth. Because cusps can be changed from attrition, abrasion, erosion and dental restoration, this value can be used to demonstrate the function of teeth associated with for example the chewing of certain types of food, nail biting habit, pipe smoking habit or using teeth for making tools. It is also widely used for assessment of crown/ root ratio values in dental substitution.

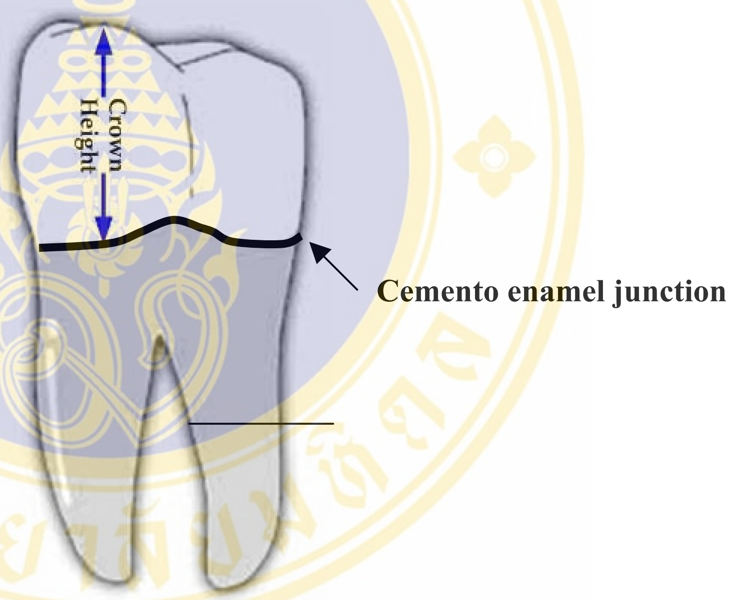


Figure 2.5 Crown height
(adapted from www.dentanet.org.uk)

This tooth parameter measurement is frequently employed to get available data in dental prosthesis, orthodontics, dental restoration and occlusion. Morphological information is utilized in the tooth selection process for dental substitution. It is also used for esthetic considerations in restorative dentistry. Some use these parameters to correct tooth and arch size in orthodontics while others who treat abnormal occlusion patients rely on this information. In brief, former research studies are based on the desired tooth parameters.

2.1.2.2 Internal parameters

Some available tooth information has been investigated in former studies. It consists of enamel thickness and dentin thickness.

1. Enamel thickness

Two types of enamel thickness measurement are occlusal wear and proximal wear. Occlusal wear measurement is normally measured at the tip of cusps or on the incisal edge. This measurement reflects the use of teeth associated with type of food consumed. Proximal wear measurement is ascertained by measurement at the plane of the maximum mesiodistal diameter of each tooth [7]. This wear occurs as teeth rub against each other during chewing. As enamel thickness decreases through out life, it can be used for age estimation. The pattern of tooth wear assessed by enamel thickness measurement is useful in dental anthropology and forensic dentistry [8], [9].

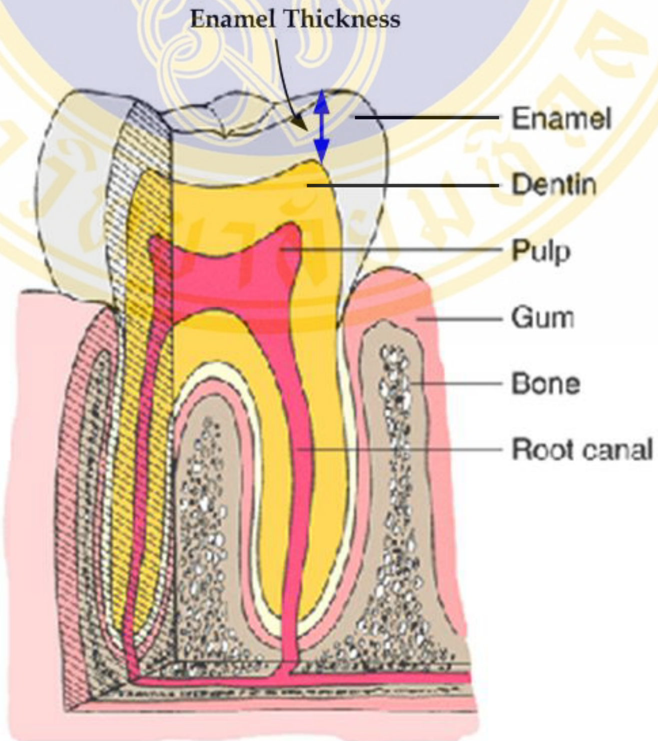


Figure 2.6 Enamel thickness

(adapted from www.luhs.org.)

2. Dentin thickness

Similar to enamel thickness, dentin thickness is measured occlusally and proximally. Unlike enamel, the external environment can affect the dentinal structure. Dentin thickness increases with age and as a response to external stimuli resulting in pulp recession. However, incases of severe attrition, dentin thickness may decrease as part of occlusal wear. Therefore, this parameter should be carefully interpreted.

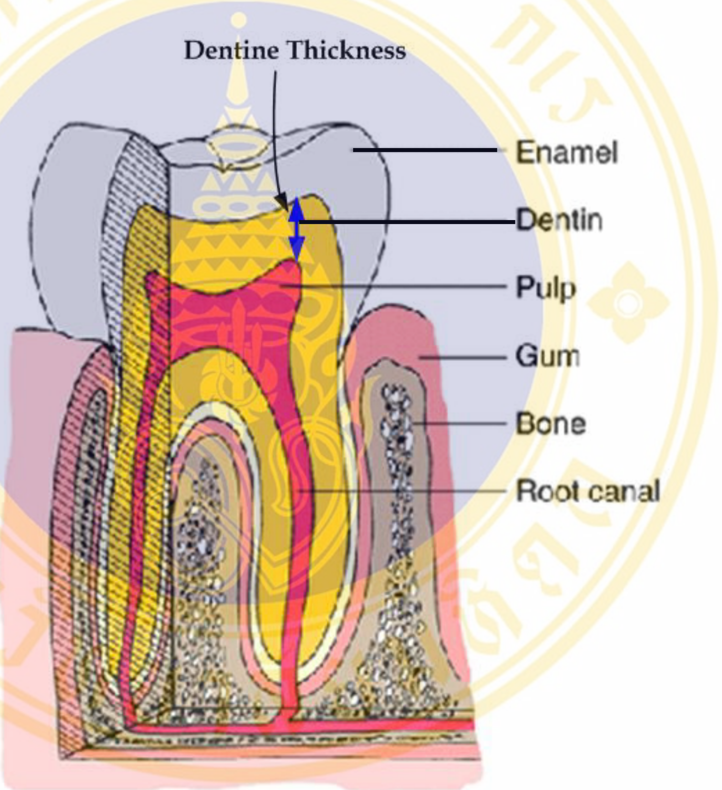


Figure 2.7 Dentin thickness
(adapted from www.luhs.org.)

2.2 Computed Tomography (CT)

To investigate the desired dental information, X-rays are widely used in conventional procedures such as image gross bone structure and lungs but X-rays are potentially damaging to biological tissue. The other main disadvantage of conventional X-rays is it produces a 2-dimensional projection image of a 3-

dimensional structure. Therefore, conventional X-ray imaging was not considered suitable for this project. The three-dimensional tooth data are required for complete tooth reconstruction. Therefore, an advanced technology, computerized tomography (CT), is a promising approach for tooth parameters measurement.

2.2.1 Overview of Computerized Tomography (CT)

X-ray CT (X-ray computerized tomography) is a product of X-ray technology. The method is based on the principle that a three-dimensional (3D) object can be reconstructed from its two-dimensional projections; for example, it generates the cross-sectional display of the body. The mathematics is based on the Randon transform, widely uses in image reconstruction from projection, which maps an n-dimensional space to a (n -1) dimensional space. A scan involves taking X-ray pictures from various angles and then combining them together to reconstruct the 3D structures of the body.

The principle of this instrument is based on X-ray generation, detection, digitalization, processing and image reconstruction. X-ray beams pass through the body in the initial process. Different tissues along the X-ray path attenuate X-rays and result in an image. The attenuated X-ray will be collected by detectors and then converted to digital numbers or data. Normally, the X-rays scan along a given direction. Therefore, to get the whole data of each object, the scanning is repeated at a series of angular views by rotating both the X-ray tube and detectors. The digital data are imported into the computed device for image reconstruction in the final analysis [10].

Scanning images are usually reconstructed in a 512x512 matrix and then multiplied by image slice numbers into volume images. Most of CT data are represented in the standardized range called the Hounsfield scale. In the past, this scale ranged from –1000 to 1000 but now, the Hounsfield scale varies from –4095 to 4095. These values were stored in 16-bit computer value.

2.2.2 Advantages and disadvantages of CT

The CT overview integrates the information from all the views in the rotation creating the final cross sectional image. The contrast and brightness are adjusted to improve details of each image. This information is then used to construct the multiplanar reconstruction images. In brief, the main advantage of CT scanning is the detailed cross-sectional images in multi-direction slices [13].

X-ray CT can enhance the dentist's appraisal of the patient's condition prior to treatment. The conventional imaging process used by dentists such as periapical film and bitewing film is the standard for oral hard tissue examination. This employs the 2-D x-ray transmission through the 3-D oral anatomy to construct the image. Therefore, required details may be superimposed with surrounding structures. From this point, the buccal and lingual cusps are difficult to determine. CT is used to correct this problem due to its capability. Hence, CT data can be used for the difference between the buccal and lingual cusp, showing for example the pattern of attrition in functional and non-functional cusp and other relevant issues. Furthermore, it can access the internal tooth structure without magnification error caused by geometric distortion [11]. Additionally, it can detect small characteristic differences (1% to 2%) in X-ray attenuation and reduce the scattered radiation from the subject whereas X-ray film cannot [12]. All of these advantages suggest using CT in dental fields.

Though CT has a lot of advantages, some points limit the usage of this equipment. The main consideration is the radiation dose of each scanning. CT imaging is superior to single X-ray scans, and although soft tissue X-ray absorption is relatively small, the patient must be exposed to radiation. In dental CT, patients obtain 14.6 mGy while the conventional radiograph patient takes a lesser radiation dose. Another consideration is the high expense for each scanning. These points detract from CT usage for general patients.

2.2.3 Cone-beam X-ray CT

Cone-beam tomography helps in generating 3D reconstructed images easily. The cone-beam technology produces high-resolution 3D images that are useful for diagnosing a variety of dental practice. Cone-beam technology refers to the use of a cone shaped x-ray beam to obtain a medical image. There are several advantages for applying the cone-beam technology in medical treatments:

1. Lower radiation than CT
2. Quick scan time (approximately 10 seconds)
3. Optimized to scan the head and neck

In addition, during scanning of patients, the patient must not move. If they move, motion artifacts are formed. In economic terms, this would result in higher costs as fewer patients can be scanned in a given amount of time. These problems can be avoided by using cone-beam tomography. Another major reason for using cone-beam tomography is its effectiveness in SPECT (Single Photon Emission Computed Tomography), which is very attractive, especially in medical diagnostics. A small photon count in SPECT results in data with large statistical improbability, which can be reduced by employing cone beam tomography.

In the tooth scanning process, the project used the CB MercuRay instrument, which is specifically designed for scanning the head and neck using this special x-ray method. The x-ray source for CB MercuRay is a low-energy fixed anode tube similar to that used in dental panoramic machines. The CB MercuRay system uses cone shaped x-ray beams with a special image intensifier and a solid state CCD sensor for capturing the image. During the scan process, the CB MercuRay rotates only one time (360° rotation) around the patient and takes approximately only 10 seconds to scan. The cone shaped x-rays provide image data of 288 views that can be presented as 2-D images or used to reconstruct a 3-D image.

Table 2.2 FOV and voxel size of each scanning mode of CB MercuRay™ (adapted from MEDIX volume 37. p. 40-45)

	D-mode Dental-mode	I-mode Implant-mode	P-mode Panoramic-mode
Maximum FOV	About 50 mm.	About 100 mm.	About 150 mm.
Voxel size	About 0.1 mm.	About 0.2 mm.	About 0.3 mm.

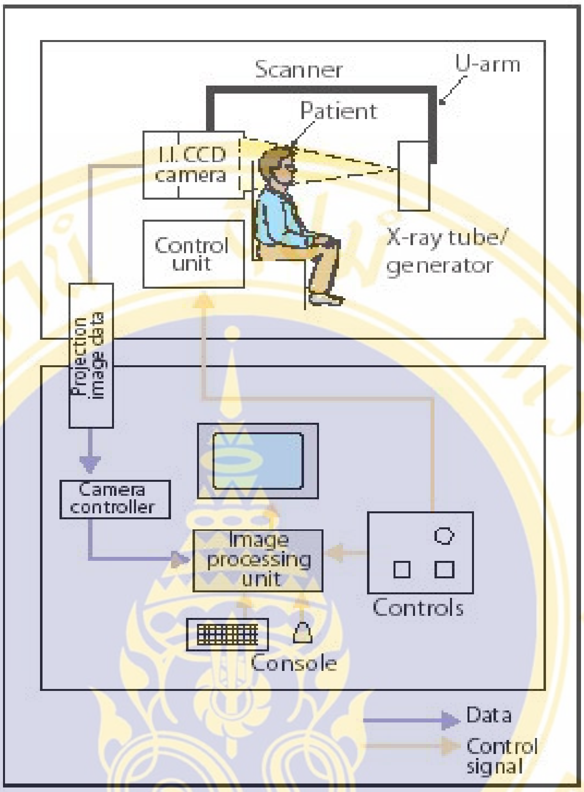


Figure 2.8 Cone beam technology (from www.hitachimed.com)

2.2.4 Conventional X-ray CT and Cone-beam X-ray CT

The continuing development of computers has lead to improvements in CT compositions and medical image qualities. The conventional CT X-ray machines utilize parallel or fan beam rose through body parts while cone-beam X-ray CT operates with the cone-beam X-ray. In general, most 3D medical images are reconstructed from integration of 2D images, which bring resolution problems. This rarely occurs with the cone-beam CT because it takes a short time for each scanning. It is suitable for the fine structure of dentomaxillary organs rather than the conventional X-ray CT [13], [14]. Additionally, cone-beam technology produces high-resolution 3D images that are useful for diagnosing in a variety of dental procedure. For these reasons, the cone-beam CT was chosen for tooth parameter study.

2.3 Image processing algorithms

2.3.1 Image reconstruction of CT

Image reconstruction of CT has a direct relationship with X-ray attenuation along the X-ray path. While x-rays are passing through each object, there are two dominant types of interactions, photoelectric absorption and Compton scattering. These interactions affect the X-ray attenuation. X-ray attenuation in different tissues can be represented by a linear attenuation coefficient μ. The photon density that emerges when a narrow beam of mono-energetic photons with energy E_0 and intensity I_0 passes through a homogeneous absorber of thickness X can be expressed as

$$I=I_0 \exp[-\mu(\rho, Z, E_0)\, x] \qquad (2.1)$$

where μ, ρ and Z are the linear attenuation coefficient, density of the absorber and atomic number.

From the equation (1), the attenuation of X-ray beams depends on density of the absorber and atomic number. In the case of two different objects, X-ray intensity will be presented as,

$$I_i=I_{0i} \exp[-(\mu_{11}\Delta x+\mu_{12}\Delta x+\ldots+\mu_{1n}\Delta x)]. \qquad (2.2)$$

Normally, the human body consists of many special tissues. To calculate the X-ray attenuation, the whole part of the body is dissected into many equal sections. When a monochromatic X-ray beam is projected in the y-direction, the output X-ray intensity is shown in the relationship of I, I_0, μ and material thickness as,

$$I(\mathrm{x}) = I_0 \exp[\int -\mu(x,y)\mathrm{dx}]. \qquad (2.3)$$

Taking the logarithm and rearranging the equation (3), the project equation can be written as,

$$p(x) = -\ln[I(x)/I_0(x)] = \int \mu(x,y)dy, \quad (2.4)$$

where the p(x) is the equivalent to a simple summation or the integration of the total of attenuation along the X-ray path. The projection data at different views are the basic information of CT image reconstruction [10], [15].

2.3.2 Image reconstruction algorithms

Image reconstruction is the mathematical formulations applied to 3D distribution of X-ray attenuation coefficient throughout the object. Many mathematicians have presented different image reconstruction approaches. These can be classified into four categories [16]:

1. Summation methods (e.g. simple back projection)
2. Series expansion methods (e.g. iterative estimate-correct)
3. Transform methods (e.g. Fourier transform)
4. Direct analytic methods (e.g. convolution or filtered back projection)

Summation method or simple back projection method is the primary way to describe the image reconstruction technique. This algorithm adds all of rays passing through each pixel together to from the reconstruction matrix. This algorithm is called summation method or simple back projection. The example of this algorithm is shown in the Figure 2.9.

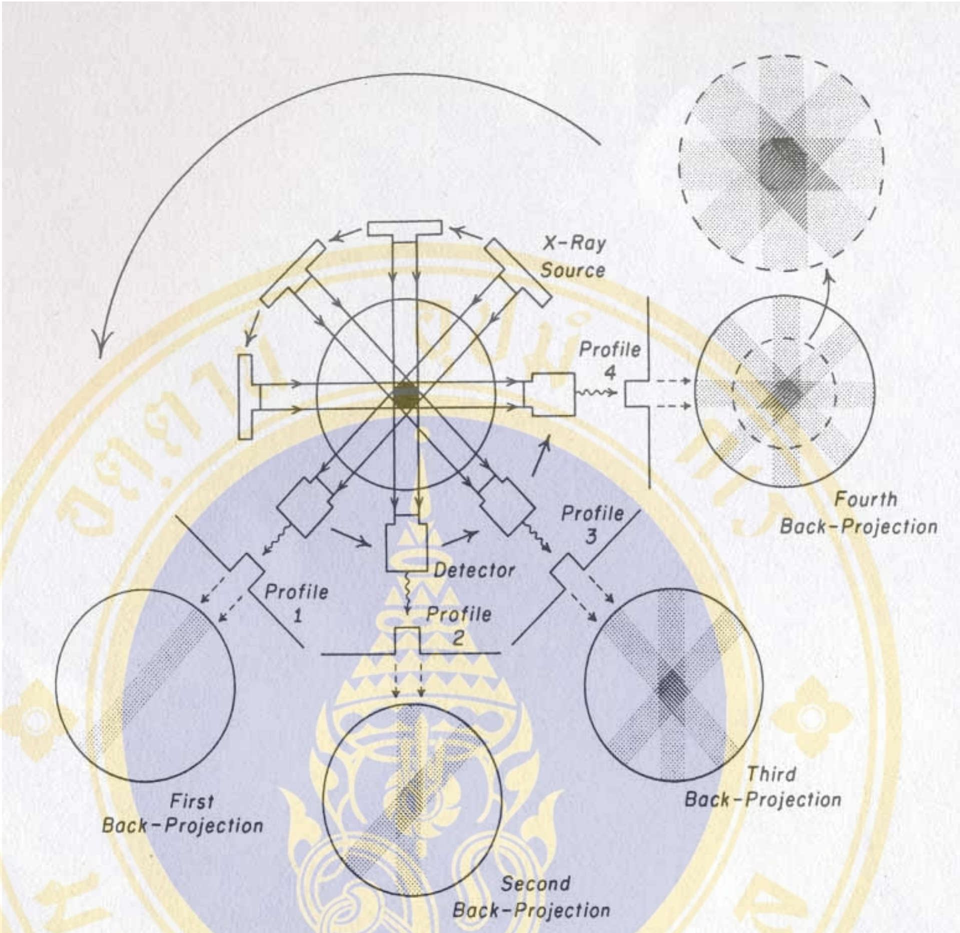


Figure 2.9 Graphical example of summation method for image reconstruction simple back projection. [from *Three-dimensional biomedical imaging: principles and practice*. 1998]

The summation method is equal to the simple back projection [16]. For a finite total number M of projections, P_j, the discrete values of the back projection image, $U(i)$, at each pixel i can be mathematically illustrated by the following formula.

$$U(i) = \sum_{j=1}^{M} P_j K_{[ij]} \qquad i = 1, N \qquad (2.5)$$

Where K_{ij} is a special unit function:

$$K_{ij} = \begin{cases} 1, \text{ if ray } j \text{ intersects pixel } i \\ 0, \text{ if ray } j \text{ does not intersects pixel } i \end{cases} \qquad (2.6)$$

When this method is employed, it can reconstruct the star-like object for every point of image reconstruction. The number of star-like spikes depends on the number and direction of CT projections. The highest-densities are located in the center of the star pattern whereas the outer densities are steady reduced. When the spikes of each reconstruction points overlap with the adjacent pixels, the reconstructed image becomes blurred.

Since the number of continuous sets of ray around a point is equivalent to $2\pi r$, the density distribution becomes proportional to $1/r$, r is the distance from the center. Hence, the resultant images are from the convolution of true images and this blurred function. Because of this problem, several ways to partially correct the blurred images are suggested. However, the spatial resolution and sharpness are not as good as for other reconstruction methods.

Because of the effect of the star-like artifact on the reconstructed image, the mathematicians developed more effective methods such as algebraic reconstruction techniques (ART) and other iterative algorithms. Even though this method gives accurate analytic approaches, no current commercial CT scanner using this algorithm is available [16].

The reconstruction method that is widely used is the filter back projection method: FBP. It is related to the simple back projection method but the significant difference is the proper filtering before the back projection process. This prefiltering step involves the convolution of projection data with the weighting function controlled by the distance of each point.

Fourier inversion formula is another approach applying a weighting function in image reconstruction. Though this algorithm seems to be similar to the previous method, it involves different computations. Three steps of Fourier transformation method are:

1. Transforming the projections of an object into Fourier space.
2. Interpolating from the values on the central sections to fill the Fourier transform space.
3. Performing an inverse Fourier transform to provide object estimation.

The Fourier transformation theorem of Image Reconstruction comes from taking the Fourier transform of both sides of the equation.

$$P(\omega,\theta)=\int_{-\infty}^{\infty}P(r,\theta)e^{-i\omega r}dr$$

$$=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}U(x,y)e^{-i\omega(x\cos\theta+y\sin\theta)}dxdy \qquad (2.7)$$

where $\omega=2\pi k$, with k being the wave number, or spatial frequency along the r-axis, and where $x\cos\theta+y\sin\theta$ is substituted for r. However, this theorem has limited resolution and is hard to compute. According to this problem, this method is mostly developed by inverse transformation of the equation. With a transformation of coordinates, this time from Cartesian to Polar and integrating over the angle variable, this inversion may be expressed as:

$$U(x,y)=\frac{1}{4\pi^2}\int_{0}^{\pi}\int_{\infty}^{-\infty}\rho(\omega,\theta)e^{i\omega(x\cos\theta+y\sin\theta)}|\omega|\,d\omega d\theta\,(4) \qquad (2.8)$$

where $|\omega|$ comes from the Jacobian of the transformation.

Equation (2.8) can be divided into two parts. The inner part represents the filtered projection while the outer integral implies to the back projection method. This formula has been proved to find out the simplest and most effective reconstruction method. As the result of this algorithm, reconstructed images are unblurred compared with the original images.

This is difficult to compute because it creates a lot of implementing. So, finite discrete Fourier series cannot represent it. Even though several choices are available, the common approach is the convolution integral.

The convolution approach has proven to be accurate and efficient for solving the inverse integral equations. This technique filters the projection data with the eliminating blurring function and then back projects the filtered projections. In addition, this method will remove the positive and negative side lobes of a convolution filter. As the result of this algorithm, reconstructed images are unblurred compared with the original images.

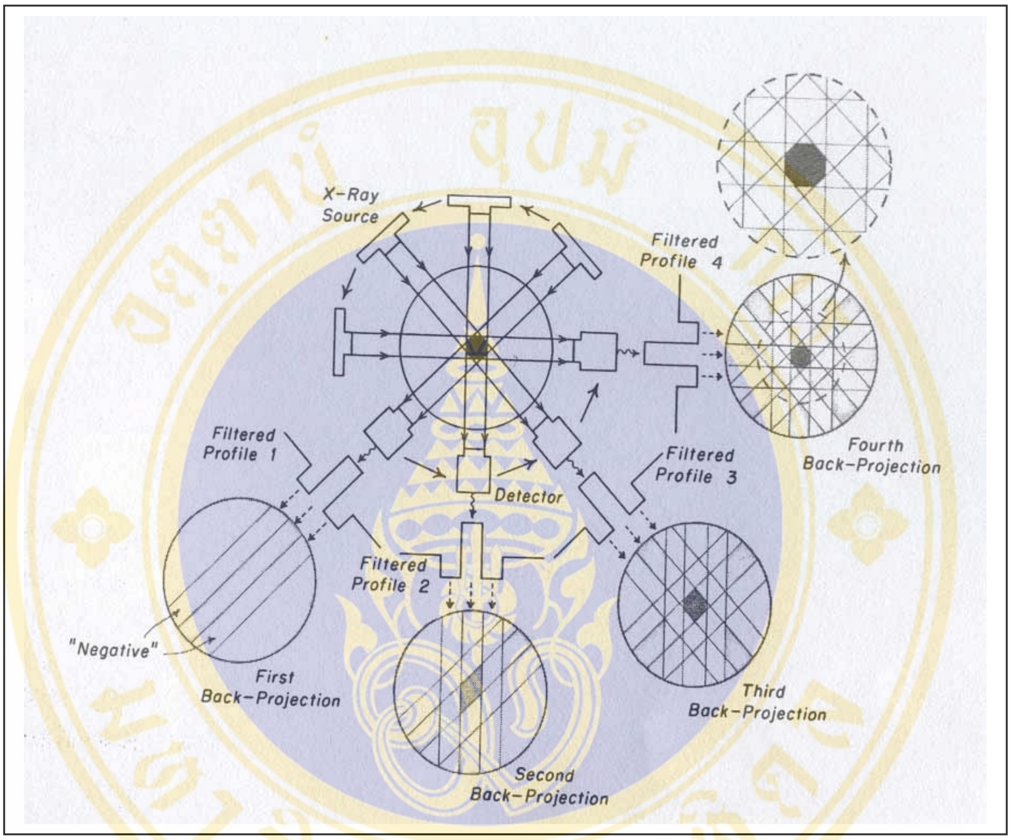


Figure 2.10 Graphical example of filtered back projection method. [from *Three-dimensional biomedical imaging: principles and practice*. 1998]

2.3.3 Developed image reconstruction methods of CT

A lot of methods are applied to achieve a higher quality CT image. The first approach is the Error Back-Propagation algorithm in CT image reconstruction. This algorithm employs an artificial neural network in the image reconstruction process. The neural system has three layers: input layer, hidden layer and output layer. The data are fed into the Back-Projection system with median filter adaptation. While the system is processing, the Error Back-Propagation algorithm adapts the weights inside the hidden layers. This decreases the error of the reconstructed image. In addition, the median filter plays an important role in noise reduction. All of these techniques improve the CT image quality [17].

The second approach is a combination of several techniques for CT reconstruction such as image pre-processing and filtering. In this approach, the pre-processing and filtering steps are added into the reconstruction process to speed-up the reconstruction procedure. These algorithms reduce the pre-processing complexity and the reconstruction filtering computations. However, the aforementioned algorithms may affect the reconstruction quality, but the image integrity is well maintained [18].

The third approach is the suggestion of noise reduction. This result is a by-product of multislice CT scanner improvement. A decrease is based on the inverse square root relationship technique in the reconstruction. This technique presents a lower noise modulation than the single spiral CT [19].

CT image reconstruction is improved from a small number of projections. The principle of this developed algorithm is based on the investigation that angular alising effects the CT image resolution. In the initial stage, projections are filtered. Next, the modified projections are passed into the back-projection process. Then, CT images are reconstructed. This produces high quality and less artifact images, although small in number. Moreover, the researchers suggested that this proposed algorithm is better than the conventional filtered back-projection algorithm [20].

Additionally, two CT image reconstruction algorithms; Algebraic Reconstruction technique (ART) and Iterative reconstruction re-projection (IRR) are utilized. In ART, only projections relevant to known data are demanded. The others may generate redundant equations. IRR is based on convolution-back-projection. The re-projection is utilized in the projection values estimation of the missing views sector. These algorithms are compared in reconstruction image improvement with the computer simulation. The result shows a lot of advantages, such as reconstruction within the limit projections, of ART over IRR. In brief, ART is a serviceable alternative way for image reconstruction [21].

Moreover, the image reconstruction methods are applied in automatic-reconstruction software. This algorithm uses the CT data for both plastic and metallic catheter reconstruction in clinical experiments. This information is identified by the user via Graphic User Interface: GUI. Next, the algorithm procedure based on image processing knowledge extracts the set of selected catheter data and then uses them for reconstruction. This introduced software is utilized in clinical treatment plans [22].

2.3.4 Image segmentation

Diagnostic imaging is an invaluable tool in medicine. Magnetic resonance imaging (MRI), computed tomography (CT), and other imaging modalities give effective information in non-invasively mapping the anatomy of various subjects. These technologies have greatly increased knowledge of the normal and the pathological anatomy for medical research in diagnosis and treatment planning. Because of technology progression, the size of medical images raises continuously. The growing size of these medical images is responsible for the necessity of using computers to facilitate processing and analysis. In particular, using computer algorithms for the delineation of anatomical structure becomes increasingly important in assisting and automating specific radiological tasks. These algorithms are called image segmentations, which play a vital role in numerous biomedical-imaging applications such as diagnosis, study of anatomical structure, treatment planning, and computer forensics [23].

An image is created from a series of measurements in two-dimensional (2-D) or three-dimensional (3-D) space. In medical images, these measurements or image intensities can be radiation absorption in X-ray imaging, acoustic pressure in ultrasound, or radio frequency (RF), and signal amplitude in MRI .

Typically, image segmentation is defined as the partitioning of an image into non-overlapping, constituent regions that are similar with respect to some characteristic such as image intensity. When the constraint that regions be connected is removed, then determining the set of segmentation problems is called pixel classification. The pixel classification is often a desirable goal in medical images rather than classical segmentation.

Labeling is the process of assigning a meaningful designation to each region and can be performed separately from segmentation. In medical imaging, the labels are often visually obvious and can be determined on inspection by a physician or technician. Computer-automated labeling is desirable when labels are not obvious and also in automated processing systems.

2.3.4.1 Thresholding

Thresholding employs segment scalar images by creating a binary partitioning of the image intensities. A thresholding procedure attempts to distinguish the intensity value called the threshold, which separates into the different classes. The segmentation is then achieved by grouping all pixels with intensities greater than the threshold into one class and all other pixels into another class. Thresholding is commonly a simple effective task for obtaining a segmentation of images in which different structures have contrasting intensities or other quantifiable features. Thresholding is usually performed interactively, based on the operator's visual assessment of the resulting segmentation.

Thresholding is often used as an initial step in the procedure of image processing. Its main limitations are that, in its simplest form, only two classes are generated, and it cannot be applied to multi-channel images. In addition, thresholding typically does not take into account the spatial characteristics of an image. This causes it to be sensitive to noise and intensity inhomogeneities, which can occur in MR images. Both of these artifacts essentially alter the histogram of the image, making separation more difficult. For these reasons, variations on classical thresholding have been proposed for medical-image segmentation that incorporates information on the basis of local intensities and connectivity.

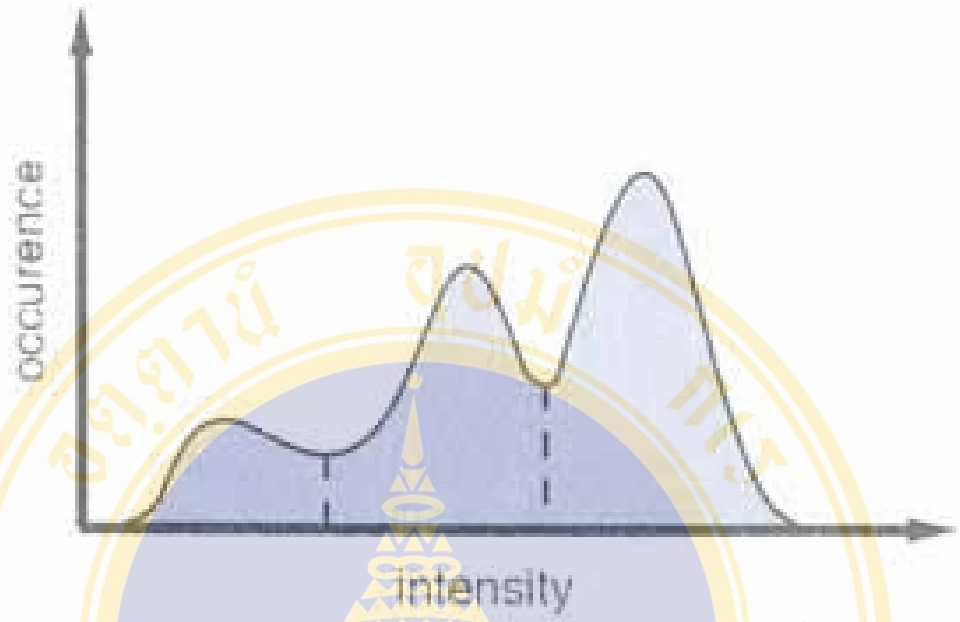


Figure 2.11 Histogram showing three classes of intensity.
(from Current Methods in Medical Image Segmentation, *Annual Review Biomededical Engineering 2000*)

2.3.4.2 Watershed

The watershed algorithm uses concepts from edge detection and mathematical morphology to dissect images into homogeneous regions. The major problem of this method is from over segmentation, which occurs when the image is segmented into an unnecessarily large number of regions. To relieve this problem, watershed algorithms in medical imaging are usually followed by a post-processing step to merge separate regions that belong to the same structure [23].

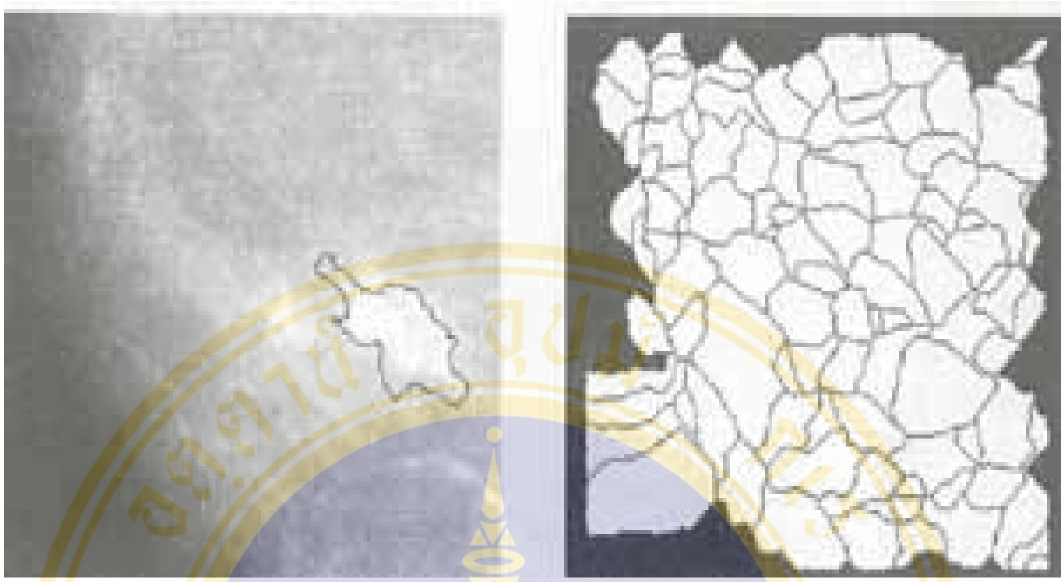


Figure 2.12 Result of watershed system in mammography.
(from Current Methods in Medical Image Segmentation, *Annual Review Biomededical Engineering 2000*)

2.4 Morphometric development of tooth

The dental information is mostly obtained by either direct or indirect measurement methods. The direct measurement technique is the use of millimeter ruler [24], digital micrometer[25], Boley gauge[26], dial caliper[27] and electronic digital caliper[28], [29]. This equipment is applied directly to each tooth, dental model, conventional radiograph or digital image.

Recently, a computer assisted method has proved valuable in many tasks including tooth measurement. The computerized dental measurement has been used widely instead of manual techniques during the measurement process. Not only the external structures but also the internal structures can be determined by this technique [25]. Examples of computer use in tooth measurement were demonstrated as follows.

Pereira et al. [30] introduced the tooth length and area measurement of teeth using radiographs and a computer measurement system. They traced the anatomy of the tooth and dental pulp cavity onto tracing paper. The tooth diameter, area of the tooth and the respective pulp cavity were mapped by computer-aided means. Stroud et al. [7] used the computer to identify and digitalize the plane representing the maximum mesiodistal diameter of teeth in their experiments for enamel and dentin thickness measurements. Because of the complexity of tooth structure, 2D image is insufficient for accurate measurement. Thus, 3D image reconstruction was applied in odontometry. A sample was shown in the study of Schwartz et al. [31]. They used the raw image data from computerized tomography as the input to software calculation. Researchers used a high-resolution CT scan and demonstrated half maximum height (HMH) technique for measurement. The measurement point at cusp tip and dentoenamel junction was marked by the thresh-holding method. The thickness could be obtained from the distance between two measurement points. The other example was in the study of Vannier et al.. They created the 3D dental image by using spiral CT. In this study, teeth, dry mandible, cadaver mandible and cadaver head were scanned with a typical protocol for dental Spiral CT (head mode, 137 kV, 240 mA, 18 sec., 2 x 2 mm.). Then, these data were reconstructed and the special developed software formed the acquired 3D image [12].

2.5 Image processing toolbox in MATLAB®

In this project, we develop the tooth type recognition to identify tooth type and morphometric libraries to extract general tooth parameters MATLAB® image processing tool box, widely used in high end engineering programming, was chosen for image processing. The image processing toolbox is a set of functions that extend the capability of the MATLAB®. It contains a lot of helpful functions, which are simple to the primary user to corroborate with almost all characteristics of image command described in its help files. This tool provides a satisfactory result in the image processing field. The toolbox supports a variety of image formats and image processing operations.

In this project, functions that are attended included:

- Image transformations
- Morphological operations
- Linear filtering and filter design
- Image analysis

2.5.1 Image format

DICOM® is the common standard for scans from hospitals. The Digital Imaging and Communications in Medicine (DICOM®) standard has been created by the National Electrical Manufacturers Association (NEMA). Its aim is to support the distribution and viewing of medical images from Computed Tomography (CT), Magnetic Resonance Image (MRI) and other medical modalities. The DICOM® format is an extension of the older NEMA standard.

A DICOM® file contains a header and the image data. The header stores information such as patient's name, the type of scan, position and dimension of image etc. The image data part contains all the image information.

In MATLAB®, the Image Processing Toolbox supports writing and reading files in Digital Imaging and Communications in Medicine (DICOM®) format, using the 'dicomwrite' and 'dicomread' function, respectively.

2.5.2 Type of images

There are a large number of image types supported by MATLAB® image toolbox. However, two types of image utilized in this experiment were:

2.5.2.1 Binary images

In a binary image, each pixel assigns one of only two discrete values; zero or one. Basically, these two values correspond to on and off. A binary image is stored as a logical array of 0 and 1.

In older version a of MATLAB®, toolbox functions that returned binary images returned them as unsigned integer 8 bit (uint8) logical arrays. The toolbox used the presence of the logical flag to signify that the data range in the file was [0,1].

In the latest version used in this project, the toolbox returns binary images as logical arrays, using the new MATLAB® logical data type.

2.5.2.2 Intensity images

An intensity image is a data matrix, whose values represent intensities within some range. MATLAB® stores an intensity image as a single matrix, with each element of the matrix corresponding to one image pixel. The matrix could be one of class double, unsigned integer 8 bit (uint8), or unsigned integer 16 bit (uint16). While intensity images are saved with a ‘colormap’, MATLAB® uses a ‘colormap’ to display them. The elements in the intensity matrix represent various intensities, or gray scales, where the intensity 0 usually represents black and the intensity 1, 255, or 65535, differed from a class of image matrix, usually represents full intensity or white.

2.6 Summary

In this chapter, a brief introduction of dominant tooth parameters including external parameters such as mesiodistal crown diameter, buccolingual crown diameter, and crown height and internal parameters such as enamel thickness and dentin thickness are discussed. Advantages and disadvantages of CT technology and 3-D reconstruction methods are also presented and compared with other methods. Information on various kinds of mathematical models of image reconstruction is also provided with some discussion. We discuss some ideas on its advantages and disadvantages. In addition, the development of morphometric studies of previous researches is demonstrated. The last part of this revision offers the information on the image processing toolbox in MATLAB®, involved in this study.

CHAPTER III
MATERIALS AND METHODS

At present, a tooth classification protocol and an automatic tooth-measuring tool simply do not exist. Therefore, a recognition and also morphometric tool to measure tooth parameters with CT tooth information was developed. A tooth type recognition tool has two main functionalities: segmentation and classification approaches whereas morphometric processes consists of tooth segmentation and measurement processes. The tooth parameter measurement using MATLAB® image processing used in this study was then compared with dental measurements from tooth sections and image processing using MIMICS®.

3.1 An Overview

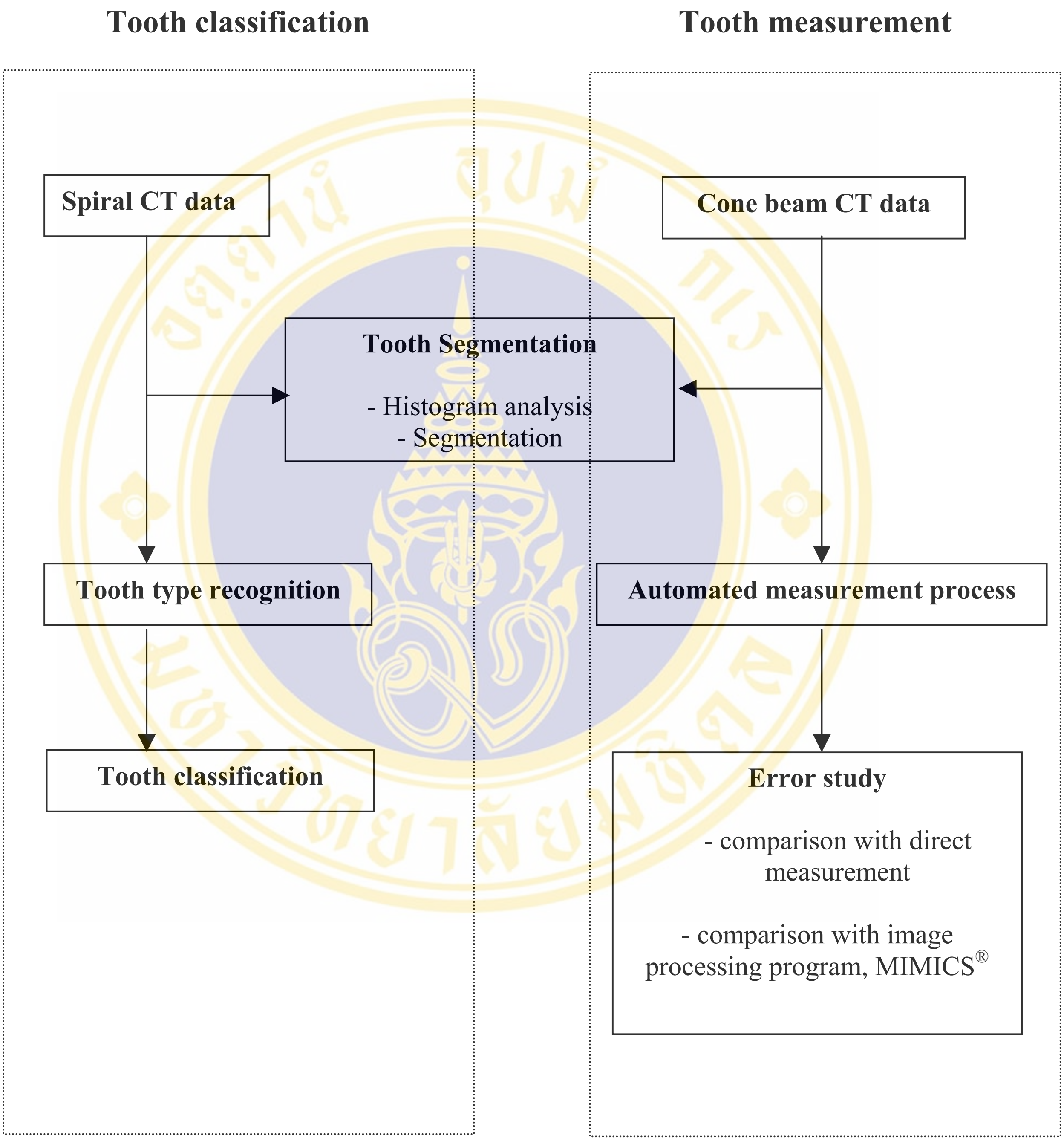


Figure 3.1 Diagrammatic representation of the research process

A diagrammatic representation of the research process is shown in Figure 3.1. The system consists of two major processes: tooth classification and morphometric measurement of an individual tooth. The first major task contains several processes such as histogram analysis, segmentation and artificial neural network. The second major task employs tooth segmentation methods the same as in tooth classification. After completing the classification phase, a morphometric tooth measurement algorithm is processed to obtain tooth parameters.

3.2 Tooth Classification

3.2.1 Sample selection

Thirty nine ancient teeth, dated 2080±60 years, from the Highland Archaeology Research Project in Pang Mapha, Mae Hongson province (phase II) were selected for use in this study. All of the specimens were dried, and had no bone support and no soft tissue support. These specimens had no restorative materials and no dental caries. Examples of a scanning set are shown in Figure 3.2.

Figure 3.2 An example of a scanning set in tooth classification.

To minimize the cost of CT scanning, teeth were scanned in one batch comprised of eight groups of teeth, two groups each of upper central incisors (ten incisors), lower canines (ten canines), lower first premolars (ten premolars), and lower first molars (nine molars), with spiral CT of GE Medical Systems, Light Speed[16] System Manual-Gen, simultaneously at 80 kV and 70 mA. (Figure 3.3). All teeth are arranged in the zigzag and in supine position, with the bucal face upwards. (Figure 3.2). The number and tooth type of samples are summarized in Table 3.1.

Table 3.1 The number and tooth type of samples in tooth classification process.

Layer	Tooth type	Number
1	upper central incisors	5
2	upper central incisors	5
3	lower canine	5
4	lower canine	5
5	lower first premolar	5
6	lower first premolar	5
7	lower molar	4
8	lower molar	5

Each group of teeth is secured in a transparent container and the containers stacked on top of each other. CT data of each individual tooth must be correctly extracted from this bulk information, which can be accomplished through the use of histogram analysis and image segmentation techniques. The stack of containers is shown in Figure 3.4.

Figure 3.3 A spiral CT is an important tool in tooth classification.

Figure 3.4 A stack of preparation teeth set.

After packing the teeth set, the ancient teeth are then scanned parallel to their longitudinal axis to prevent the loss of crown information. The scanning data are then sent to the next step.

3.2.2 Histogram analysis

Histogram analysis is the initial stage of segmentation. This process assesses the difference of each image depending on its intensity level. The result of performing the histogram analysis is to roughly isolate each group of teeth. First, the histogram of each CT slide is computed (Figure 3.5).

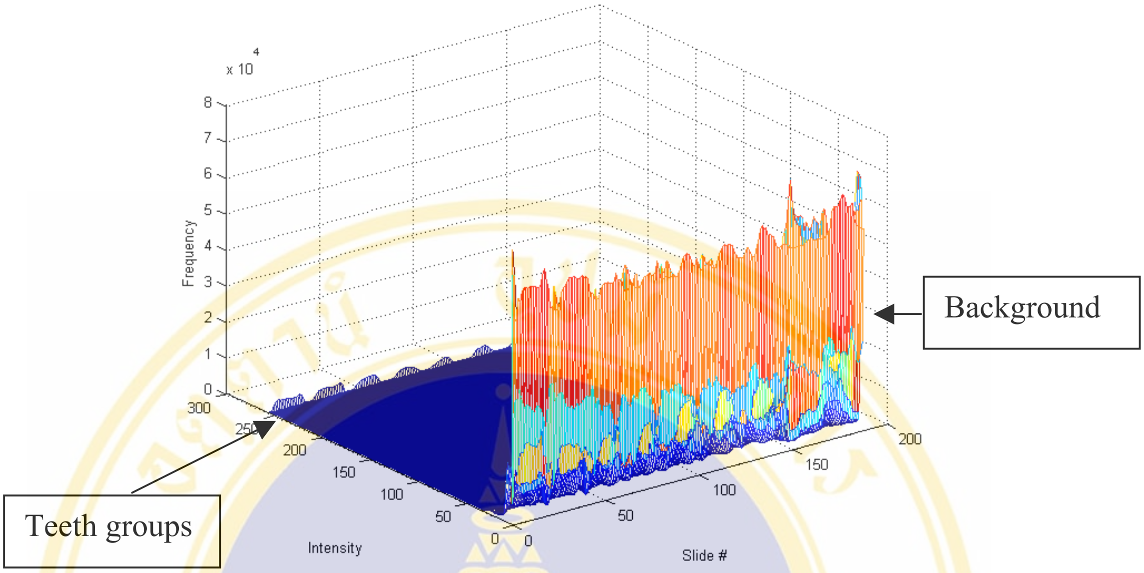


Figure 3.5 Histogram analysis of CT data.

Figure 3.5 shows the intensity level of each image slice (0-255). This graph has three main sections. Firstly, the highest intensity level gives us the intensity information of enamel. Secondly, the middle-height illustrates the number of tooth groups involved in this project. It can be used to indicate the location of the group separation line (the valley between two hills at the intensity = 255). Lastly, the lowest intensity represents the background for the images.

3.2.3 Segmentation

Once each group of teeth is isolated, the CT slide becomes a manageable size for image segmentation. Because a three-dimensional image is the result of a series of two-dimensional images, to isolate each part of an image completely, therefore, three-dimensional segmentation could be more preferable than two-dimensional segmentation. Our method uses an image labeling operation based on 18-connected neighborhoods as a three-dimensional segmentation and performs on the binary image of the isolated CT data which has a thresh-hold at the mean value of the image intensity. An example of a segmented tooth is shown in Figure 3.6.

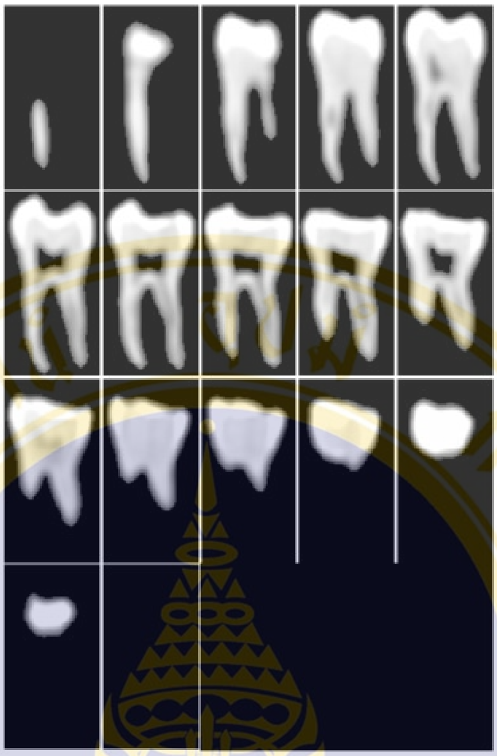


Figure 3.6 Images of an individual molar after tooth segmentation.

3.2.4 Recognition engine

Using raster (pixel) information directly as an input to the recognition engine may not be practicable. Scale, shift and rotation invariant recognition is highly preferable for many applications including the technique used in this study. To accomplish such a recognition system, the usage of radial distances is proposed, which is the distance from the center to the outermost of a tooth, to represent the shape of the tooth type. This shape information is later used for training of a supervised neural network.

3.2.5 Feature extraction

The cross section images of the CT tooth data, shown in Figure 3.6, are used as inputs to extract the radial distances. A radial distance is measured from the center of the image to the outer border of the tooth every 22.5˚. There are sixteen distances per cross section. The distances from all cross section images form a radial distance surface which are resampled to be 8 x 16 where 8 and 16 are the number of layers and angles, respectively. The example of radial distance is shown in Figure 3.7.

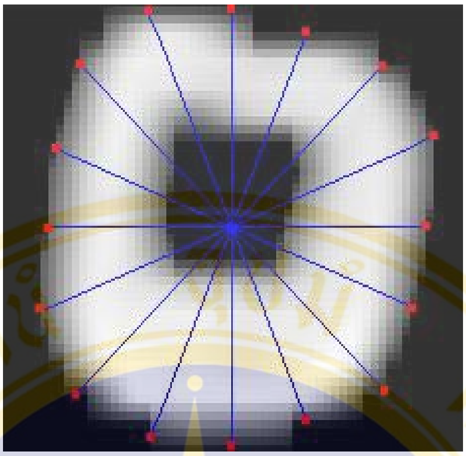


Figure 3.7 The radial distances of a tooth cross-section.

3.2.6 Artificial neural network

The radial distance surfaces of the chosen teeth are used as a training set since teeth in the same group are of the same tooth number. Therefore, one tooth per group is selected to be the training set (Figure 3.8). The radial surfaces are normalized for scale invariant recognition before being stretched into a 128-element vector. For rotation invariant recognition, each radial surface has sixteen possible rotations (from 16 angles). Therefore, there are sixteen training sets for every group of teeth.

Figure 3.8 The training teeth of each group from groups 1-8.

Figure 3.8 presents the training teeth set from group one to eight. The two top layers are lower molars. Next are two lower premolars and two lower canines. Two layers of central incisors are located in the bottom.

To get the precise tooth morphometric values, the specific parameters of each tooth group are particularly important. In incisors, important parameters are mesio-distal crown diameter, bucco-lingual crown diameter, crown height, enamel thickness, dentin thickness and root length. For the canine group, required values are the same as incisors. For premolars, the desired information includes cuspal inclination. Similar to premolars, molar parameters also involved cuspal inclination. These data are utilized as the initial information in accurate three-dimensional tooth measurement.

3.3 Tooth measurement

Tooth measurement is an approach that correctly estimates the general tooth parameter in both outer part such as breadth and length, and inner part, for instance, the tooth thickness. In this step, a set of developed libraries is used to determine tooth morphology without human assistance. There were three main procedures as followes:

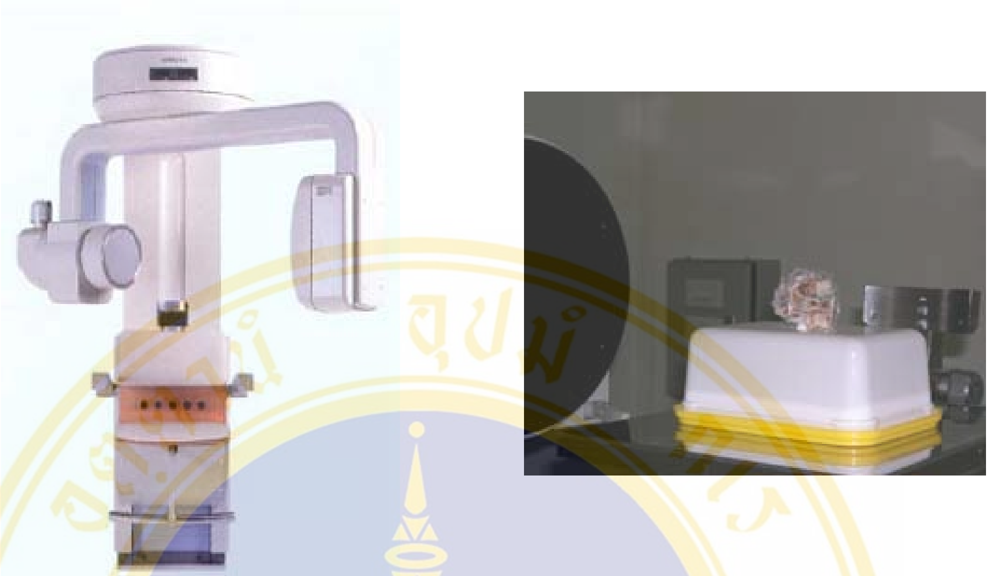
3.3.1 Sample preparation

Thirty upper molars and thirty lower molars are selected as samples. All of the samples are divided into four groups: two sets of upper molars and two sets of lower molars. Each group consists of fourteen ancient molars and a contemporary molar. All of the ancient teeth were from the Highland Archeology Research Project in Pang Mapha whereas the modern day teeth were donated, after removal because of periodontal disease. These teeth were sound. A two-sided tape is used to separate each tooth completely. Then all of them are arranged in a 5-mm-diameter ball shape. After this process, samples are ready for the next step.

Figure 3.9 A set of teeth arranged for the measurement process.

3.3.2 CT scanning

The whole data set from the previous operation is scanned with Hitachi (CB MercuRay ™ Maxillofacial Imaging) that belonged to the faculty of dentistry, Chulalongkorn University. In order to get high-resolution images, Dental Mode (D-Mode) was used as a protocol in this study. Therefore, the maximum Field Of View (FOV) and voxel size in this approach is about 50 mm. and 0.1 mm, respectively. It took about ten seconds for each scan.



(a) (b)

Figure 3.10 Conebeam X-ray CT scanning
(a) Conebeam X-ray CT System Model CB MercuRay.
(MEDIX VOL.37 P.40~45, Hitachi Medical Coorperation)
(b) Arrangement of teeth for scanning.

3.3.3 Experimental environment

The experiments were conducted on a notebook computer with Intel Pentium4 M microprocessor with 768 MB RAM running Microsoft Windows XP Professional. The libraries were developed on MATLAB® Version 6.5.1.199709 Release 13 (Service Pack 1) environment.

3.3.4 Data preprocessing

A major purpose of this step is to prepare the original information before feeding it to the libraries. It begins with tooth segmentation, and then ends up with tooth arrangement.

3.3.4.1 Isolation by thresholding technique

After obtaining the original data on DICOM files, it was firstly segmented by applying threshold technique from the histogram analysis information. From this graph, the threshold was grossly separated into three parts. Because enamel mostly consists of inorganic materials such as Hydroxyapatite (HA.), the highest threshold belonged to this component whereas the two following peaks shows the characteristic of dentin and background, respectively.

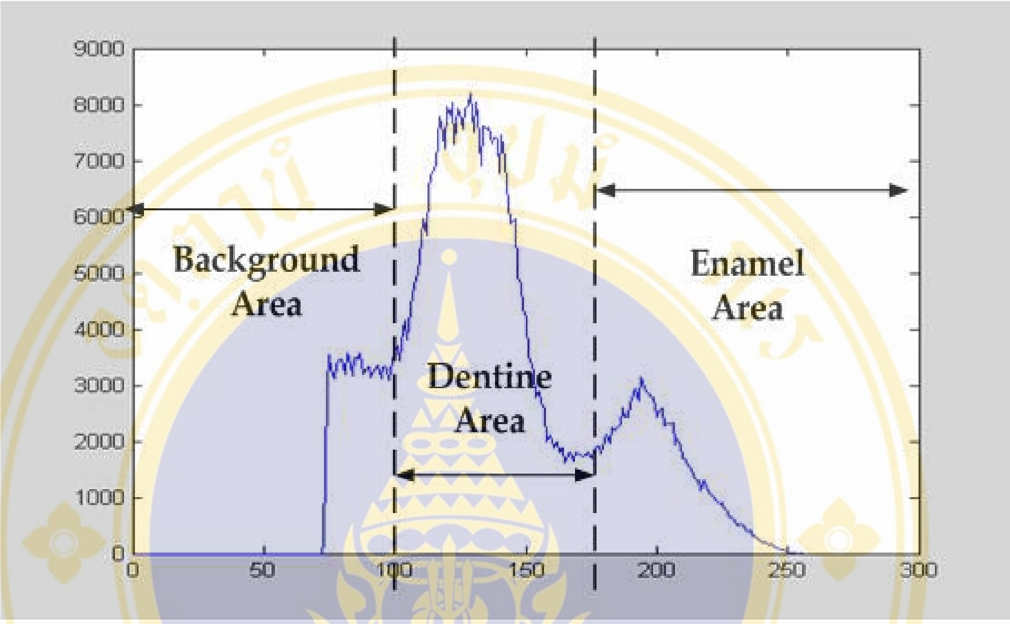


Figure 3.11 Histogram analysis of DICOM images.

Regarding the histogram analysis of Figure 3.7, the threshold of enamel is over 175, while dentin threshold range is from 100 to 175. If threshold is less than 100, this pixel is classified into background. At the end of this step, a tooth is extracted from a bulk of data set and noises. The isolated tooth information is then fed to developed libraries for parameter measurement.

3.3.4.2. Tooth Rotation

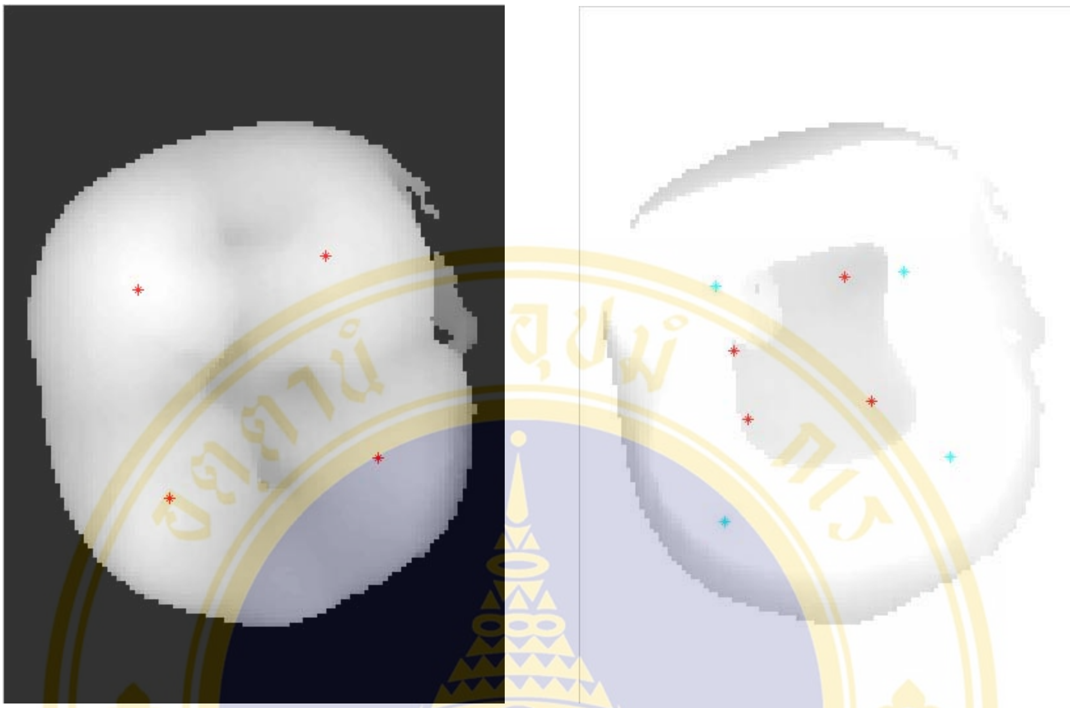
In the scanning process, the scanning teeth are not arranged in one direction to save on cost. This meant they needed to be adjusted into a suitable direction for the foremost algorithm. In this study, they were rotated in the same manner as the initial data and then the developed libraries were used to process them in the next step.

(a) (b)

Figure 3.12 A demonstration of tooth rotation.
(a) Before rotation
(b) After rotating a tooth into a suitable direction

3.3.5 Data Processing

Subsequent to data preprocessing, data are fed into a measurement process. Tooth length and tooth width needed to be measured first. The next step was the process of extraction of tooth structure information. The principle of feature extraction is on the grounds that the tips of the cusp in three layers of tooth structure are coincident and dentin is the best layer to be the reference point in tooth measurement. Thus, the tip of the dentin cusp was marked from the peak of dentin surface and then the enamel was the computed thickness from this point to the outer part of the enamel. Similarly, dentin thickness comes from the number of voxels on the line from dental pulp to peak of dentin cuspid surface. After the process, it was found that the mentioned principle was incorrect for the reason that the tips of dentin cusp and dental pulp are not identical. Figure 3.13 presents this mentioned problem.



(a) (b)

Figure 3.13 The position of cusp tips from dentin information and pulp information.
(a) Cusp tips in dentin
(b) A comparison between dentin cusp tips and pulp horns in dental pulp

To locate the cusp tip precisely, another methodology was proposed on the basis of tooth enlargement. The center of each dentin cusp (centroid) was employed to identify the position of cusp tip instead of peak of dentin surface. Therefore, the enamel and dentin thickness were obtained from the number of voxels that were positioned on the line from enamel to dentin and from dentin to dental pulp, respectively. The enamel volume and dentin volume were also obtained from the number of voxels in the enamel and dentin layer, and then multiplied by the voxel size to obtain the value in mm^3. The strategy in parameter measurement is shown below.

3.3.5.1. External parameters

3.3.5.1.1. Mesiodistal crown diameter (crown length)

Mesiodistal crown diameter, known as tooth length, is the greatest mesiodistal dimension taken parallel to the occlusal and facial surface.

Typically, this parameter is taken using calipers with arms machined to a fine point, but in this study, it is calculated by counting the number of voxels in the maximum mesio-distal width of enamel between mesial and distal contact point.

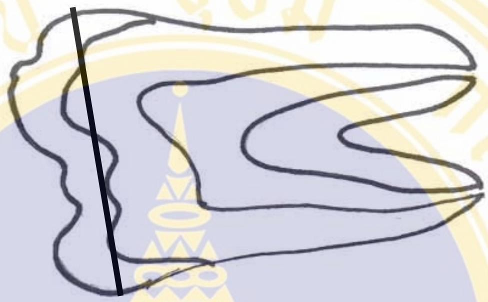


Figure 3.14 Mesiodistal crown diameter

3.3.5.1.2. Tooth Length

Tooth length is the maximum distance from the highest tip of tooth cusp to the end point of the root. As shown in Figure 3.11, it is obtained from the number of voxels in vertical direction between the tip of the cusp to the root tip.

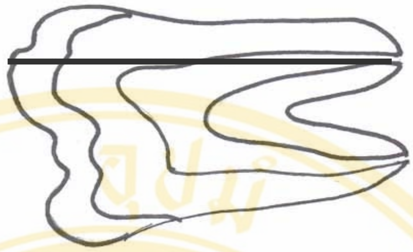


Figure 3.15 Tooth length

3.3.5.2 Internal parameters

3.3.5.2.1. Enamel thickness

As was mentioned before, enamel thickness is defined as the quality or condition of the hard substance covering the crown of tooth, which is called enamel. Normally, the quality of enamel layer is measured between the outermost surface and dentinoenamel junction at the tip of the cusp. The enamel thickness is calculated from the number of voxels in the enamel layer (Figure 3.16).

Figure 3.16 Enamel thickness

3.3.5.2.2. Dentin thickness

In the same manner as enamel, dentin is defined as the quality or condition of dentin layer. This value is taken from the distance between the dentinoenamel junction and pulp horn. To obtain the dentin thickness in this data set, the number of voxels was counted from dental pulp to the tip of the cusp in the dentin layer in the vertical dimension.

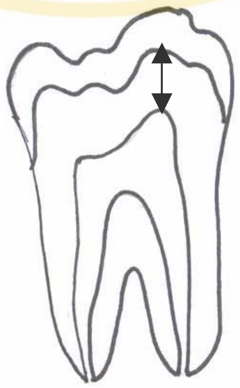


Figure 3.17 Dentin thickness

3.4 Error study

In tooth type recognition, the output from the programming in the classification section is essential for accuracy testing. From this point, the testing data set is fed into the system next to the training data set. The correct tooth type identification acted as the error study of this section.

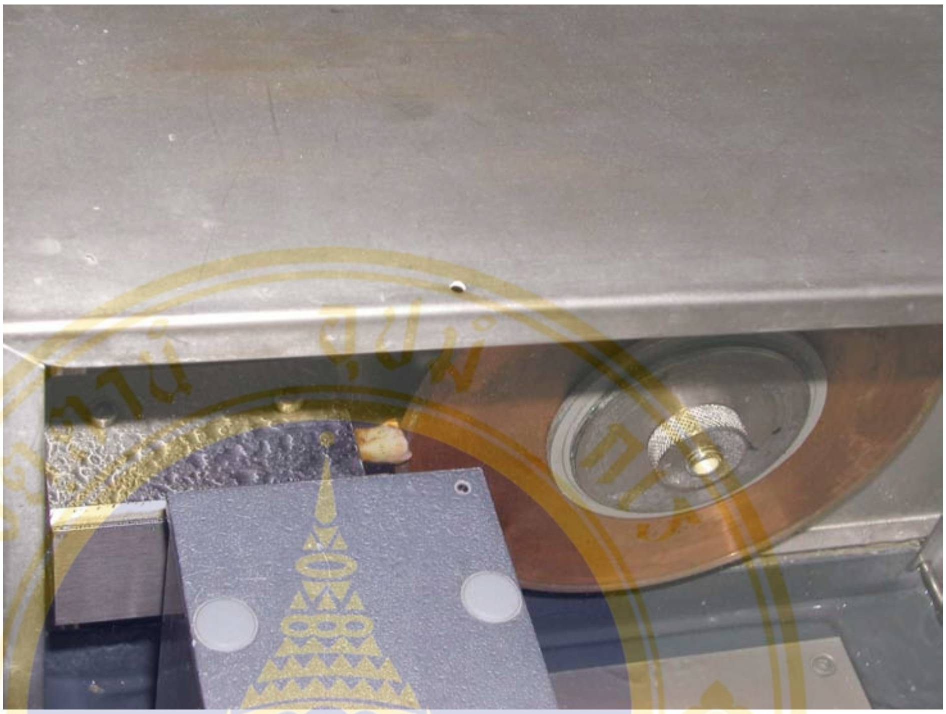
In the tooth measurement processing, the precision of this system is performed by error study. A contemporary tooth of each data set was picked up for slicing. Subsequently, the internal and external parameters were estimated with a manual approach and computer-assisted measurement. A caliper was employed in manual measurement while laser scanning image and a previous measurement program was applied in the computer-assisted technique. A commercial programme, such as MIMICS®, supported by National Metal and Materials Technology Center (MTEC) was implemented in the computer-assisted technique for error study. For testing the same information with MIMICS® , the threshold of enamel was 3225 or over whereas the threshold of dentin was ranged from 1950 to 3225. After these processes, the output of the developed libraries was compared to the direct sliced teeth assessment and manual measurement computer programming for accuracy results. Step pictures of error study from actual tooth sectioning and tooth section measurement are presented in Figure 3.18 and Figure 3.19, respectively.

(a)

(b)

(c)

(d)



(e)

Figure 3.18 Step of an actual tooth sectioning.

(a) A landmark for tooth sectioning.

(b) Waxing in the preparation step.

(c) Ready for tooth sectioning.

(d) Fix into a hole of low speed cutting machine.

(e) Cutting process.

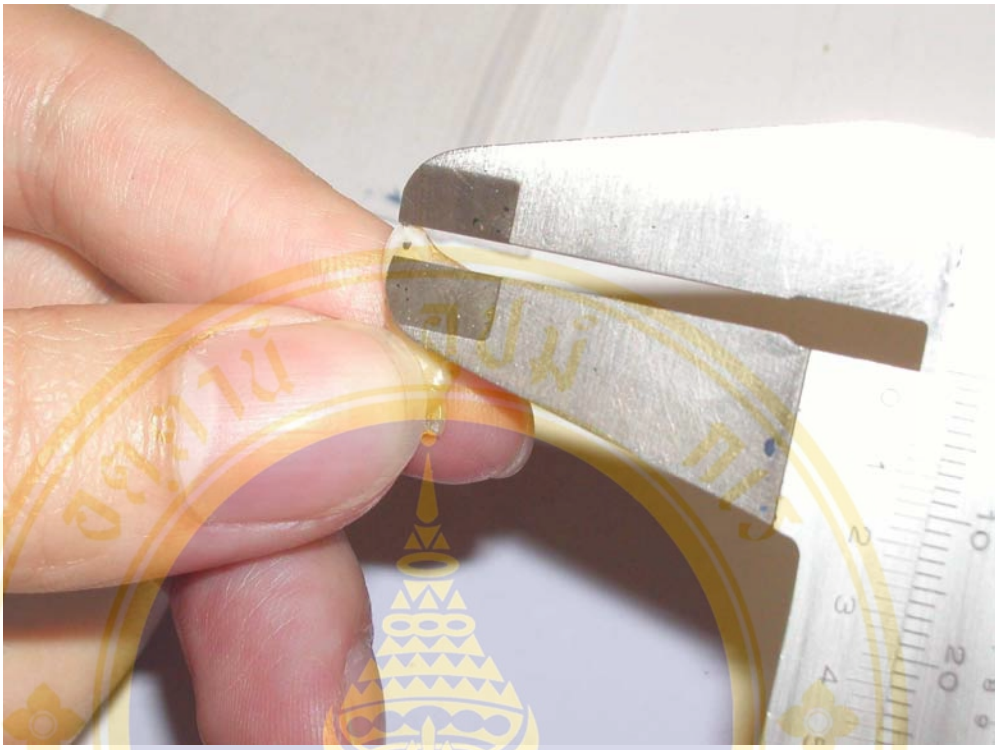


Figure 3.19 Direct tooth measurement in actual tooth sectioning.

3.5 Estimated Budget

This project was launched with the foundation support of Biomedical Engineering Program and Faculty of Graduate Studies, Mahidol University. The overall expenses in this study are shown in following detail.

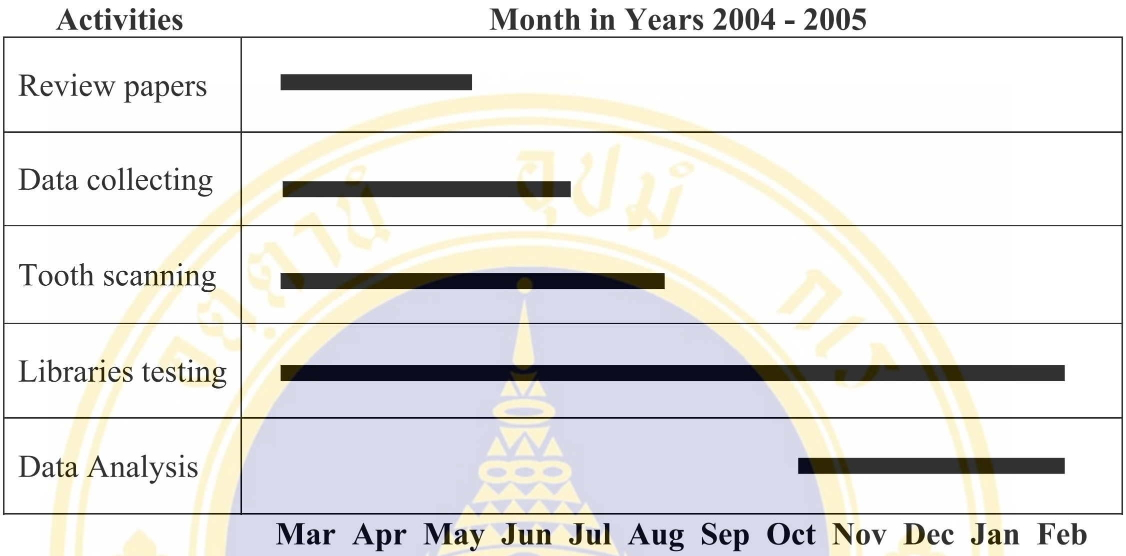
CT scanning	(5000 x 4)	20,000 Baht
Tooth Slicing		1,000 Baht
Summary		21,000 Baht

3.6 Summary

In this chapter, the procedure of an automatic measuring system is presented, which consists of two main processes: tooth classification and tooth measurement. In the beginning phase, tooth information is prepared for classification with segmentation. Then, it is passed to the classification approach. The information is utilized to be a training set and testing set of tooth classification. At the end of this procedure, teeth are well identified. Moreover, the outcome of these data are fed back again to the training set for comparing and checking with the set of teeth to obtain more accurate results.

The second procedure is to measure tooth parameters. Initially, the data is segmented and rotated into an appropriate direction. Following this, the teeth set are scanned and automatically measured with the developed libraries. The outcomes of the second process are mesiodistal crown diameter, tooth length, enamel thickness and dentin thickness. Finally, the whole results are compared with other traditional approaches such as new testing sets and other commercial manual tooth measurement programs, for instance, MIMICS® for accuracy and reliable examination.

3.7 Research Plan



3.7.1 Research Resources and Location

The Thailand Research Fund Office: TRF

14th Floor, SM Tower 979/17-21 Phaholyothin Rd,

Phayathai, Bangkok 10400

Highland Archaeology Project at Pang Mapha, Mae Hongson province (phase II), Bangkok Branch.

808, 8th floor Barohmrachachonnanee Rd. Talingchan Bangkok 10170

National Metal and Materials Technology (MTEC)

114 Paholyothin Rd., Klong 1, KlongLuang, Pathumthani 12120, Thailand

CHAPTER IV
EXPERIMENTAL RESULTS

The experiments on tooth information were conducted in two phases: tooth type recognition and tooth parameter extraction. The results were compared with the known set of data. Direct measurement from tooth section and MIMICS® were used for the accuracy of the proposed methods and algorithms.

4.1 Tooth Type Recognition

The final results show that the proposed method of tooth type recognition correctly identifies 28 out of 39 teeth (71.79%). The radial distance method was able to classify nine molars as molar type. It also identified seven premolars as premolar type, but misidentified three premolars as a molar, a canine and an incisor, respectively. It correctly recognized six canines, but misrecognized six canines. The last tooth type, incisor, was correctly identified six out of eight times. In conclusion, Canine and Incisor had a higher rate of misidentification. In contrast, Molar and Premolar had a high incidence of correct identification.

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Table 4.1 The recognition matrix of teeth

Actual specimens	**Identification results**				
	Molar	Premolar	Canine	Incisor	% of accuracy
Molar	9	0	0	0	100
Premolar	1	7	1	1	70
Canine	3	1	6	2	50
Incisor	1	0	1	6	75

4.2 Tooth Measurement

For tooth measurement, the result shows that values of both internal and external tooth parameters can be extracted automatically. The next step is to extract the general characteristics of teeth. The outcomes of the developed operation, such as information of enamel and dentin, are demonstrated in the following paragraphs.

In the beginning, the data of the outermost of each tooth are extracted. The inner parameter information, dentin, is drawn out, subsequently.

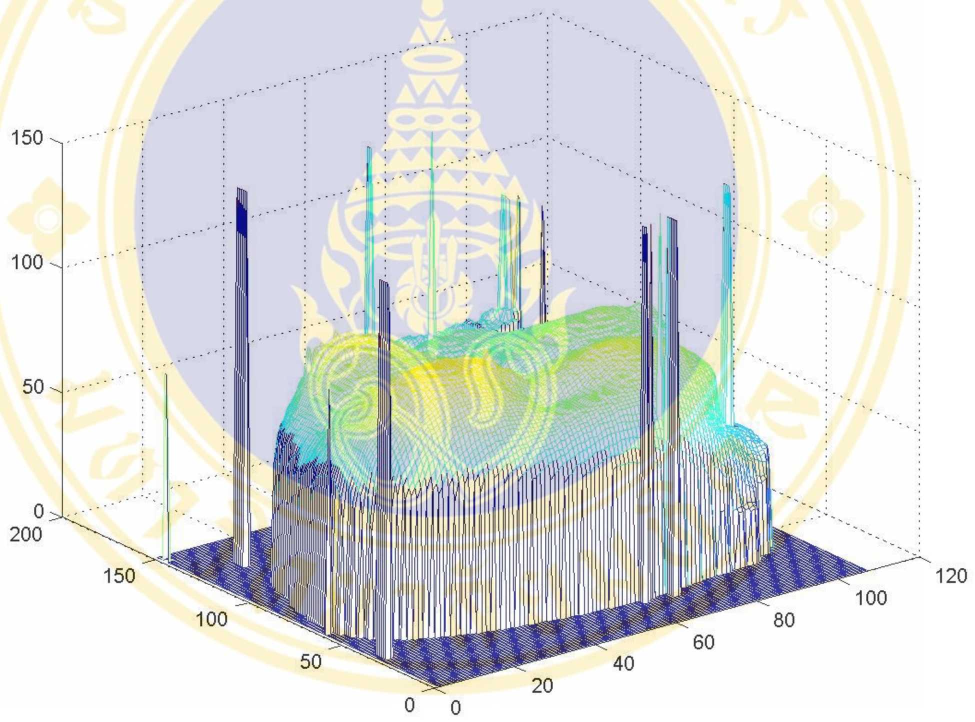


Figure 4.1 An example of enamel surface, which is collected from the image processing technique.

From Figure 4.1, the high intensity pixels, from 175 to 255, represent the composition of enamel. The number of pixels in each column is counted and then meshed to form the enamel surface.

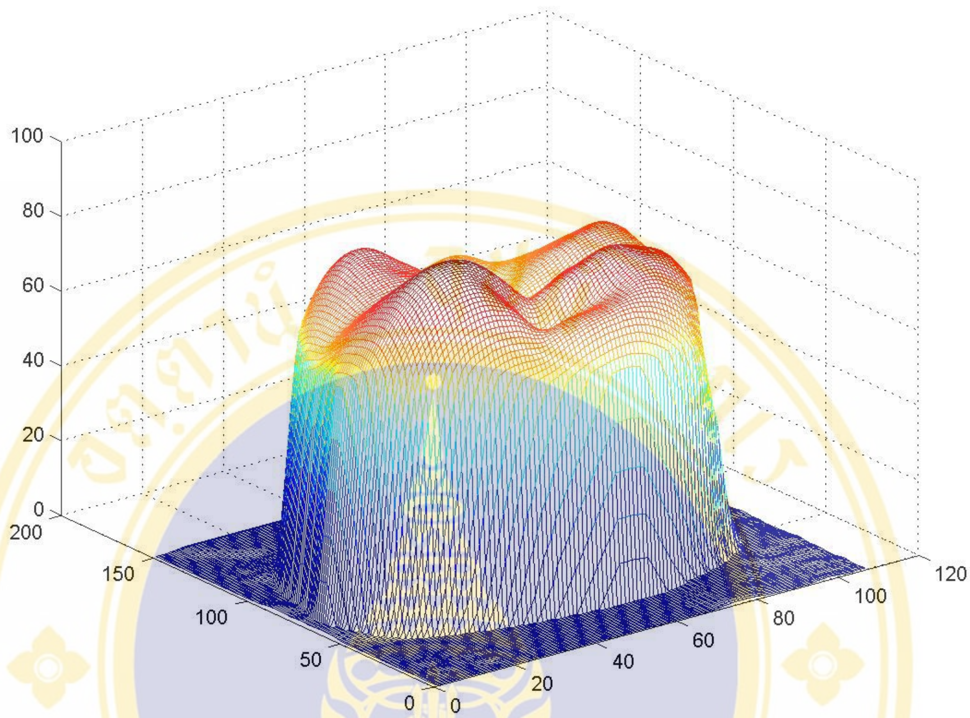


Figure 4.2 An example of dentin surface, which is collected from image processing technique.

Based on histogram analysis, the middle intensity, from 100 to 175, belongs to dentin. Similar to enamel, the dentin surface is gathered from the pixel counts and consequently are plotted as dentin surface as demonstrated in Figure 4.2.

After getting the morphologic information, the whole occlusal area is divided into five cusps according to their well-defined primary grooves. An example of tooth cusp division is represented in Figure 4.3. Consequently, the maximum pixel count in dentin, which is the peak, is used to determine all major cusp tips.

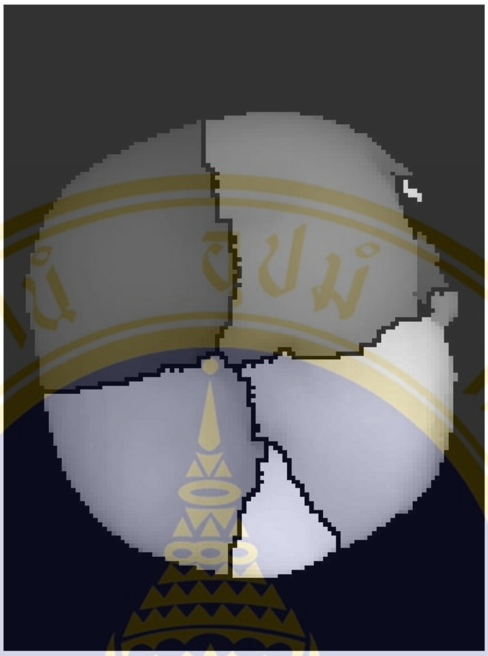


Figure 4.3 An example of cusp division in the first lower molar.

Figure 4.3 is obtained from the watershed process. The different intensity of each cusp is the crucial information for image segmentation. After information passes through this procedure, this picture shows that the occlusal surface of this tooth is then segmented into five portions. Following this process, this division is fed into cusp labeling.

Searching through the image information for a location of a cusp is a challenging task. Using the peak of the cusp is the first trial approach. The second approach is to define all the cusp tips from the centroid of each cusp. Both of these methods give the same result of marked cusp tips on the occlusal surface of the lower first molar as in Figure 4.4.

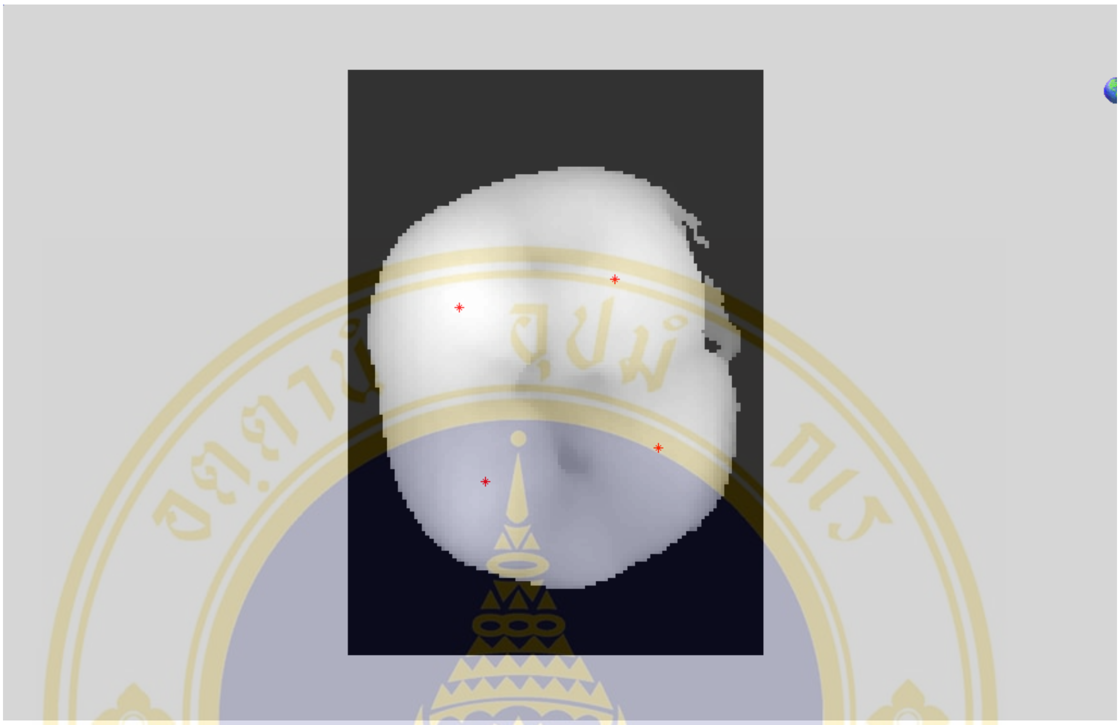


Figure 4.4 Label of all cusps in a sample.

In this experiment, the position of the major cusp tips, which are mesio-buccal cusp, disto-buccal cusp, mesio-lingual cusp and disto-lingual cusp are correctly identified. The fifth cusp tip cannot be marked because the peak is too small. In conclusion, all of the location marks for cusps on this tooth are similar to those derived using human judgment.

The second result represents the thickness parameter. Table 4.2 gives the information of enamel thickness compared with the other measurements of the same tooth at the same points whereas Table 4.3 presents the data of dentin thickness compared with MIMICS and tooth slicing in the same manner as in Table 4.2.

Table 4.2 An example of enamel thickness comparison analyzed by actual tooth sectioning, MIMICS®, and the developed method.

Tooth / Method	Enamel Thickness (mm.)							
	Mesiobuccal cusp		**Distobuccal Cusp**		**Mesiolingual Cusp**		**Distolingual Cusp**	
	Sample1*	Sample2**	Sample1	Sample2	Sample1	Sample2	Sample1	Sample2
Tooth section	1.17	X	1.64	X	0	X	0	X
MIMICS	1.40	2.96	1.63	2.69	0	2.02	0	2.03
Proposed method	0.6	3.6	0.3	2.0	0	1.7	0	0.2

* Sample 1 is a representation of severe attrition tooth.

** Sample 2 is a representation of non-wearing tooth.

X is defined as no information from this process.

0 is defined as cannot locate cusp tip therefore measurement cannot be done.

This table shows an example of enamel thickness analyzed by actual tooth sectioning, MIMICS® and the proposed method. There are two cusps, mesiobuccal cusp and distobuccal cusp, involved in enamel thickness assessment in Sample 1, while there are four cusps considered in Sample 2. A comparison of enamel thickness between the developed model and the commercial program shows that there is a large difference between the result of the proposed method and Tooth Section in Sample 1, being 0.57 mm. in the mesiobuccal cusp and 1.34 mm. in the distobuccal cusp. MIMICS® provided results that are closer to the values given by Tooth Section thus in this sample the commercial program provided superior results.

In Sample 2, the table presents only the comparison between the proposed method and the commercial programme because the tooth section data was unavailable. The value of enamel thickness for the mesiobuccal cusp in the proposed method is higher than for the commercial programme but the thickness in the distobucal cusp is smaller. However, the results are fairly close for the two methods.

Table 4.3 An example of dentin thickness comparison analyzed by actual tooth sectioning, MIMICS®, and the proposed method.

Tooth / Method	Dentin Thickness (mm.)							
	Mesiobuccal cusp		**Distobuccal Cusp**		**Mesiolingual Cusp**		**Distolingual Cusp**	
	Sample1*	Sample2**	Sample1	Sample2	Sample1	Sample2	Sample1	Sample2
Tooth section	10.48	X	8.56	X	0	X	0	X
MIMICS	9.036	9.02	8.54	7.42	0	5.29	0	4.13
Our method	9.5	9.1	8.2	8.3	0	8.1	0	7.4

* Sample 1 is a representation of severe attrition tooth.

** Sample 2 is a representation of non-wearing tooth.

X is defined as no information from this process.

0 is defined as cannot locate cusp tip therefore measurement cannot be done.

Table 4.3 shows the information of dentin thickness among tooth section, MIMICS® and the proposed method of two samples. For the first sample, there are little differences when comparing tooth section with MIMICS® and tooth section with the proposed method. The differences of the two programming approaches and tooth section are approximately less than 1 mm. This result shows that two methodologies are available for dentin thickness measurement.

The latter sample shows the difference between MIMICS® and the new approach ranges from 0.8 to 3.27 mm. in dentin thickness. Because there was no tooth slicing, judgment on the accuracy of this method was not possible.

In conclusion, the experimental results imply that the trend of the proposed method is quite similar to the two former methods in enamel thickness measurement, even though there are some differences in the value of dentin thickness. This proposed method can measure enamel volume on each cusp while it was not possible from direct measurement of tooth section or using the commercial method.

CHAPTER V
DISCUSSION

From the results in this study, several points are discussed as followed.

1. Spiral CT and Conebeam CT

Initially, the information for the thirty-nine ancient teeth was used in the pilot study of the proposed libraries. This information was obtained from spiral CT (GE Medical Systems, Light Speed[16] System Manual-Gen, at 80 kV and 70 mA.) with the FOV 7 mm. A voxel size for the resulting image is about 0.3 mm. This information is good enough in for tooth classification because it gives an accuracy of 71.79 %. To utilize this information as the original data for morphologic measurement, the resolution was questionable. As mentioned, the next aim of this study was to measure the fine portions such as enamel and dentin thickness. An error in 1-2 mm. may affect the age calculation of these ancient teeth. Therefore, conebeam CT, which has 0.1 mm. of voxel, is introduced into this study.

2. Tooth position in this study.

From the experiment conducted by the Highland Archeology Project in Pang Mapha, Mae Hongson province, it was found that longitudinal scanning will give better occlusal surface details than cross-sectional scanning. This observation was taken into account when making arrangements for the positioning of the teeth in this study.

3. Tooth type recognition technique

The accuracy of the proposed tooth recognition system is approximately 72%. The majority of errors may be contributed from the following reasons:

3.1. Too small number of tooth samples for the conducted experiment. Because of the limitation and complexity in the tooth collecting process, all teeth were from ancient mountain people provided by the Highland Archaeology Project in Pang

Mapha, Mae Hongson province. Thus, the number of teeth may not have been sufficient for this study. Another important factor was that the high cost of CT scanning inhibited further collecting of three dimensional tooth data. With a limited budget, only a small number of samples could be used in the experiment. The accuracy of the proposed system is expected to be higher as the number of samples grows larger. Odd Shaped teeth are rare in the general population but the sample used in this study had several odd shaped teeth leading to some confusion in the results. All these factors led to the accuracy of the method being lower than anticipated.

3.2. In the feature extraction step of the proposed method, the tooth type recognition system used the radial distances defined in the previous chapter as the inputs. The number of layers and the number of angles in each layer plays an important roll in representing the tooth shape. The higher number implies a closer approximation of tooth shape and also implies that the complexity of the neural network would be higher by $O(n^2)$. The neural network training may not converge as a result. Although the network could converge, there may have existed an over-fitting behavior which is undesirable in detection of common features such as shape. In the experiment, the numbers of layers and angles per layer was 8 and 16. More experiments may have been needed to figure out the appropriate number of layers and angles to closely approximate the tooth shape without causing the convergence problem and/or over-fitting problem.

The solution is to increase the number of sample teeth, so that the regular-shaped teeth would be statistically common. For the second problem, more experiments may need to be conducted with the number of layers and angles varied. The sensitivity analysis on these parameters determines the appropriate range of the numbers. Therefore, the highest accuracy of the tooth classification can be obtained.

4. Tooth measurement

From the experimental procedures, several interesting points are mentioned below:

4.1 In the tooth segmentation process, some teeth can be divided into four or five cusps correctly, while others cannot be distinguished. The expected cause is the condition of teeth involved in this study. The teeth samples are from both non-wearing teeth and severely worn teeth. The tooth in Sample 1 represents a non-wearing tooth whereas the tooth in Sample 2 represents severe attrition.

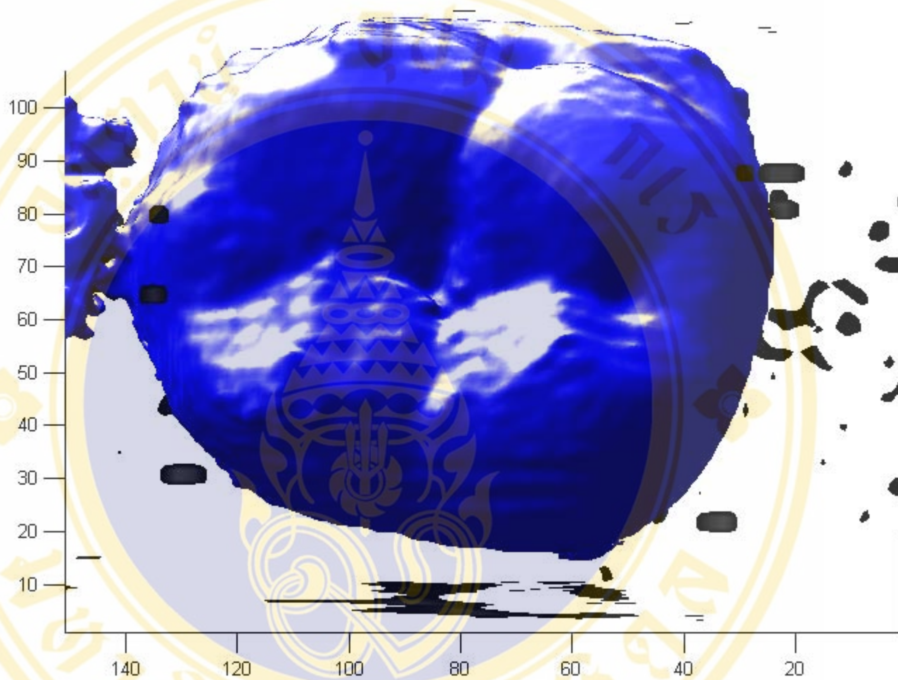


Figure 5.1 An example of non-wearing tooth

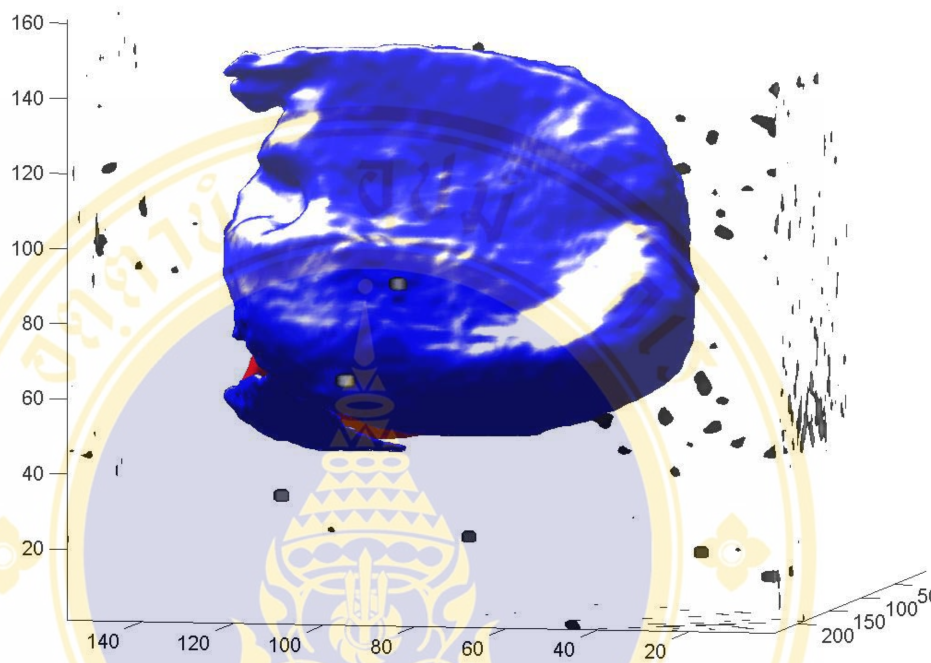
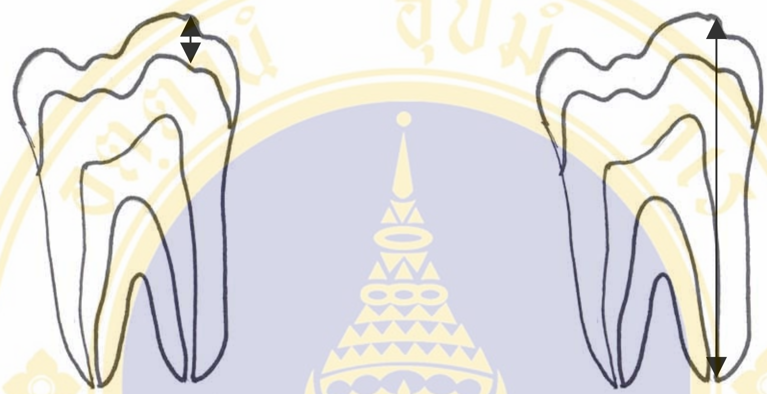


Figure 5.2 An example of a severely worn tooth

As mentioned in the parameter extraction procedure, information on dentin was collected and then used as a reference for cuspal isolation. Hence, the wearing of dentin in severe attrition is an important factor for poorly defined tooth cuspid. This is responsible for unidentified enamel and dentin thickness in wearing cusps. To assess the severe dental cusps, dental pulp horn is the possible solution. However, error testing is essential for accuracy of obtained results.

4.2 The differences in enamel and dentin thickness come from a process of image processing. Some of the pixels in the interface area of the object and the background may not be correctly gathered into enamel and dentin information. This junction causes one to two pixels error in thickness information and becomes a big error in volume information. This error must be carefully considered. Correction of this problem may reduce the error in the odontometric process.

4.3 In enamel thickness, the result shows that the obtained values are close to the typical enamel thickness, while the results for dentin thickness are not. The reasons for this result may be the difference in measurement.



(a) (b)

Figure 5.3 The measurement of enamel and dentin.

(a) Enamel thickness

(b) Dentin thickness

To adjust the dentin values, the suggested idea is to change the direction of measurement from a vertical measurement to measure from the tip of pulp horn to the tip of dentin cusp. The suggested idea is shown in Figure 5.2.

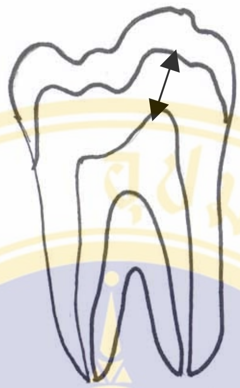


Figure 5.4 The suggested dentin thickness measurement.

5. Suggested works

At present, the proposed algorithm implemented in MATLAB® uses the command line environment. Before it can be used in clinical practice, it should be completely rewritten in graphical user interface (GUI) to make it easier for general users. It should also be evaluated and experimented with for more segmentation and measurement of tooth data than those conducted in the work of this thesis. Moreover, more tooth parameters may be extracted in details. This study is useful not only in the dental field but also in many other fields.

In the future, this study may provide fundamental information for several research projects, such as a dental anthropology, archeology, and dental forensics. An illustration of related projects is shown in Figure 5.3.

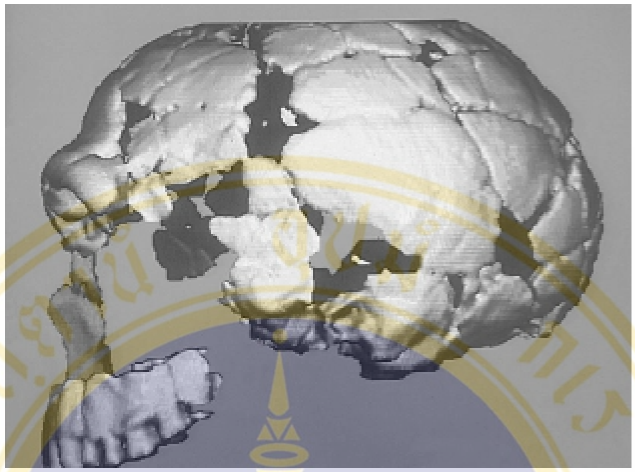
For dental anthropology, general tooth parameters from Thai populations may be stored and then utilized as the Thai's database. This database may be used as the reference for other researches. Further research could include the typical tooth characteristics of Thai people, and the study of tooth size and tooth shape related to malocclusion in orthodontics. This information may be used to predict the future transformation of teeth. In conclusion, corresponding teeth studies may be based on these tooth parameters.

In archeology, the application of a morphometric study may be divided into two facets. First, it may act as the information for 3D imaging of fossils. To construct the sharpest image, it will require sufficient information from each parameter. Secondly it may be utilized in the 3D reconstruction of fossils in a computer using a comparison between the remaining components of the fossil with the Thai's database to predict the size and shape of missing components. The best examples of fossil reconstruction are shown in the study of three dimensional imaging in paleoanthropology and prehistoric archeology [32] as demonstrated in Figure 5.3.

For dental forensic purposes, the isolated tooth parameter information may be applied in human identification. The character of oral information is unique; therefore the extracted parameters may be the primary key in a human database. The important task in this field is to match the pre-mortem and postmortem data together. If a match is found, the victim or missing person will be correctly identified. As in archeology the large number of Thai tooth parameters could be utilized in a reconstruction process. It can be seen that tooth parameters could play a vital role in this field.

It may be possible to apply the extracted parameters in dental diagnostic and dental treatment. The data will be collected to form a database, as mentioned above; the application in dental diagnosis is to specify the morphological abnormality of tooth, for illustration of mesiodens, the extra central incisors, and peg-shaped lateral incisors, the lateral incisor that is smaller than the typical tooth ratio. This information may be employed in dental treatment too. The mentioned database may be employed in tooth replacement. A lot of tooth substitution could be implement with the database information. Therefore, the lost or missing tooth could be replaced with the same size artificial tooth in a few minutes because of the readily available substitution.

The aforementioned applications are based on tooth parameters. There are more interesting applications in many fields that rely on the use of these parameters.] More research may be conducted to find a further use for these parameters.



(a)

(b)

Figure 5.5 Reconstruction of cranium and dentition.
(from Three-Dimensional Imaging in Paleoanthropology and Prehistoric Archaeology. Applications and pittfalls of CT-based 3-D imaging of hominid fossils. In: Mafart B and Delingette H (Eds.): BAR International Series 1049)
(a) Representation of bone fragments of Tabun C1 cranium.
(b) Antero-inferior view of dentition in Mauer1.

CHAPTER VI
CONCLUSION

6.1 Background

CT scanning was chosen to analyze dental specimens discovered from Log Coffin caves by the Highland Archaeology Research Project in Pang Mapha, Mae Hongson province (phase II), northern of Thailand. A fast and accurate method is needed to assess both internal and external dental parameters with minimal human interference and causing as little damage as possible to the specimens.

6.2 Objectives

1. To develop a new methodology for external and internal three-dimensional tooth measurement specific for ancient tooth specimens using CT information. This methodology consists of
   a. Tooth type recognition (eg. incisors, canines, premolars and molars) using morphological data.
   b. Dental parameter measurement.
2. A proposed approach will require least human interference in the computation.

6.3 Experimental processes

Image processing toolbox in MATLAB® was used for three-dimensional data extraction. Experimental processes were divided into two parts:

1. Tooth recognition process to classify the tooth type.
2. Morphometric process to measure enamel thickness, dentin thickness and enamel volume.

6.4 Sample selection

1. For tooth recognition process study, four different types of ancient teeth were chosen, nine molars, ten premolars, twelve canines and eight incisors.

2. For morphometric study, twenty five upper molars and twenty five lower molars of ancient teeth were used as experimental samples. Ten contemporary teeth, five upper molars and five lower molars, served as control.

6.5 CT Scanning

Selected teeth were scanned longitudinally using spiral CT (GE Medical Systems, Light Speed[16] System Manual-Gen) for tooth recognition process whereas conebeam CT (Hitachi CB MercuRay ™ Maxillofacial Imaging) was used for morphometric process.

6.6 Tooth type recognition

This process consisted of tooth segmentation and tooth classification.

6.7 Tooth measurement

Morphometric process consisted of tooth segmentation and dental parameter extraction such as enamel thickness, dentin thickness and enamel volume.

6.8 Results

In tooth type recognition, it can identify tooth type correctly for 71.79%.

In morphometric process, enamel thickness measurement was satisfactory while dentin thickness and enamel volume measurements need some modifications.

6.9 Error study

The results from morphometric process was compared with direct measurement from modern human tooth sectioning and with data processed by MIMICS®.

6.10 Evaluation of results

1. At the end of this study, tooth recognition and tooth measurement libraries were developed to support the study of ancient teeth.

2. Even though the proposed approach was not proven that it's best result, at least it took the least human interference.

6.11 Suggested application

This proposed method could be applied for archaeology, dental anthropology and dental forensic researches.

6.12 Others

A paper, A Neural Network method for CT-based Tooth Number Identification, has been accepted for presentation to an International Symposium on Biomedical Engineering, 2004 at Rama Garden Hotel, Thailand. (Appendix 2)

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APPENDIX

APPENDIX

Tooth parameter extraction source code

```
%=================================================================
% Final Version : Tooth Parameter Extraction based on 3D Reconstructed
%                         Computerized Tomography Data
% This m.file extract enamel and dentin of MHS2_3_2
% Student: Sirilawan Tohnak
% Major-Advisor: Songpol Ongwattanakul
% get data from MSH2_3_2
% Last modified 11/02/05
%================================================================
 clear all
hold off
%=================================================================
% histogram analysis
%=================================================================
temp1 = [];
temp = [];
imdata222=[];
 for no_image=328:434,                                                     %     MHS2_3_2
      fname = printf('MHS2_3%03d', no_image);
      no_image = no_image+1;
      imdata = dicomread(fname);
      imdata22=medfilt2(imdata);
      select=uint8(double(imdata22(70:220,200:500))*255/4095);     %    MHS2_3_2
      temp1 = cat(3, temp1,select);
  end
[aa,bb,cc]=size(temp1);
wim(temp1, 'work');
temp2 = rim('workA', cc);
save sirilawan_a temp2
%=================================================================
% search for enamel area and save into enamel and data_e array
%=================================================================
 imdata222_d=double(temp1);
 tooth=double(temp2);
 tooth_gray=uint8(double(tooth)./max(max(max(tooth)))*255);
  sizetooth_gray=size(tooth_gray);
enamel_gray=tooth_gray(1:sizetooth_gray(1),1:sizetooth_gray(2)/2,1:sizetooth_gray(
3));
 dentin_gray=tooth_gray;
 enamel=zeros(size(tooth_gray));
 no_enamel=zeros(size(tooth_gray));
  for  row = 1:sizetooth_gray(1),
      for no = 1:sizetooth_gray(3),
```

```
            index = 0;
            for col = 1: sizetooth_gray(2)/2,
                index = index +1;
                if (enamel_gray(row, col, no) >= 40 & enamel_gray(row, col, no) < 175)
                    enamel(row, col, no)=175;
                elseif enamel_gray(row, col, no) >= 175
                    enamel(row, col, no)=tooth_gray(row, col, no);
                    break;
                end
            end
        for col_new = index:sizetooth_gray(2),
            no_enamel(row,col_new,no)=dentin_gray(row,col_new,no);
        end
    end
end
for  row = 1:sizetooth_gray(1),
    for no = 1:sizetooth_gray(3),
            dept = 0;
            for col=1:sizetooth_gray(2)/2,
                if enamel(row, col, no) == 0
               dept = dept + 1;
            else
               break;
            end
        end
        data_e(row,no) = dept;
    end
end
%==========================================================================
% search for dentine area
%==========================================================================
 % data_e_size=size(data_e);
% data_e_add=zeros(data_e_size(1)+1,data_e_size(2)+1);
% data_e_add(1:data_e_size(1),1:data_e_size(2))=data_e;
for  row = 1:sizetooth_gray(1),
    for no = 1:sizetooth_gray(3),
            dept = 0;
            for col = 1:sizetooth_gray(2)/2,
               if no_enamel(row, col, no) == 0
                 dept = dept + 1;
               else
                 break;
               end
            end
            data_d(row,no) = dept;
    end
end
```

```
data_d = max(max(data_d))- data_d;
%=====================================================================
% processing watershed algorithm to find a peak of each cusp
%=====================================================================
data_d = filter2(ones(5)/25,data_d);
% ===== start watershed loop ========
for  row = 1:sizetooth_gray(1),
     for no = 1:sizetooth_gray(3),
          if data_d(row,no) <= min(min(data_d)),
             temp(row,no) = data_d(row,no)+1000;
          end
     end
end
% ===== end watershed loop ========
data_d_new = data_d;
data_d_new2 = data_d-min(min(data_d_new));
data_d_new3 = data_d_new2;
for  row = 1:sizetooth_gray(1),
     for no= 1:sizetooth_gray(3),
          if data_d_new2(row,no) <= 0
             data_d_new3(row,no) = 0;
          end
     end
end
data_d_new4 = max(max(data_d))- data_d_new3;
w_data_d = watershed(data_d_new4);
qq = w_data_d .* data_d;
data_d_area = size(find(data_d~=0));
xx2 = 0;
for  cusp = 1:max(max(w_data_d))
      temp_M = w_data_d == cusp;
      M = data_d .* temp_M;
      M_area = size(find(M~=0));
      if M_area > (data_d_area.*0.1)
          xx2 = xx2 + 1;
          temp_M = w_data_d == cusp;
          max_M = data_d.*max(max(M));
          [m,n] = size(max_M);
          [x,y] = meshgrid(1:n,1:m);
          X{xx2} = (sum(sum(M.*x)))/sum(sum(M));
          Y{xx2} = (sum(sum(M.*y)))/sum(sum(M));
          e_thick_M = abs((data_d.*temp_M)-(data_e.*temp_M));
          e_volume(xx2)=sum(sum(e_thick_M))*(0.1)^3;
      else
          continue;
      end
end
```

```
imshow(data_d/max(max(data_d)))
hold on
for  no_cusp = 1:xx2,
      plot(X{no_cusp},Y{no_cusp},'*r')
      e_thick_cusptip=abs(data_d(round(Y{no_cusp}),round(X{no_cusp}))-
data_e(round(Y{no_cusp}),round(X{no_cusp})))
end
% ==========================================================
% store second zero data into data_d_pulp
% ==========================================================
for  row = 1:sizetooth_gray(1),
      for no = 1:sizetooth_gray(3),
          dept = 0;
          dept2 = 0;
          for col = 1:sizetooth_gray(2)/2,
               if no_enamel(row, col, no) == 0
                 dept = dept + 1;
               else
                 while (no_enamel(row, col, no) ~= 0) & (col < sizetooth_gray(2)/2)
                     dept2 = dept2 + 1;
                     col = col+1;
                 end
                 break;
              end
         end
         data_d_pulp(row,no) = dept + dept2;
         data_d_pulp_dentin(row,no) = dept;
     end
end
% ==========================================================
% calculate the pulp area using data_d_pulp.
% ==========================================================
temp = 150 - data_d_pulp;
temp3 = temp < max(max(temp)) & temp>0 ;
[LL,num] = bwlabel(temp3);
for  nnn = 1:num,
      MM = data_d_pulp.*(LL==nnn);
      MM_max = data_d_pulp.*max(max(MM));
      [m,n] = size(MM_max);
      [x,y] = meshgrid(1:n,1:m);
      X2{nnn} = (sum(sum(MM.*x)))/sum(sum(MM));
      Y2{nnn} = (sum(sum(MM.*y)))/sum(sum(MM));
end
size_temp3=size(temp3);
C=[];
temp4 = LL == 2;
temp5 = temp.*temp4;
```

```
temp5_section=watershed(max2(temp5) - temp5);
uu = temp5_section.*temp5;
imshow(uu/max(max(uu)))
% ==========================================================
%find out the pulp horn and then represent it as spots in the figure.
% ==========================================================
data_d_pulp_area = size(find(data_d_pulp~=0));
L_area = [];
for  cusp2 = 1:max(max(temp5_section)),
      temp_L = temp5_section == cusp2;
      LL = temp5.*temp_L;
      L_area = size(find(temp_L~=0));
      L_whole(cusp2) = L_area(1);
      if L_area > (data_d_pulp_area.*0.05)
          [m3,n3] = size(data_d_pulp);
          [x3,y3]=meshgrid(1:n3,1:m3);
          LL = LL.*temp5;
          X3{cusp2} = (sum(sum(LL.*x3)))/sum(sum(LL));
          Y3{cusp2} = (sum(sum(LL.*y3)))/sum(sum(LL));
      else
          continue;
      end
end
imshow(data_d_pulp/max(max(data_d_pulp)))
hold on
for  i=1:length(X3),
     if isempty(X3{i}) ~= 1
        plot(X3{i},Y3{i},'*r');
    end
end
for  no_cusp=1:xx2,
      plot(X{no_cusp},Y{no_cusp},'*c')
end
% ==========================================================
% End of File
% ==========================================================
```

A NEURAL NETWORK METHOD FOR CT-BASED TOOTH NUMBER IDENTIFICATION

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ABSTRACT

In this paper, we propose a method for CT-based tooth number identification which employs an artificial neural network as its recognition engine. This tooth number identification system is a part of an autonomous tooth parameter extraction system. A few samples of teeth data are used in the training process of the artificial neural network. The radial distances from the center of each cross-section to the outer surface of the teeth are the inputs to the recognition engine. The outputs indicate the type of teeth (i.e. Molar, Premolar, Canine, and incisor) for the corresponding inputs. The result shows that, with the radial distances scheme, the accuracy of tooth number identification is beyond 70%.

1. INTRODUCTION

The name of tooth is called the tooth number. Although there are many variations, the main objective remains the same. The tooth number is important to refer to a tooth position in the mouth which is mostly used in the field of dentistry. Surprisingly, this information is also useful in the field of anthropology. Because the tooth number is unique, it may be used to estimate the number of people at a burial site through the minimum number of identication method. This method suggests that the estimation is based on the number of the same teeth. If there are six lower right first molar in an area, it implies that at least six people were buried at the site. To obtain the accurate data for further analysis, each tooth must be identified at least twice at the beginning. The common problems of tooth identification mostly caused by both intra- and inter-observers are reliability. Factors that affect the observers are the lack of knowledge, inexperience, and fatique. These problems may rapidly arise when a large amount of samples are being observed. The introduction of computerized tomography (CT) could be the answer to the problems. CT is a non-destructive way to investigate both external and internal structure of a valuable sample, especially historic tooth and bone. Moreover, the results of CT procedure can be easily visualized in three-dimensional representation. Even though CT has been widely used in various fields, using CT data for tooth number identification has not been reported in the history.

To automatically extract tooth parameters (*i.e.* root length, height) from CT tooth data, the tooth number of the test sample must be identified prior to the measuring processes because different type of tooth requires different measurements. The measuring method should be fast and highly accurate.

2. LITERATURE REVIEW

2.1 Dental anthropology

Teeth are an excellent tool for study in anthropology because they are preserved in greater number than other skeleton parts are. The dental pulp also contains genetic code that is closely protected by its own structure. In addition, teeth are easily treated by quality method [1].

In dental anthropology, research studies are involved in the comparison of tooth morphological details among population for a certain period of time. Eventhough, the theoretical expectations have assumed that changes in human dentition have occurred for a long time ago, the information is inadequate to draw any conclusion. In recent years, human dentition evolution has revealed the similarity and dissimilarity of tooth appearance among people from different races, sexual dimorphism and body size. Although some studies show the variations in all of these points [1], other may suggests that these differences are insignificant for data analysis [2].

2.2 Computed Tomography

CT is recently introduced into dentistry field for morphological classification purposes. The advantages of CT are that internal morphology of both soft tissues and skeleton structures can be seen without destroying the sample. Because the teeth collected from the historical area are invaluable, nondestructive studying is required. The CT data may be used in the morphometric measurement step with three-dimensional reconstruction. Unlike conventional X-ray film, CT scans process is no magnification errors from geometric distortions. Hence, the images data are more accurate than X-ray [3].

3. IMAGE PROCESSING

To save the cost of CT scanning, eight groups of teeth are scan simultaneously. There are four to five teeth per group. Each group of teeth is secured in a transparent container and stacks on top of each other. Therefore, the CT data of each individual tooth must be correctly extracted from this bulk information which can be accomplished through the use of histogram analysis and image segmentation [4] techniques.

3.1 Histogram Analysis

The purpose of performing the histogram analysis is to roughly isolate each group of teeth. First, the histogram of each CT slide is computed as shown in Figure 1.

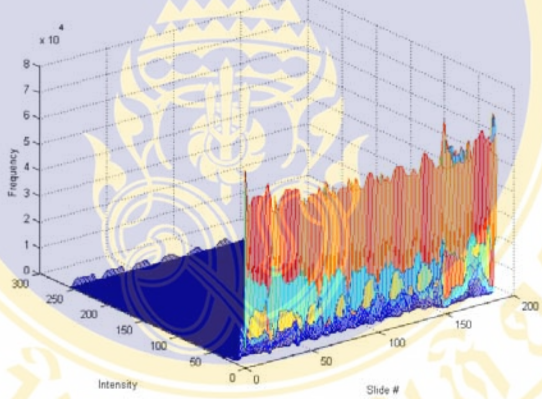

Figure 1. Histogram analysis of CT teeth data.

The highest intensity level may be referred to as the enamel which, in Figure 1, can be used to indicate the location of the group separation line (the valley between two hills at the intensity = 255).

3.2 Segmentation

Once each group of teeth is isolated, the CT slide becomes a manageable size for image segmentation. A series of two-dimensional images is equivalent to a three-dimensional image. Therefore, three-dimensional segmentation is preferable. Our method uses an image labeling operation based on 18-connected neighborhood as a three-dimensional segmentation and performs on the binary image of the isolated CT data which is thresholded at the mean value of the image intensity. An example of segmented tooth is shown in Figure 2.

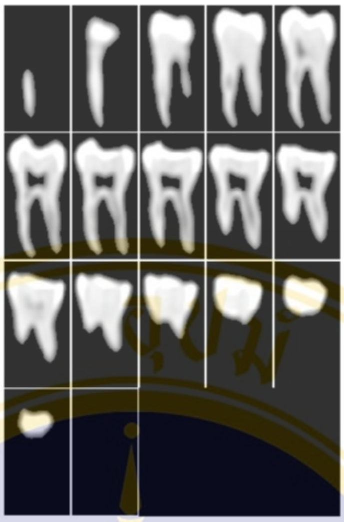

Figure 2. An individual tooth sample

4. RECOGNITION ENGINE

Using raster (pixel) information directly as an input to the recognition engine may not be a practice. Scale, shift and rotation invariant recognition is highly preferable for many applications including ours. To accomplish such a recognition system, we propose the usage of radial distances to represent the shape of the tooth. This shape information is later used for training of a supervised neural network.

4.1 Feature Extraction

The vertical cross section images of the CT tooth data, shown in Figure 3, are used as inputs to extract the radial distances. A radial distance is measured from the center of the image to the outer border of the tooth every 22.5˚. There are sixteen distances per cross section. The distances from all cross section images form a radial distance surface which are resampled to be 8 x 16 where 8 and 16 are the number of layers and angles, respectively. The example is shown in Figure 3.

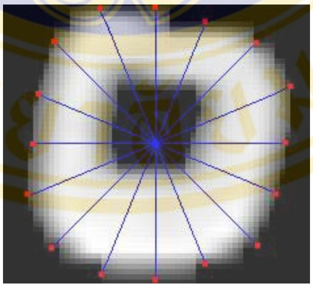

Figure 3. The radial distances of a tooth cross-section.

4.2 Artificial Neural Network

The radial distance surfaces of the chosen teeth are used as a training set. Since teeth in the same group are of the same tooth number. Therefore, one tooth per group is selected to be the training set (shown in Figure 4). The radial surfaces are normalized for scale invariant recognition before being stretched into a 128-element vector. For rotation invariant recognition, each radial surface has sixteen possible rotations (from 16 angles). Therefore, there are sixteen training set for every group of the teeth.

There are many choices for artificial neuralnetwork which can be used as a recognition engine. Our choice of network is an error back-propagation network because of its robust performance and the ease of implementation [5]. The network is trained to recognize the radial distance surfaces in the training set with the tolerance less than $5x10^{-4}$. It consists of two hidden layers which have 41 and 23 neurons.

Figure 4. The training teeth of each group from group 1-8.

5. EXPERIMENTAL RESULTS

From Figure 4, the first two rows are Molar teeth. Rows 3-4 are the Premolar teeth. Rows 5-6 and 7-8 are the Canine and Incisor, respectively. These eight teeth are assumed to be a perfect set of teeth for training. The rest of the teeth (39) from the same batch of CT scanning are used for testing. The maximum corresponding output from the neural network becomes the final result.

The final results show that our implementation of tooth number identification correctly identifies 28 out of 39 teeth (71.79%). Table 1 indicates that Canine and Incisor have a higher number of occurrences of misidentification.

Table 1. The recognition matrix

	Molar	Premolar	Canine	Incisor
Molar	9	0	0	0
Premolar	1	7	1	1
Canine	3	1	6	2
Incisor	1	0	1	6

6. CONCLUSION AND FUTURE WORK

A new non-destructive method for CT-based tooth number identification is presented. The accuracy level of the system is considered acceptable and remains unmatched to human recognition capability.

The accuracy of this method may be enhanced in several ways. One way is by refining the shape of the tooth for a better neural network training set. Another way is the increase the resolution of the radial distance surface.

7. REFERENCES

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