OPTIMISATION OF QUALITY PERFORMANCE PARAMETERS FOR DIGITAL DENTAL CONE BEAM COMPUTED TOMOGRAPHY (CBCT) SYSTEM

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by

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LIST OF SYMBOLS

θ	Angle of the scattered photon
Z	Atomic number
E_B	Binding energy of the shell from which the electron was ejected
cm	Centimetre
ρ	Density of materials
ρ_e	Electron density of absorbing materials
E	Energy
E_{rt}	Energy transferred to charged particles
$C_5O_2H_8$	Formula of acrylic (PMMA)
Cu_3Zn_2	Formula of brass
$C_{12}H_{20}O_2$	Formula of nylon
C_2F_4	Formula of tetrafluoroethylene (Teflon)
H_2O	Formula of water
Gy	Gray
keV	kiloelectron Volt
Kg	Kilogram
K(-e)	Kinetic energy of the electron
K(+e)	Kinetic energy of the positron
kVp	kiloVoltage peak
σ / ρ	Mass attenuation coefficient of Compton scattering
τ / ρ	Mass attenuation coefficient of photoelectric process
MeV	Megaelectron Volt
μ	Micro
mA	milliAmperage
mAs	milliAmperage seconds
h	Planck constant
m_0c^2	Rest energy of the electron
S	Second
Sv	Sievert
V	Volt

LIST OF ABBREVIATIONS

AMDI	Advanced Medical and Dental Institute
AAPM	American Association of Physicist in Medicine
ACR	American College of Radiology
ANOVA	Analysis of Variance
ALARA	As Low as Reasonably Achievable
AEC	Automatic Exposure Control
BB	Ball Bearings
B & A	Bland and Altman
BCCDC	Brithish Columbia Centre for Disease Control
$CTDI_c$	Central axis Computed Tomography Dose Index
CCD	Charge Couple Detector
CAT	Computed Axial Tomography
CT	Computed Tomography
CTDI	Computed Tomography Dose Index
$CTDI_{vol}$	Volume Computed tomography Dose Index
$CTDI_w$	Weighted Computed Tomography Dose Index
$CTDI_p$	Peripheral axis Computed Tomography Dose Index
CTIQ	Computed Tomography Image Quality
CBCT	Cone Beam Computed Tomography
CNR	Contrast to Noise Ratio
DOA	Degree of Agreement
DPR	Dental Panoramic Radiography
DIN	Deutsches Institut für Normung
DRL	Diagnostic Reference Level
DICOM	Digital Imaging and Communications in Medicine
DAP	Dose Area Product
DI	Dose Index
DLP	Dose Length Product
EADMFR	European Academy of Dental and Maxillofacial Radiology
EC	European Commission

EFOMP	European Federation of Organisations for Medical Physics
ESTRO	European Society for Radiotherapy and Oncology
EHS	Environmental Health Services
FOV	Field Of View
FPD	Flat Panel Detector
FDA	Food and Drug Administration
HU	Hounsfield Unit
II	Image Intensifier
IQ	Image Quality
IJ	ImageJ
ICC	Inter-Class Correlation
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiation Protection
IEC	International Electrotechnical Commission
LOA	Limit of Agreement
LP	Line Pair
LCD	Low Contrast Details/ Liquid Crystal Display
MRI	Magnetic Resonance Imaging
ML	MATLAB
MATLAB	Matrix Laboratory
MOH	Ministry Of Health
MDCT	Multidetector Computed Tomography
OS	Operating System
OPG	Orthopantomography
PDL	Periodontal Ligament
PC	Personal Computer
PSP	Photostimulable Phosphor
PACS	Picture Archiving and Communication System
PMMA	Polymethylmethacrylate
PTFE	Polytetrafluoroethylene
PET	Positron Emission Tomography
QA	Quality Assurance
QC	Quality Control

ROI	Region Of Interest
R	Romexis
SNR	Signal to Noise Ratio
SPECT	Single Photon Emission Computed Tomography
SSDE	Size Specific Dose Estimate
SDD	Source to Detector Distance
SID	Source to Image Distance
SF	Spatial Frequency
SR	Spatial Resolution
SD	Standard Deviation
3D	Three dimensional
2D	Two dimensional
USM	Universiti Sains Malaysia

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PENGOPTIMUMAN PARAMETER KUALITI PRESTASI BAGI SISTEM PERGIGIAN DIGITAL TOMOGRAFI BERKOMPUTER BIM KON (CBCT)

ABSTRAK

Sistem tomografi berkomputer bim kon (CBCT) telah digunakan secara meluas dalam pengimejan pergigian untuk pelbagai aplikasi *dentomaxillofacial*. Protokol pengujian standard untuk penilaian pelbagai parameter prestasi dan kualiti imej CBCT adalah masih terhad dan alatan ujian komersial sediada adalah tidak mampu dimiliki oleh sesetengah institusi. Kajian ini bertujuan untuk menilai parameter prestasi dan mengoptimumkan penilaian jaminan kualiti (QA) untuk sistem CBCT pergigian digital. Dalam kajian ini, sebuah fantom khusus dibangunkan untuk pandangan imej tomografik dan dinilai menggunakan unit CBCT pergigian di Unit Imejan, Pusat Perubatan USM Bertam (PPUSMB), Institut Perubatan dan Pergigian Termaju (IPPT), Universiti Sains Malaysia (USM). Satu algoritma automatik telah dibangunkan untuk penilaian herotan imej dalam pengimejan CBCT panoramik. Beberapa parameter prestasi untuk pelbagai paparan imej (pandangan *cephalometric*, panoramik, dan tomografik 3D) bagi pengimejan CBCT pergigian telah dinilai dan standard jaminan kualiti bagi unit CBCT pergigian dioptimumkan. Daripada keputusan penilaian, ia menunjukkan bahawa fantom CBCT yang direka khusus adalah bersesuaian digunapakai sebagai fantom QA ringkas untuk pandangan 3D pengimejan CBCT pergigian. Algoritma automatik yang dibangunkan membolehkan penilaian secara herotan imej panoramik bagi CBCT pergigian. Daripada analisis bagi pandangan 3D, nilai hingar imej berjulat antara 0.78 % dan 2.75 %, dengan keputusan keseragaman

CT adalah baik dengan kebanyakan data ukuran melebihi 95 % (antara 97 % hingga 99 %). Bagi penilaian kontras tinggi dalam pandangan *cephalometric*, protocol perolehan 60 kV dan 2.5 mA serta 70 kV dan 10 mAs (dengan tembaga) adalah disyorkan kerana tetapan ini menghasilkan sisihan yang kecil bagi frekuensi spatial dengan fantom TOR CDR dan TOR DEN. Kesimpulannya, kalkulator automatik yang dicadangkan menghasilkan pengukuran lebih mudah, cepat, dan tepat untuk penilaian herotan imej panoramik dalam ujian QA bagi CBCT pergigian. Selain itu, fantom yang dibangunkan boleh digunakan sebagai alat ringkas sesuai penilaian QA dalam pengimejan tomografi CBCT pergigian. Prosedur penilaian yang ditubuhkan dalam kajian ini boleh dijadikan sebagai panduan rujukan dan penambahbaikan ke arah pengoptimuman ujian QA rutin untuk sistem CBCT pergigian.

OPTIMISATION OF QUALITY PERFORMANCE PARAMETERS FOR DIGITAL DENTAL CONE BEAM COMPUTED TOMOGRAPHY (CBCT) SYSTEM

ABSTRACT

The cone beam computed tomography (CBCT) system has been widely used in dental imaging for various dentomaxillofacial applications. A standardised testing protocol for evaluation of a wide range of CBCT performance and image quality parameters is still limited and the commercially available testing tool is unaffordable by some centres. This study aims to evaluate the performance parameters and optimise the quality assurance (QA) test for digital dental CBCT system. In this study, a customised phantom was developed for tomographic (3D) image view and evaluated using the dental CBCT system at Imaging Unit, USM Medical Centre Bertam (PPUSMB), Advanced Medical and Dental Institute (AMDI), Universiti Sains Malaysia (USM). An automated algorithm was developed for the assessment of image distortion in panoramic CBCT imaging. Several performance parameters for the different image views (cephalometric, panoramic, and 3D tomographic views) of dental CBCT imaging were evaluated and the quality assurance standard of the dental CBCT system was optimised. From the results, it demonstrated that the fabricated CBCT phantom can be adopted as a simple QA phantom for 3D view of dental CBCT imaging. The developed automated algorithm offers simple and faster measures for evaluation of panoramic image distortion in dental CBCT. From the analysis on the 3D view, the image noise values ranged between 0.78 % and 2.75 %, with good CT uniformity findings where most measurements exceeding 95 % (ranging from 97 % to

99 %). For the high-contrast evaluation in the cephalometric view, the acquisition of 63 kV and 2.5 mAs and 70 kV 10 mAs (with copper) is recommended as these settings produced the least deviation in spatial frequency using the TOR CDR and TOR DEN phantom, respectively. In conclusion, the proposed automated calculator provides simple, faster, and accurate measure for the assessment of image distortion in panoramic dental CBCT QA test. Furthermore, the fabricated phantom serves as a simple phantom suitable for QA test in tomographic dental CBCT imaging. The evaluation procedure established in this study offers reference guidelines and improvement toward optimising the routine QA testing for dental CBCT system.

CHAPTER 1

INTRODUCTION

1.1 Background of study

Imaging with cone beam technology has rapidly become famous and frequently used to aid diagnostic task and improve patient care. Cone beam imaging technology is often referred to as cone beam computed tomography (CBCT). The terminology “cone beam” refers to the conical shape of the scan beam that is in a circular course around the vertical axis of the head in contrast to the multi detector-row computed tomography (MDCT) often used in medical imaging that has fan-shaped beam and more complicated scanning movement (Abramovitch & Rice, 2014; Dhillon & Kalra, 2013). Cone beam computed tomography (CBCT) is a doubtlessly low-dose CT approach for the visualization of mineralized peripheral tissues in the head and neck vicinity (AAPM, 2016).

Recently, dental radiography has become the most common x-ray test in the United Kingdom (Gallichan et al., 2020; Mah et al., 2011). Most states and regulatory bodies have suggestions mentioning the regular quality assurance of all radiographic tools to be performed. This means that ordinary trying out to notice gear malfunctions, and planned monitoring and scheduled renovation to produce a steady diagnostic radiographic image. All dental services using x-ray equipment, from a simple intraoral dental unit to an advanced 3-dimensional (3D) imaging system, such as CBCT will benefit from adopting a quality assurance program (Mah et al., 2011).

CBCT which is a latest imaging technology, is carried out using a rotating gantry to which an x-ray source and detector are fixed. A divergent cone-shaped radiation-rays beam is projected to the region of interest and the transmitted beam is detected by the digital detector on the opposite side. The x-ray source and detector rotate around a rotation fulcrum constant inside the core of the region of interest. During the rotation, multiple (from 150 to more than 600) sequential planar projection images of the field of view (FOV) are obtained in a complete, or sometimes partial, arc. This method varies from a usual medical computed tomography (CT), which makes use of a fan-shaped x-ray beam in a helical progression to collect individual image slices of the FOV and then stacks the slices to obtain a 3D representation. Each slice requires a separate scan and separate 2D reconstruction. Because CBCT exposure incorporates the entire FOV, only one rotational sequence of the gantry is fundamental to acquire ample information for image reconstruction. Obvious advantages of such a system, which provides a shorter examination time, include the reduction of image un-sharpness caused by the translation of the patient, reduced image distortion due to internal patient movements, and increased x-ray tube efficiency (Scarfe & Farman, 2008).

The introduction of a standard quality assurance (QA) program in dental CBCT is instrumental in the optimum performance of the dental CBCT device. The goal of QA program is to ensure the optimum performance of the modality and accurate diagnosis of patient (Periard & Chaloner, 1996). The importance of this QA in dental CBCT will be adequately met by a QA program whose primary objective is to maintain the quality of diagnostic images, minimize the radiation exposure to patient and staff; and to be cost effective. The QA program consists of a series of standardised tests that been developed to evaluate the performance of CBCT system in comparison with recommended acceptable level. A standard phantom can be used as a tool for the QA tests that cover a wide range of performance parameters. In local practice, a specific phantom for dental CBCT system is limited due to high price. The purpose of routine

QA tests is to allow prompt corrective action to maintain the quality of x-ray images and optimise the machine's performance. The QA program in dental CBCT is crucial to ensure that all steps are in place to ensure that the diagnostic quality of radiographs taken provides the requisite information to the clinician, thus negating the need for repeat radiographs that increase the dose of ionising radiation for both patients and the dental team. This QA programme also identify the causes of errors and allow them to be corrected, improve efficiency, and reduce cost.

The QA program in dental CBCT is instrumental to provide confidence in the suitability of an imaging technique for its intended purpose and to ensure the safe use in clinical practice. The benefit of performing QA is that it can guarantee that radiological images are of the highest quality and that they are generated at the lowest possible radiation dose. This leads to improved patient outcomes and makes clinical practice more satisfying and it allow all image quality parameters stated by the European Commission to be evaluated (EFOMP-ESTRO-IAEA, 2019).

1.2 Problem statement

Dental CBCT has been used in dental radiography for over 10 years and has been widely available for both specialists and general dental practitioners in most developed countries. Recently, the use of CBCT for dental imaging has grown rapidly, especially in the fields of implant dentistry, orthodontic treatment, and endodontic treatment. Major concerns have been raised regarding the indications for CBCT use because of the radiation doses that patients received. At national level of Malaysia, there is not yet established a quality control (QC) standard specifically for digital dental CBCT that cover all the 3 different image views (cephalometric, panoramic, and tomographic view). Therefore, the need to establish a standard protocol for the assessment of related performance parameters (such as uniformity, noise, contrast-to- noise ratio, low contrast resolution, and spatial resolution) of dental CBCT unit, as well as the dose quantity assessment is crucial (Torgersen et al., 2014).

Special attention is needed regarding quality assurance education in dental imaging because doses (and hence risk) incurred during dental examinations are in general relatively lower than MDCT scans of the dental area. However, the dose in dental CBCT is generally higher than conventional dental radiography (in comparison to intraoral and panoramic view). Furthermore, the utilisation of dental radiography accounts for nearly one third of the total number of radiological examinations in the European Union countries (Alahmad, 2015; American Dental Association, 2012; Feragalli et al., 2017; Metsälä et al., 2014; Pauwels et al., 2014; Tsiklakis, 2011).

The importance of image quality assessment is to identify the problem such as the image magnification and distortion that commonly occur in panoramic view of dental CBCT imaging that is caused by patient misalignment (jaws are not positioned near the focal zone of the x-ray beam). Even when properly taken, dental panoramic radiography images are associated with enlargement of the dental structures by about 15–25 %, and distortion happens once horizontal magnification differs from vertical magnification due to poor patient positioning. (Devlin & Yuan, 2013b).

One problem with the current QA evaluation for dental CBCT is the number of the commercially available phantoms in term of the unaffordable price, the properties, and dimension of these phantoms that cannot meet the requirement of QA test for dental CBCT. Currently, there is no dental CBCT phantom available at this study centre because the commercially available phantoms are quite expensive and unaffordable. Besides, the commercial phantoms have limited properties and range of parameters that can be evaluated. A study by Marcus et al, (2017) reviewed the available phantoms used in dental CBCT and reported that, only 7 phantoms out of 25 phantoms allows evaluation of more than 4 image quality parameters, while another 11 phantoms can only test 1 parameter. However, only two phantoms permit the evaluation of 6 image quality parameters as stated by the European Commission (EC). Besides, one of the described phantoms does not allow the evaluation of the presence of artefacts since it only focuses on image uniformity.

The study also showed that most of the phantoms used in CBCT QA test cannot be accommodated within the small FOV and require several or multiple exposures to evaluate all image quality parameters. This is because most of the phantoms' size is large and thus, some parts of the phantom were located outside the FOV, and incomplete view of the phantom images will be produced and lead to inaccuracy in QA assessment. Hence, the need of a suitable phantom to adapt the comprehensive QA program and tailor the small FOV sizes of the CBCT unit is crucial. Thus, this study aims to develop a suitable low-cost phantom that allows evaluation of wide range of image quality parameters and tailor the small FOV of CBCT system.

1.3 Research aims and objectives

1.3.1 General objectives

This work aims to develop a designated phantom for quality assurance (QA) assessment and establish a standard QA protocol for digital dental CBCT system that covers a wide range of performance parameters for different image views.

1.3.2 Specific objectives

1. To evaluate the performance parameters for general x-ray part (cephalometry view) of dental CBCT system.
2. To evaluate the performance parameters for orthopantomography (OPG) part (panoramic view) of dental CBCT unit.
3. To evaluate the performance parameters for the 3D tomography view and establish a quality assurance standard of dental CBCT unit.

1.4 Scope and limitations

In this research, a new customed phantom is designed and fabricated for assessment of the performance of dental CBCT unit. This is to test for its applicability as CBCT imaging tissue equivalent materials. Few materials that have similar attenuation properties to human tissues with correct CT number and densities were identified for fabrication of the phantom for quality assurance testing. During the phantom study, this phantom will be exposed using the digital dental CBCT system to validate the performance parameters of CBCT system.

The limitation of this work, which is inherent with all CBCT research, is that, in other CBCT system, the exposure protocols or diagnostic tasks may not necessarily be relevant to the findings in this study. This is because the contrast to noise ratio (CNR) varies between the different CBCT systems, and other factors rather than exposure time, such as voxel size and slice thickness, may affect it (Al-Ekrish, 2012). More specifically, the CBCT hardware, exposure parameters, field of view size and parameter of reconstruction vary greatly between different devices, so no two CBCTs are the same. These distinctive features affect the quality of the image, the ranges of dose delivered and the image interpretation as well, hence, the reason for the establishment of standard quality assurance for dental CBCT unit (Wolf et al., 2020).

Although this study initially intended to test and validate the developed phantom on various CBCT system available in other imaging centres, however, due to the outbreak of the pandemic which led to restriction in movement, that lead to limitation of data collection. However, the results from this study can still be compared with results that may be obtained from other CBCT units but with experimental verification because this study was limited to a single CBCT system (Planmeca ProMax 3D Mid CBCT unit) since it is the only model available in the study institution. Besides, the dose evaluation only involved measurement of computed tomography dose index (CTDI) for tomography view of the CBCT unit and it did not involve the dose measurement for the other views such as cephalometric and panoramic that used dose area product (DAP) value.

Furthermore, the customised phantom developed in this study can only test few image quality parameters and was limited in its application for high and low contrast. Hence, the commercially available TOR DEN and TOR CDR phantoms were used. This study demonstrates the adaptability and robustness of the developed phantom in providing accurate image quality assessment across widely different CBCT scanner. Therefore, findings from this work which is tested on a single CBCT model may be applied to any other dental CBCT model, but it is recommended for further experimental verification. Hence, conclusion drawn from this study is limited to the experimental set-up of this study and it is subject to the interpretation of the results with references to standard set by international and national organisations.

1.5 Significance of study

Due to the recent increment on the uses of CBCT in dental practice, the need for a standard quality assurance (QA) program are crucial to ensure the beneficial and optimisation of practice in the dental CBCT imaging. The important performance parameters must be evaluated periodically in ensuring the optimisation of dental CBCT system such as quantification of the radiation dose delivered to the patients, evaluation of technical parameters associated with image quality, and assessment of diagnostic quality. By means of an appropriate phantom, these aspects can be evaluated in single performance assessment that involve quantitative and objective analysis of the image quality and radiation dose. Ideally, the development of a designated phantom should be complemented with the established quality assurance (QA) protocol that can be widely adopted (Ruben Pauwels et al., 2011).

The customised phantom developed in this study may be employed for image quality assessment for tomographic CBCT view such as uniformity, noise, CT number test, CNR and signal to noise ratio (SNR) test. This customised phantom offers few advantages such as cost effective, simple, and easy in handling due to light weighted property. Hence, it eases the operating staff in handling the phantom for routine tests of CBCT system which is performed periodically.

Furthermore, the automated measurement algorithm developed in this study for the assessment of image distortion in panoramic images is simple and was proved to be effective in measurement of ball phantom diameter and distance between the balls of the phantom image. Besides, this developed automated algorithm may assist the medical physicist to perform routine analysis on image distortion assessment with less time consuming and efforts. Besides, the QA standard established in this study serve as a reference standard for the local QA performance testing for dental CBCT, which covers a wide range of performance even with different CBCT views.

Hence, the findings of this study will be beneficial for dental and maxillofacial applications and the medical physicist team, as they will be able to optimise the current CBCT practice and planning a more accurate imaging procedure more effectively. Precise imaging technique may save the actual procedure time, resulting a better diagnostic result, for more effective treatment planning and improved patient outcomes. Besides, it will also be beneficial for patients as they will receive lower radiation dose as the delivery of dose is optimised.

1.6 Outline of the thesis

This thesis consists of five chapters that discussed different aspects of the research work. The first chapter discussed in detail the introduction that covers the background of the study, the statement of problems that led to this work, the objective of the study, and the significance of the study to be conducted. The basic knowledge related to this work such as principles of radiation interaction with matter and the principle of operation of the dental CBCT will be the main topic of discussion in Chapter 2. Additionally, it also reviews recent research that are relevant to this study. In Chapter 3, a description of the research tools that have been used in this research will be described, then the methodology employed will also be discussed. The discussion on the research methodology will focus on preparation of phantom materials, tests for manufactured and fabricated phantom materials, fabrication of the new phantom and the performance testing for the dental CBCT. Meanwhile, Chapter 4 will focus on the research findings and scientific discussions on the results obtained from each part such as phantom materials tests, analysis of selected phantom materials and results of the

CBCT performance test. The conclusion and future recommendations will be summarised in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

For more than a century, physicists have contributed significantly to the development of non-invasive imaging techniques, initially using x-rays but more recently employing other energy sources such as ultrasound and electromagnetic fields. Diagnostic imaging today, has advanced from early, basic uses of radiographs for diagnosing bone fractures and identifying foreign bodies to a collection of strong techniques that may be used not just for patient treatment but also for fundamental research of biological structure and function. Advancement in digital radiography, computed tomography (CT), magnetic resonance imaging (MRI), and other nuclear, ultrasound, and optical imaging techniques have resulted in a variety of modern methods for non-invasively interrogating intact 3D bodies and extracting unique information about tissue composition, morphology, and function (John, 2015).

However, the primary limitation on image quality arises from the need to minimise the amount of radiation that a patient is exposed to (Brenner & Hall, 2012). When organ-specific cancer risk was adjusted for cancer levels of CT usage, it was determined that 1.5-2 % of cancers may eventually be caused by the ionizing radiation used in CT (Bloomfield et al., 2015; Bloomfield et al., 2015; Borge et al., 2015; Ekpo et al., 2018; McCollough et al., 2009; Portugal, 2014).

Dental cone beam computed tomography (CT) is an advanced dental x-ray technology that will be employed when regular dental or facial x-rays are not sufficient. However, the use of CBCT should be optimised in routine applications since the radiation dose from this scanner is notably greater than common dental x-rays scan. The

CBCT scanner technology enables the generation of three dimensional (3-D) images of dental structures, soft tissues, nerve paths and bone in the craniofacial region in a single scan through tomographic acquisition using wider cone beam.

Cone beam CT (CBCT) is not the same as common CT imaging. However, dental CBCT can be used to produce images that are comparable to those produced by using common CT imaging. With CBCT, an x-ray beam used is wider and has cone shape. The x-ray tube is moved around the patient to produce a wider range of images that cover larger area of maxillofacial region, also referred to as views. Both CT and CBCT scans produce high quality images (RadiologyInfor.org, 2019). This work will focus on the optimisation on quality performance parameters in digital dental CBCT imaging.

2.2 Fundamentals of radiation interactions with matter

In medical imaging procedures, the radiation is used, and the energy of the radiation used must be high enough to penetrate through human body. Radiation is defined as energy that travels and spreads out as it travels. This energy changes as the radiation pass through body and interact differently with various tissues inside the body. The principle of radiation interactions is used in image production creating different greyscale of different body structures. In the electromagnetic spectrum (the range of all types of electromagnetic radiation), the energies ranged beyond the visible light are the higher energy that usually employed in x-ray imaging which are x-rays and gamma rays. These types of radiation are widely used in mammography, computed tomography (CT), cone beam CT (CBCT) and in nuclear medicine. In diagnostic imaging, the radiation source could be as external radiation (radiology), internal radiation source (nuclear medicine), or a combination of radiation sources (in hybrid imaging such as PET/CT). The x-ray and γ (gamma) ray are the examples of ionising radiation used in diagnostic imaging, (Groenewald, 2017). Basically, the anatomical images obtained from the medical imaging is dependent on the attenuation properties of the radiation as it passes through the body (Portugal, 2014).

When x-rays pass through a patient, several interactions will occur, and this depends mainly on the initial energy of the incoming x-ray photons. The higher energy x-ray photons will penetrate the body tissues without interaction, while the lower energy photons will be absorbed or scattered by the tissues. In diagnostic energy range, different types of interactions will occur such as Coherent scattering, Compton scattering, and photoelectric absorption. In CBCT imaging, the x-rays used are usually in the ranges of 60 kVp to 140 kVp. Thus, in CBCT imaging, the major interaction of x-ray photons in soft tissues are Coherent scattering, Compton scattering (except in bone), and photoelectric effect (Kareliotis, 2015; Lee, 2011). In these interactions, some or all the energy of the x-ray photons will be transferred to electron of the atom of the matter. The mechanism for these interactions relies primarily on the energy of the x-rays photon and the atomic number (Z) of the absorbing materials expressed by Equation 2.1, 2.2 and 2.3 (Faiz & John, 2014).

In general, the reduction of the x-rays energy as it passed through body is known as attenuation. The attenuation coefficient depends on the photons and the nature of the absorbing material (human body). The attenuation coefficient for the Compton scattering is obtained by dividing the linear attenuation coefficient, σ with the density, ρ of the absorbing material given by Equation 2.1 (Faiz M. & John P., 2014).

$$\frac{\sigma}{\rho} \propto \frac{\rho_e}{E} \qquad 2.1$$

Where,

$\frac{\sigma}{\rho}$: is the attenuation coefficient of Compton scattering,

ρ_e: is electron density of absorbing materials,

E: is the energy of the photon.

Similarly, the attenuation coefficient for the photoelectric effect is obtained by dividing the attenuation coefficient, τ by the density, ρ of the absorbing material, as described by Equation 2.2 (Faiz M. & John P., 2014).

$$\frac{\tau}{\rho} \propto \frac{Z^3}{E^3} \tag{2.2}$$

Where,

$\frac{\tau}{\rho}$: is the attenuation coefficient of photoelectric process

Z: is the atomic number of the absorbing materials

E: is also the energy of the photon

These interactions involve photon interaction with either the target atom or nucleus (Coherent scattering), or orbital electron of the atom (Compton scattering and photoelectric absorption). Both Compton and photoelectric interactions cause atoms to lose orbital electrons through ionisation process. Photoelectric interaction causes the emission of scattered radiation that is referred as the secondary radiation (Faiz & John, 2014). After the interaction with the patient body, some of the x-rays will be absorbed, scattered, or transmitted from the body. The transmitted photon will interact with the receptor of an imaging system and detected as signal. The detected photons will be converted into images that can be viewed (radiograph). (Groenewald, 2017).

2.2.1 Coherent scattering

Coherent scattering occurs for lower energy x-ray photons and the energy is not enough to ionise the electron of the atom through ionisation. The photon's energy is lower than the binding energy of the orbital electron. Therefore, there is no energy loss as the x-ray's photon interacts with the atom of the attenuating medium since it is unable to release the electron from its bound state. As a result of coherent scattering, there is no energy deposition and therefore no dose contribution. It only causes the change in the photon's direction, or scattering. It involves interaction without energy loses which is known as elastic scattering. However, at diagnostic energy range, coherent scattering is not a significant interaction that occurs.

There are two types of Coherent scattering, the Rayleigh and Thomson scattering. Coherent scattering varies with the atomic number of the absorber (Z) and incident photon energy (E) according to Equation 2.3 (Faiz M. & John P., 2014).

$$\frac{Z}{E^2} \tag{2.3}$$

2.2.2 Compton scattering

Compton scattering is an interaction of incoming x-ray photon with the one of the loosely bound (outer shell) electrons of an atom. It involves simple collision between an x-ray photon and the outer shell electron. The incident photon is deflected from its original path with energy loses (known as an inelastic process), resulting in wavelength shift. The outer shell electron is loosely bound to the atom having weak binding energy. So, when the incoming x-ray photon collides with it, the electron will be ionised and ejected from the atom. The energy of the striking photon is absorbed by the electron and is ejected as recoil electron. Equation 2.4 shows the energy of the scattered photon which is determined by the scattered angle at which it was emitted as well as the energy of the initial photon (Dance et al., 2014).

$$\mathrm{E_{sc}} = hv' \frac{hv_0}{1+\frac{hv_0(1-\cos\theta)}{m_0c^2}} \qquad 2.4$$

Where:

h is Planck constant,

v' is frequency of the scattered photon

v_0 is frequency of the incident photon

θ is angle of the scattered photon

m_0c^2 is rest energy of the electron

The Equation 2.3 implies that an incident photon of energy, *hv* can collide with a free electron of rest mass, m_0c^2. This photon is scattered through an angle (scattered angle), θ with an energy of *hv* ($<h\grave{v}$),while the recoil electron with a kinetic energy, K_e at an angle θ.

2.2.3 Photoelectric effect

In photoelectric effect, the striking photon interacts with an electron which is tightly bound to the atom (inner shell electron) and the electron is ejected (ionisation) from the K-shell, known as photoelectron. This will create a hole or vacancy at the inner shell which is filled by another electron from a higher energy shell (L, M, or N shell). For this interaction to occur, the incident photon must possess enough energy (*hv)* to overcome the binding forces of the electron with the nucleus (binding energy, E_B) and to ionise the electron. For this photoelectric process to occur, $hv > E_B$ according to Equation 2.5 (Schafers & Viel, 2014)

$$hv \geq E_{rt} \geq hv - E_B \qquad 2.5$$

Where:

E_{rt} is energy transferred to charged particles (photoelectron and Auger electron)

h is Planck constant

v is frequency of the incident photon

E_B is binding energy of the shell from which the electron was ejected.

2.3 Imaging in dentistry

The introduction of advanced imaging technique has significantly improved the quality of care in health services to patients. Medical imaging is the technique and process of cresting visual description of the interior of a body for diagnosis and medical intervention as well as visual representation of the function of some organs or tissues. Medical imaging aims to visualise the internal structures within the body region for diagnosis and treatment planning purposes. It also enables them to perform keyhole surgeries for reaching the internal parts without making large openings on the body (Dhawan, 2011). The dental CBCT is an imaging modality that is used by the clinicians for diagnosing and planning the treatment of any pathologies related to the dentomaxillofacial region (Smith & Webb, 2011).

The goal of radiographic imaging in implant dentistry is to acquire the most practical and comprehensive information that can be used for the various phases of implant treatment. Dental radiology can be divided into intraoral and extraoral techniques. Usually, extraoral techniques present a higher radiation exposure level than intraoral image techniques (Batista et al., 2012). There are different methods of radiographic imaging to assess the candidate area of implant inserting. This includes peri-apical, dental panoramic radiography (DPR), lateral cephalometry, conventional tomography, computed tomography (CT), and cone-beam computed tomography (CBCT). Though the advanced imaging techniques (CT and CBCT) have several benefits like cross-sectional information and multi-dimensional views, DPR keeps its values in pre-surgical planning phase of dental implantation (Shahidi et al., 2018).

2.4 Dental CBCT imaging

The introduction of cone beam CT (CBCT) represents a radical change for dental and maxillofacial radiology. The first computed tomography (CT) scanner was invented by Sir Godfrey N. Hounsfield in 1967. In the late 1990s, the cone beam computed tomography (CBCT) technology was independently developed by two inventors, Yoshinoro Arai in Japan and Piero Mozzo in Italy that later has been commercially available for oral and maxillofacial radiology since late 1990s. CBCT offers cross-sectional imaging at potentially high geometric accuracy, a feature of specific interest to dentistry practitioners planning for dental implant treatment. The utilisation of CBCT has been expanded to few potential applications in several branches of odontology (Andraws Yalda et al., 2019).

Until recently, oral and maxillofacial radiology was based on two-dimensional (2D) imaging, such as intra-oral and panoramic radiographs. As a result of the complex anatomy within the oral and maxillofacial region, a shift from 2D to three-dimensional (3D) imaging evolved. Though, dental CT and, specifically, multidetector row CT

(MDCT) have provided a lot of helpful information in the investigation of oral and maxillofacial pathology, the possibly higher radiation dose is a currently mentioned disadvantage of this method. Moreover, MDCT needs considerable space and is expensive, and thus is employed relatively rarely for oral and maxillofacial pathology compared with conventional radiographs (Nemtoi et al., 2013).

2.4.1 Components of dental CBCT

CBCT undoubtedly represents a great advance in dental and maxillofacial imaging. The main principles of dental CBCT imaging are (1) data acquisition, (2) image reconstruction, and (3) image display. During the acquisition phase, the patient is positioned on the head holder with the head is stabilised to avoid patient motion throughout the scanning procedures and acquisition of the data volume. Figure 2.1 shows the positioning of the head phantom within the CBCT unit to simulate the patient positioning during CBCT scanning in routine clinical. In a single rotation, the region of interest (ROI) is scanned by using a cone-shaped x-ray beam around the vertical axis of the patient's head.

During the data acquisition, a complete 3D image data is acquired in a single breath-hold and a cone-shaped x-ray beam is used (Smith & Webb, 2011; Suryadevara et al., 2018). The development of the CBCT imaging was revolutionised in medical radiology since early 1970s, when the physicians were able to obtain high-quality tomographic (cross-sectional) images of internal structures over the body (Erzen, 2009). Tomography is imaging by sections. The word comes from the Greek word "tomos", which imply "a section", "a slice" or "a cutting.

Figure 2.1 Principle of operation of dental CBCT. (Hartshorne, 2018, www.fda.gov)

The three-dimensional (3D) data perhaps provides an improved image quality and diagnosis for a broad range of clinical applications, and usually at lower doses than with MDCT imaging. However, CBCT offers increased radiation doses to patients compared with conventional dental radiographic techniques. Nonetheless, whenever ionising radiation is used for clinical purposes, the fundamental principles of radiation protection must be applied and legal requirements recognised (Horner et al., 2009).

Digitised information of objects (digital signal) of the body structures are obtained from more than one angles. These imaging records are then processed by specialty software that subsequently constructs tomographic images of the ROI in multiple anatomic planes, particularly the well-known coronal, axial, and sagittal anatomic planes and their various para-planar derivatives, the parasagittal, para-coronal and para-axial planes (Abramovitch & Rice, 2014). The x-ray source and detector panel which rotate around patient head are either flat panel detector or image intensifier/CCD combination giving rise to many cephalometric exposures which are made in rapid succession as the machine rotates and this ach exposure is called a basis image. These set of basis images is called projection data. A complex mathematics creates a 3-D data set from the projection data. The 3-D data set divides the patient anatomy into small cubes called voxels. The surface of a voxel is called a pixel and the smaller the voxel, the better the image resolution. For a given size, the more pixels, the clearer the image (Miracle & Mukherji, 2009).

During a rotational scan of an object, more than one exposure is acquired at constant intervals (angles) of the rotation. Each of these exposures is referred to as a "foundation" or "basis" image (Abouei et al., 2015). The images are preferred as radiographic images captured on the detector, and the signal of each projection is special for each of the unique angles in the rotational arc. Instantaneously, the image information for every foundation image is sent to a data-storage location so that the detector can be cleared to capture the subsequent foundation image at a position interval further along the rotational arc. Once the rotation is complete and all the foundation images are made, the entire set of images forms the "projection data" (Abouei et al., 2015). The variety of images taken depends on the radiographer's preferences and the scanner's capability. The total number of images taken could range from 100 to 600 images per scan.

There are several associated factors that determine the image quality and radiation dose received by patient during CBCT imaging. The larger the number of scanned images, the longer the scan time, the larger the radiation dose, and the better the quality of the developed images. Although the time of exposure is normally controlled by the automatic exposure control system, however the exposure time is certainly based on the number of CBCT images, and the degree of spatial resolution requested in the voxel size. The smaller the voxel size and the longer the scanning range, the longer the exposure time needed. The most important difference in a CBCT exposure as compared to exposure of intraoral and panoramic imaging is that it’s exposure consists of capturing the sequence of multiple images.

Because of the CBCT principle is as of basis-image projection, the x-rays are not generated all through the complete rotational path. In most units, the exposure is pulsed at intervals so that there is time between basis-image acquisition for the signal to be transmitted from the detector area to the data storage location and the detector to rotate to the subsequent site or angle of exposure. Hence, the x-ray tube does not generate x-rays for the whole rotational cycle. These intervals may additionally can inherently minimise patient exposure throughout the exposure time in which the detector is not prepared to detect subsequent x-ray photons. These intervals are also helpful for the x-ray duty cycle, decreasing heat build-and prolong the tube lifetime.

In general, the longer the exposure time and the greater number of images produced, the longer it takes to complete the data acquisition in the rotational arc. This time for the images acquisition is regarded as the frame rate. For a shorter exposure, the rotational arc remains the same, however, the frame rate is reduced. In this situation where less images are taken, the radiation exposure is lesser, the rotational arc takes lesser time, and the scanner parts rotate faster.

2.4.2 Image reconstruction in CBCT

CBCT scanners use back-projection reconstructed tomography to acquire information of the area of interest through a single or partial rotation of the conical x-ray beam and reciprocal image receptor. CBCT provides detailed images of the bone and is performed to evaluate diseases of the jaw, dentition, bony structures of the face, nasal cavity, and sinuses. It does not provide the full diagnostic information available with conventional CT, particularly in evaluation of soft tissue structures such as muscles, lymph nodes, glands, and nerves. However, CBCT has the disadvantage of higher radiation exposure compared to conventional CT and one major determinant of radiation dose to the patients undergoing CBCT are the exposure settings (kV, mAs) (Andraws Yalda et al., 2019).

In anatomical imaging, x-ray CT is one of the clinical standards for all stages in the management of tumour patients, e.g., detection, characterization and staging of the lesion, control of therapeutic response and determination of recurrence (Moser et al., 2009). New applications are being explored to improve the image quality and to minimize the exposure of the patients to dangerous radiation dose. After patient positioning, a scout view will be acquired to affirm that the region of interest is within the FOV. This is because FOV is another major determinant of radiation dose in CBCT, and guidelines emphasizes the importance of using the tiniest FOV compatible with the clinical task. It is therefore reassuring to discover that the "smallest" or the "medium" FOVs were the most commonly used. This step is quite encouraged for small FOV scans to verify that the desired region is included, to avoid additional scans and exposing the patient to extra radiation (Diane & Regina, 2020).

Furthermore, image acquisition using cone-beam is very technically sensitive, and therefore, the patient’s head must remain still during image acquisition to avoid motion artefacts which can degrade the image quality (Bueno et al., 2018). Besides, metal artefacts are also the prominent problems for dental CBCT applications, as metallic restorations are often within the FOV of most dental CBCT scans (Abramovitch & Rice, 2014). The metallic restorations then cause the resultant beam hardening and streak artefact, which then compromises the image quality with the various areas of dark and light artefact.

Depending on the type of sensing element used, there are two cases of image reconstruction. The resulting 3D reconstruction can be spherical or cylindrical in appearance. The main clinical difference is the peripheral deformation experienced by the spherical reconstruction with a CCD/II detector. If a measurement is shuffle in the centre of the intensity, the measurement will be an accurate representation compared to a measurement made near the edges of the volume. The flat control panel detector does not experience this type of distortion; thus, accuracy in the measurement will be found in the centre of the volume as well as the edges of the volume (Diane & Regina, 2020).

However, it must be noted that CBCT examinations must not be carried out unless a history and clinical examination have been performed and these examinations must be justified and potentially add new information to aid the patient’s management for each patient in order to demonstrate that the benefits outweigh the risks and should not be repeated ‘‘routinely’’ on a patient without a new risk/benefit assessment been performed. Also, this equipment should offer a choice of volume sizes and examinations must use the smallest size that is compatible with the clinical situation if it provides less radiation dose to the patient. Where the CBCT equipment offers a choice of resolution,