From Pixels to Precision: Evolving Radiological Approaches in Head and Neck Imaging

Dr. Surekha S[1], Dr. Nandhini Ganesan[2], Dr. Saraswathi K. Gopal[3]

[1]Post Graduate Student, Department of Oral Medicine and Radiology, Meenakshi Ammal Dental College and Hospital, Chennai, Tamil nadu, India
Corresponding Author Email: *mailtosurekha21[at]gmail.com*
[2]Associate Professor, Department of Oral Medicine & Radiology, Faculty of Dentistry, Meenakshi Ammal Dental College & Hospital, Meenakshi Academy of Higher Education Research Institute, Chennai – 600095
[3]MDS., Head & Professor, Department of Oral Medicine & Radiology, Faculty of Dentistry, Meenakshi Ammal Dental College & Hospital, Meenakshi Academy of Higher Education Research Institute, Chennai – 600095

Abstract: ***Advanced radiological imaging has greatly enhanced the evaluation and management of head and neck lesions. Given the anatomical complexity of this region, traditional imaging methods often lack the detail necessary for accurate diagnosis. Modern modalities such as computed tomography (CT), cone-beam CT (CBCT), magnetic resonance imaging (MRI), and nuclear imaging techniques like positron emission tomography (PET), single-photon emission computed tomography (SPECT), and hybrid combinations (e.g., PET/CT, PET/MRI, SPECT/CT) offer superior anatomical and functional information. CT and CBCT provide high-resolution images of bony structures, while MRI excels in soft tissue evaluation without radiation exposure. Nuclear imaging techniques contribute metabolic and physiological insights, especially useful in cancer detection and monitoring. Hybrid imaging fuses structural and functional data, improving lesion localization, staging, and post-treatment assessment. These advancements allow clinicians to detect disease earlier, differentiate between benign and malignant lesions, and plan more targeted treatments. The integration of artificial intelligence and 3D reconstruction further improves diagnostic precision and efficiency. This review highlights how advanced imaging modalities play a critical role in enhancing diagnostic accuracy, guiding therapy, and improving outcomes in head and neck pathology.***

Keywords: Advanced, Oral lesions, Diagnosis

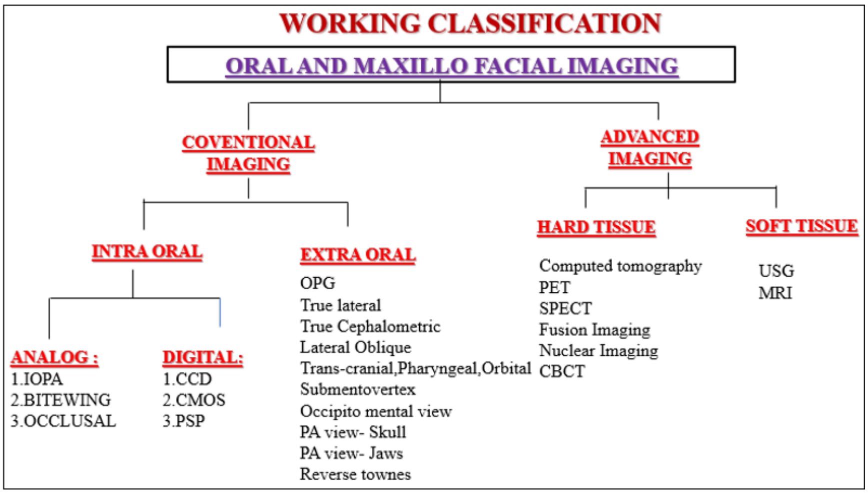
Abbreviation: CT- Computed Tomography, PET- Positron Emission Tomography, SPECT- Single-Photon Emission Computed Tomography, SPECT – Cone Beam Computed Tomography, MRI -Magnetic Resonance Imaging

1. Introduction

Dental and maxillofacial radiology has undergone significant advancement since Wilhelm Conrad Röntgen's discovery of X-rays in 1895, becoming integral to the diagnosis of head and neck pathologies (1). Radiographic techniques enable the evaluation of both hard and soft tissues with increasing precision and reduced patient morbidity (2). Recent years have seen a transformative shift with the adoption of advanced imaging modalities, particularly cone-beam computed tomography (CBCT), which offers three-dimensional (3D) imaging at lower radiation doses than conventional CT (9). CBCT facilitates precise evaluation of impacted teeth, osseous lesions, TMJ disorders, and pre-implant planning (10). Other imaging modalities, including multidetector CT (MDCT), magnetic resonance imaging (MRI), ultrasound (US), and nuclear imaging (NI), are increasingly employed in complex or soft tissue-dominant lesions, offering superior anatomical and functional information when used alongside conventional radiographs (3).

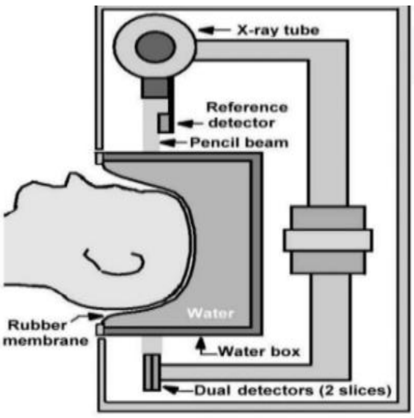
The integration of digital and advanced imaging technologies has substantially enhanced diagnostic accuracy and clinical decision-making in dental and maxillofacial practice. This review aims to explore contemporary radiological modalities used in the assessment of head and neck lesions, highlighting their indications, benefits, and limitations.

2. Working Classification



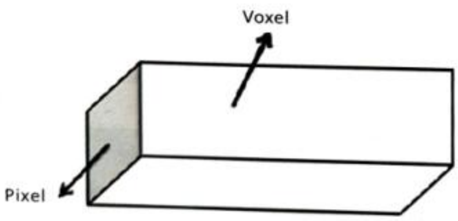
3. Computed Tomography

Computed Tomography (CT) is an advanced imaging technique that utilizes X-rays to generate cross-sectional views or "slices" of the body. These images are constructed by measuring how X-ray beams are attenuated as they pass through different tissues. This data is then mathematically processed to create detailed internal images. Introduced in 1972 by Godfrey Hounsfield, CT scanning involves positioning the patient supine on a motorized table that gradually moves through a rotating gantry.



As the gantry completes a 360° rotation around the patient, multiple projections are captured by detectors. These analog signals are digitized and processed by computer software to calculate the linear attenuation values of each pixel within the scanned volume. [4]

These values are then converted into CT numbers (Hounsfield Units), ranging from approximately -1000 (representing air) to +1000 (representing dense structures such as bone), enabling display of anatomical structures in varying shades of gray.[5]



Working Principle:

A CT (Computed Tomography) scanner works by directing X-rays toward the patient's body. As these X-rays pass through the body, some are absorbed by tissues, while others continue through and reach detectors placed on the opposite side. The amount of X-ray absorption, known as attenuation, varies depending on the density and type of tissue denser materials like bone absorb more X-rays, whereas less dense substances like air absorb less.

The detectors measure the intensity of the X-rays that pass through the body. These measurements reflect how much radiation was absorbed along each path. The data is then processed and stored as two-dimensional pixels and three-dimensional voxels, each representing a specific point or volume in the scanned area. Every pixel or voxel is assigned a value based on how much attenuation occurred, and these values are used to calculate linear attenuation coefficients.

These coefficients are converted into CT numbers, also called Hounsfield Units (HU), which range from around -1000 for air to +1000 for very dense bone. The CT system then reconstructs the scanned region into a digital image using these numbers. To make the image easier to interpret, a process called **windowing** is used to assign shades of gray to different CT number ranges, helping to clearly differentiate various tissues such as bone, soft tissue, and air.

Types of Windows

1) **Soft Tissue Window**:
- Muscle, skin, salivary glands, and vessels appear in gray tones.
- Bone appears white; fat and air appear black.

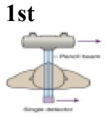
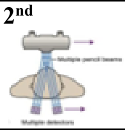
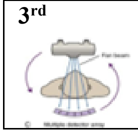
2) **Hard Tissue (Bone) Window:**
- Bone is shown in high contrast (white).
- Soft tissues appear less distinct and in uniform gray.

Use **hard tissue window** for assessing bone lesions.

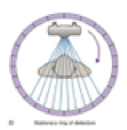
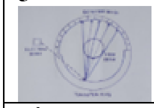
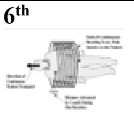
Use **soft tissue window** for analyzing glands, muscles, or soft tissue pathology.

Multiple 2D slices are processed using **interpolation algorithms** to reconstruct a **3D image** for comprehensive visualization.[6]

There are seven generation in CT as follows [4,6]:

Generation	Beam Type	Detector Type	Motion Type	Scan Time	Key Features	Disadvantages
1st 	Pencil beam (1°)	Single detector	Translate / Rotate	25–30 minutes	High geometric precision	Very slow, poor resolution
2nd 	Narrow fan beam (10°)	Linear array (~30 detectors)	Translate / Rotate	~18 seconds (per slice)	Faster than 1st gen, some image improvement	Still slow, scattered radiation, limited resolution
3rd 	Wide fan beam (40–60°)	Large curved array (>800 detectors)	Rotate / Rotate	~1–2 seconds	Covers entire slice, no translation needed, much faster	Detector calibration errors → ring artifacts

Paper ID: SR26421191510 DOI: https://dx.doi.org/10.21275/SR26421191510

4th 	Fan beam	Full circular stationary detector ring	Rotate / Stationary	Faster than 3rd gen	Eliminates detector drift, improved reliability	Only 1/4 of detectors used at a time, high scatter sensitivity
5th 	Electron beam	Stationary circular detector ring	Stationary / Stationary	<100 microseconds	Ultrafast scanning, suitable for dynamic imaging (e.g., heart motion)	Very expensive, limited application
6th 	Helical fan beam	Rotating detectors with slip ring	Continuous Helical Scan	Single breath-hold (10–30 s)	Continuous scanning, 3D data acquisition, faster throughput	Data interpolation needed (no true full slice)
7th 	Cone beam	Flat panel / multidetector array	Continuous	Very fast (subsecond)	High efficiency, superior spatial resolution, more data per rotation	Complex reconstruction, more scatter, dose considerations

Interpretation:
- Hyperdense- Tissues with high density – Appears white and bright Eg: Bones
- Isodense – Have the density as the surrounding structures and appear grey Eg:Muscles
- Hypodense – Tissue with less density ,appear dark, black Eg,Water

Ultrasonography:
Ultrasound, also known as **sonography**, is a widely used medical imaging technique that relies on **high-frequency sound waves** to visualize internal organs, tissues, and blood flow. It is a safe, non-invasive method that does not involve ionizing radiation, making it suitable for a wide range of diagnostic and therapeutic applications[7].

Types of Ultrasound Probes and Their Clinical Applications [8]

1) **Convex (Curvilinear) Probe**
   - Ideal for scanning **abdominal organs** and other **deep anatomical structures**.
   - Frequently employed in emergency settings for **FAST (Focused Assessment with Sonography in Trauma)** scans.
   - Offers a wider field of view suitable for internal organs.
2) **Linear Probe**
   - Designed for **superficial structures** such as tendons, muscles, and small vessels.
   - Commonly used in **vascular imaging** and for **guiding needles** during interventions.
   - Provides **high-resolution images** of shallow regions due to its high frequency.
3) **Phased Array Probe**
   - Specially designed for **cardiac imaging**, including **trans-thoracic echocardiography**.
   - Provides excellent imaging at various depths using a **narrow footprint**.
   - Capable of imaging in areas with limited acoustic windows like between the ribs.

The process begins when an electric signal is transmitted to the transducer. The transducer then converts this electrical energy into high-frequency sound waves, typically ranging between 1 to 5 mhz. These sound waves are directed into the body, where they interact with various tissues and organs. Some of the waves are reflected back toward the transducer, some are absorbed by the tissues, and others continue deeper into the body. The reflected sound waves are picked up again by the transducer, which then converts them back into electrical signals. These signals are sent to a receiver, which forwards the data to a processor. The processor analyzes the differences between the original and returning signals to determine the properties of the tissues they encountered. Based on this information, an image is generated and displayed on the monitor, allowing real-time visualization of internal structures.

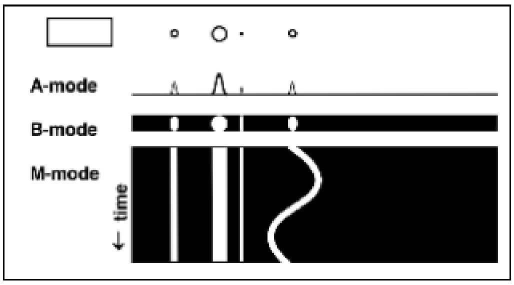
Ultrasound Classifications
Ultrasound can be broadly categorized into two main types[9]:

1) **Diagnostic Ultrasound**
A non-invasive method used to **visualize internal body structures** by emitting sound waves above the human hearing range, typically in the **megahertz (MHz)** frequency. It is further subdivided into:
- **Anatomical Ultrasound**: Captures images of body organs and structures to aid in anatomical assessment.
- **Functional Ultrasound**: Supplements anatomical imaging by providing additional data on **blood flow**, **tissue movement**, **elasticity**, and **velocity**, resulting in informative diagnostic "maps".

2) **Therapeutic Ultrasound**
This modality uses **high-frequency sound waves** for **treatment rather than imaging**. It modifies tissues through:
- **Mechanical movement** of tissue
- **Thermal effects** (heating targeted areas)
- **Clot dissolution**
- **Targeted delivery** of medications
- **Tissue ablation**, such as destroying abnormal growths or tumors using **focused high-intensity beams**

Therapeutic ultrasound is largely **non-invasive**, with the benefit of avoiding surgical wounds, cuts, or scarring.

Ultrasound imaging can be presented in several display formats based on the diagnostic need[10]:

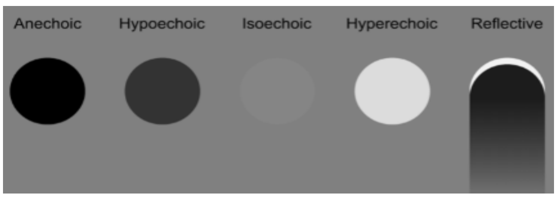


a) **A-Mode (Amplitude Mode)**: One-dimensional display, used primarily in **ophthalmology** to measure internal eye structures.
b) **B-Mode (Brightness Mode)**: Produces **two-dimensional black-and-white images**; the most commonly used imaging mode.
c) **Gray Scale Imaging**: Enhances contrast in **B-mode** imaging for clearer visualization.
d) **M-Mode (Motion Mode)**: Records **movement of structures** over time, commonly used in **cardiac imaging**.
e) **D-Mode (Doppler Mode)**:
   - **Color Doppler**: Visualizes **blood flow direction and velocity** using color overlays.
   - **Spectral Doppler**: Displays **blood flow velocity** as a waveform graph.
   - **Duplex Imaging**: Combines **color Doppler** and **spectral Doppler** for comprehensive vascular evaluation.[11]

f) 3D and 4D Ultrasound:
   - **3D**: Generates volumetric images of anatomical structures.
   - **4D**: Adds real-time motion to 3D imaging, useful in obstetrics and fetal monitoring[12].

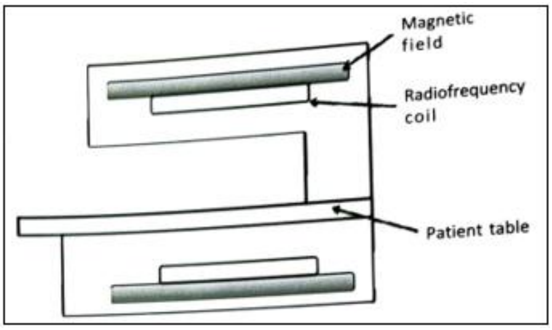
Interpretation:

Hyperechoic means the structure reflects a lot of sound, and so appears bright (e.g. bone, cartilage, fat)., **Hypoechoic** means the structure reflects some sound, and so appears grey (e.g. muscle), **Anechoic** means the structure reflects no sound, and so appears black (e.g. fluid).



Magnetic Resonance Imaging:

Magnetic Resonance Imaging (MRI) is a non-invasive diagnostic tool that generates highly detailed images of the body's internal structures, including organs, bones, soft tissues, muscles, and blood vessels. Unlike CT or X-rays, MRI does not use ionizing radiation; instead, it employs **strong magnetic fields and radiofrequency waves** to visualize internal anatomy with excellent soft tissue contrast[13]. MRI was first introduced into clinical practice around **1980**, revolutionizing diagnostic radiology[14].



Working Principle:

Human body is largely made up of cells that contain water (H_2O), and each water molecule includes hydrogen atoms. These hydrogen atoms have protons, which are positively charged particles with a property called magnetic spin. In MRI imaging, a powerful magnetic field is generated by the scanner, causing the hydrogen protons in the body to align in the direction of the field. The scanner then briefly alters the strength or direction of this magnetic field, disturbing the alignment of the protons. As the protons respond to these changes, they emit signals that vary depending on the type of tissue they are in. Once the magnetic field is turned off, the protons gradually return to their original alignment a process known as relaxation. Different tissues relax at different rates based on their molecular composition. For instance, muscle, fat, and fluid each emit distinct signals due to their unique relaxation times. These differences enable the MRI system to construct highly detailed, high-contrast images that clearly distinguish between various soft tissues within the body.

Understanding MRI Signal Properties

MRI relies on the behavior of hydrogen protons when placed in a magnetic field. When exposed to a radiofrequency (RF) pulse, these protons are disturbed and then relax back to their original alignment. This relaxation process is characterized by two key parameters [15]:

- **T1 Relaxation Time**: Refers to the time it takes for protons to realign with the external magnetic field after being disturbed. Tissues with a short T1 relaxation time, such as **fat**, realign quickly and appear bright on **T1-weighted images**.
- **T2 Relaxation Time**: Represents how quickly the protons lose synchronization (dephase) with one another after the RF pulse is turned off. Tissues containing **water or fluid** have a long T2 time and appear bright on **T2-weighted images**. [16]

Contrast-enhanced MRI (CE-MRI)[17] is an advanced imaging technique used to improve the visibility of internal tissues and structures, providing greater detail for diagnostic purposes. It involves the intravenous administration of gadolinium-based contrast agents, which temporarily alter the magnetic behavior of nearby tissues. This change enhances the contrast on MRI images, making certain areas appear either brighter or darker depending on the imaging sequence used. CE-MRI is especially useful for evaluating soft tissues, organs, and the brain, and is commonly employed in the diagnosis of tumors, vascular disorders, and inflammatory conditions, offering improved accuracy and clinical insight compared to standard MRI.

Interpretation:
- Hyperintense structures - Appear white and bright
- Isointense - Appear grey
- Hypointense-Appear dark, black and produce a weak Signal

Contraindications of MRI
- Implanted devices and other metallic devices
- Intraocular metallic foreign bodies
- Unstable patients
- Pregnancy
- Severe agitation
- Claustrophobia (may require anesthesia assistance)

Nuclear Medicine:

Nuclear medicine is a specialized branch of medical imaging and treatment that employs small amounts of radioactive substances, known as radiopharmaceuticals, for the **diagnosis and management of various diseases**. It is broadly divided into two categories: **diagnostic** and **therapeutic** applications[18].

Diagnostic Nuclear Medicine

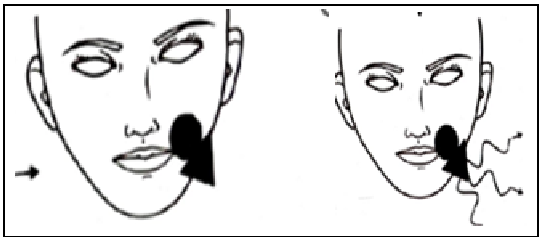
Diagnostic nuclear medicine primarily involves imaging techniques that assess the function and metabolism of specific organs. This is achieved by introducing radiopharmaceuticals into the body usually by intravenous injection, though oral and other routes may also be used depending on the clinical requirement. Once administered, the radioactive tracer accumulates in the target organ and emits **gamma radiation**, which is captured using a **gamma camera**. The captured signals are then processed to create two-dimensional or three-dimensional images of the organ being studied. The level of tracer uptake reflects the **metabolic activity or function** of that particular organ.

One of the widely used diagnostic methods is **scintigraphy**, which gets its name from the "scintillator" crystals within the gamma camera that detect gamma rays. In this procedure, radiopharmaceuticals like **technetium-99m (99mTc)** or **thallium-201 (201Tl)** are used. These isotopes emit gamma rays as they decay, and the emitted radiation is visualized to produce functional images of organs. Scintigraphy is commonly used to assess the **salivary glands** and **skeletal system**.

The process typically involves[19]:

In nuclear medicine imaging, the process begins with the binding of a radionuclide- such as technetium-99m to a radiopharmaceutical that is designed to target a specific organ. For example, pertechnetate is used for imaging salivary glands, while diphosphonates are used for bone scans. Once the radiopharmaceutical is prepared, it is administered intravenously into the patient's bloodstream. As the compound circulates, it selectively accumulates in the target organ based on the biological affinity of the tracer. The radionuclide then emits gamma rays from within the body. These emissions are detected by a gamma camera positioned outside the patient. The gamma camera captures the radiation and sends the data to a computer system, which processes the signals to reconstruct detailed diagnostic images. These images provide valuable functional information about the organ in question, aiding in accurate diagnosis and evaluation.

In **salivary gland scintigraphy**, three distinct imaging phases are observed:
1) **Flow Phase (15–20 seconds)**: Represents initial vascular perfusion and early tracer accumulation in the salivary glands.
2) **Uptake Phase**: Shows active transport and concentration of the tracer within the gland. Normally, tracer presence is observed in the oral cavity around 10–15 minutes post-injection.
3) **Excretory (Washout) Phase**: The patient is stimulated (usually with a lemon drop or citric acid), and normal glands promptly release the tracer. Delayed or incomplete washout may indicate gland dysfunction, blockage, or inflammation[20].



Therapeutic Nuclear Medicine[21]

Therapeutic applications involve the use of **radioactive isotopes** to treat diseases, particularly in the field of oncology. A commonly used therapeutic radionuclide is **iodine-131**, administered in the form of **sodium iodide**. This treatment is used to selectively destroy abnormal or malignant tissues such as in **thyroid cancer**, **hyperthyroidism**, or to **shrink tumors** and relieve **cancer-related pain**.

In therapeutic nuclear medicine, the goal is not imaging, but rather the **targeted destruction or modulation of pathological tissue**. It has emerged as a promising alternative to conventional therapies in oncology due to its ability to deliver treatment directly to diseased cells with minimal impact on surrounding healthy tissues.

PET and SPECT are nuclear medicine imaging techniques that utilize radioactive tracers to visualize and assess the function of organs and tissues within the body. Although both methods rely on detecting gamma rays emitted by these tracers, they differ in how the data is captured and processed.

Fusion/ Hybrid Imaging (PET/CT, PET/MRI, and SPECT/CT)

Traditional nuclear medicine imaging techniques offer valuable functional and molecular data but are limited by relatively poor spatial resolution, which can make pinpointing the precise anatomical location of pathology challenging. To address this limitation, **hybrid or fusion imaging** techniques have been developed by combining the metabolic insights of PET or SPECT with the detailed anatomical resolution provided by CT or MRI. These integrated modalities—such as **PET/CT**, **PET/MRI**, and

SPECT/CT- allow for the simultaneous acquisition and **registration of functional and structural information**, significantly improving diagnostic accuracy [23].

4. Conclusion

The advent of advanced radiological techniques has revolutionized the landscape of oral disease diagnosis, treatment planning, and post-treatment monitoring. Imaging modalities such as computed tomography (CT), magnetic resonance imaging (MRI), and nuclear medicine techniques provide unparalleled anatomical clarity, superior soft tissue contrast, and valuable functional data, offering a distinct advantage over traditional imaging methods. These technologies empower clinicians to identify pathological changes at earlier stages, accurately distinguish between benign and malignant lesions, and tailor targeted, minimally invasive interventions. Furthermore, the integration of multi-modality imaging approaches and artificial intelligence driven diagnostic tools is rapidly advancing the precision, speed, and reliability of oral healthcare delivery.

References

[1] White SC, Pharoah MJ. Oral Radiology: Principles and Interpretation. 8th ed. Elsevier; 2020.
[2] Koong B. Contemporary diagnostic imaging for the general dental practitioner. Aust Dent J. 2005;50(3 Suppl):S15–S22.
[3] Mah JK, Danforth RA, Bumann A, Hatcher D. Radiation absorbed in maxillofacial imaging with a new dental computed tomography device. Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology. 2003 Oct 1;96(4):508-13.
[4] Mahesh M. The essential physics of medical imaging. Medical physics. 2013 Jul;40(7):077301.
[5] Hounsfield GN. Computerized transverse axial scanning (tomography): Part 1. Description of system. The British journal of radiology. 1973 Dec 1;46(552):1016-22.
[6] Kalender WA. Computed tomography: fundamentals, system technology, image quality, applications. John Wiley & Sons; 2011 Jul 7.
[7] Hoskins P, Martin K, Thrush A, editors. Diagnostic ultrasound: physics and equipment. CRC Press; 2019 Apr 29.
[8] Hertzberg BS, Middleton WD. Ultrasound: the requisites. Elsevier Health Sciences; 2015 Jul 17.
[9] Kennedy JE. High-intensity focused ultrasound in the treatment of solid tumours. Nature reviews cancer. 2005 Apr 1;5(4):321-7.
[10] Kremkau FW. Sonography principles and instruments. Elsevier Health Sciences; 2015 Nov 6.
[11] Evans DH. Doppler ultrasound: Physics, instrumentation, and clinical applications. (No Title). 1989 Mar 27.
[12] Merz E, Abramowicz JS. 3D/4D ultrasound in prenatal diagnosis: is it time for routine use? Clinical obstetrics and gynecology. 2012 Mar 1;55(1):336-51.
[13] McKillop G. Clinical Magnetic Resonance Imaging, RR Edelman, JR Hesselink, MB Zlatkin, JV Crues III (Eds.) (2006), Hardback. £ 265.00., ISBN: 0721603068.
[14] Aydingöz Ü. The Nobel Prize in Medicine for 2003 goes to magnetic resonance imaging. Turkish Journal of Medical Sciences. 2003;33(6):345-6.
[15] Houser T. Assessment of Magnetic Resonance Imaging Safety: Allied Health Professional Clinical Competence (Master's thesis, East Tennessee State University).
[16] Haacke EM. Magnetic resonance imaging: physical principles and sequence design. (No Title). 1999 May.
[17] Runge VM, editor. Contrast media in magnetic resonance imaging: a clinical approach. Lippincott; 1992.
[18] Cherry SR, Sorenson JA, Phelps ME. Physics in nuclear medicine. Saunders; 2013 Jul.
[19] Habibian MR, Delbeke D, Martin WH, Sandler MP, Vitola JV. Nuclear medicine imaging: a teaching file. Lippincott Williams & Wilkins; 2012 Oct 9.
[20] Chen YC, Chen HY, Hsu CH. Recent advances in salivary scintigraphic evaluation of salivary gland function. Diagnostics. 2021 Jun 28;11(7):1173.
[21] Habibian MR, Delbeke D, Martin WH, Sandler MP, Vitola JV. Nuclear medicine imaging: a teaching file. Lippincott Williams & Wilkins; 2012 Oct 9.
[22] Sekine T. PET in the Diagnosis of Head and Neck Cancer. Diagnostic Imaging in Head and Neck Cancer. 2020:187-221.
[23] Wernick MN, Aarsvold JN. Emission tomography: the fundamentals of PET and SPECT. Elsevier; 2004 Dec 7.
[24] Kanis JA, Johnell O, Odén A, Johansson H, McCloskey EF. FRAX™ and the assessment of fracture probability in men and women from the UK. Osteoporosis international. 2008 Apr;19:385-97.
[25] Blake GM, Fogelman I. The role of DXA bone density scans in the diagnosis and treatment of osteoporosis. Postgraduate medical journal. 2007 Aug;83(982):509-17.