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Advances in Diagnostic Imaging for Pathologic Conditions of the Jaws

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Abstract Advances in dental and maxillofacial imaging are delineated along with the advantages and disadvantages of each imaging modality. The imaging modalities that are included are intraoral radiography, panoramic radiography, cone-beam computed tomography, multidetector computed tomography, magnetic resonance imaging, nuclear medicine, and ultrasound.

Keywords Imaging · Radiology · Dental · Maxillofacial · Advances · Diagnostic

Dental and maxillofacial imaging applications began within weeks of Wilhelm Conrad Roentgen's discovery of X-rays in 1895. Since then, the use of advanced diagnostic imaging modalities in managing patients with dental and maxillofacial pathoses has expanded dramatically, especially in the last decade. From a radiological perspective, most pathologic lesions of the jaws are initially visualized with intraoral radiography, panoramic radiography, or cone-beam computed tomography (CBCT) simply because of the availability of these modalities in dental settings. Significant advances in these three imaging modalities are noted almost annually. Other advanced modalities used to diagnose and manage pathologic conditions of the jaws such as multidetector computed tomography (CT), magnetic resonance (MR), nuclear medicine (NM), and ultrasound (US) have also experienced significant advances.

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Dedicated Dental and Maxillofacial Imaging Modalities

Intraoral and panoramic radiography, in addition to dental cone-beam computed tomography, are typically based in individual dental offices or are relatively easily accessed from dental and maxillofacial imaging centers. These systems are specifically designed for dental and maxillofacial applications.

Intraoral Radiography

Digital imaging has revolutionized existing intraoral and panoramic radiography. From a diagnostic perspective, digital imaging allows postprocessing of the image to enhance details for specific diagnostic inquiries (dental caries, inflammatory lesions, cortical vs. medullary osseous lesions; Fig. 1). However, judicious use of enhancement algorithms is paramount since artifacts can mimic pathosis and result in an incorrect diagnosis [1]. Digital imaging may also decrease radiation exposure and associated health risks compared to analog radiographic film techniques. When highest spatial resolution is required, intraoral radiography remains the modality of choice [2]. Computer-assisted diagnostic programs, such as Logicon (Carestream Dental; Atlanta, GA, USA) for dental caries, have been introduced to assist the clinician in diagnosing specific pathoses [3]. Advantages of digital intraoral imaging are availability, relatively low cost, low relative radiation risk, high image spatial resolution, wide availability, ease of

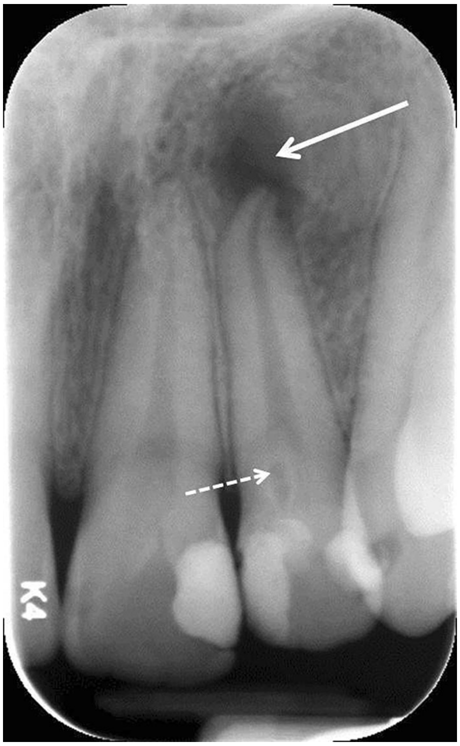

Fig. 1 Intraoral periapical radiograph. A relatively well-defined periapical inflammatory lesion is present on the lateral incisor (*solid arrow*). The high resolution of this modality is adequate to depict the lack of lamina dura at the apex of the involved tooth. The differential diagnosis of a periapical inflammatory lesion is granuloma, inflammatory cyst, or abscess. Note the invagination referred to as dens in dente (*dashed arrow*) in the same tooth; dens in dente often results in a periapical inflammatory lesion

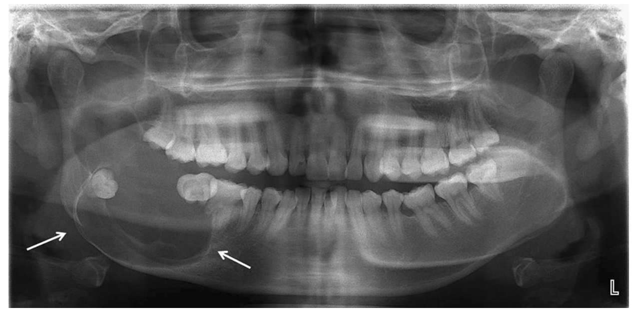

Fig. 2 Panoramic radiograph. A large, expansile, well-defined, corticated, radiolucent lesion is visualized in the right mandibular body and ramus (*arrows*). The right second and third molars are displaced and external dental root resorption is noted on the mandibular right first molar. The histopathologically confirmed diagnosis was ameloblastoma

data transferability using DICOM algorithms, and post-processing algorithms to enhance interpretation. Disadvantages include lack of 3D visualization, limited field of view, and the necessity of superior acquisition technical skills especially when using solid-state image receptors. Advances include thinner digital sensors, larger active image areas, and improved software design, which includes computer-assisted diagnosis.

Panoramic Radiography

Panoramic radiographs are an excellent initial imaging investigation for most maxillofacial pathologic lesions (Fig. 2) and may indeed be the only imaging modality needed in some cases. This imaging modality, with its curved tomographic image layer, is widely available and has a larger field of view than intraoral radiographs; however the spatial resolution is not as optimal as intraoral imaging. Positioning the patient for panoramic radiography is technically sensitive and is the cause of most reacquisitions [4]. Interpretation of panoramic images may sometimes be challenging, as this imaging modality creates a single flat image from the complex 3D anatomy of the maxillofacial structures (e.g. the nasal turbinates, which are anatomically oriented in an anteroposterior position are imaged as horizontal entities spread laterally across the panoramic radiograph) [5]. Advantages of digital panoramic imaging are availability, relatively low cost, low relative radiation risk, moderately broad field of view, ease of data transferability using DICOM algorithms, and postprocessing algorithms to enhance interpretation. Disadvantages include reduced spatial resolution compared to intraoral radiography, somewhat thick image layer, image distortion, and phantom (ghost) images [6]. Recent advancements include automatic exposure control and the innovative new feature of the multifocal image layer. Based on tomosynthesis, multifocal image layers allow the operator to correct some common positioning errors after the image is acquired [7]. Multifocal layers are particularly helpful in imaging patients with asymmetry, whether from tumor growth, swelling, or developmental anomalies.

Cone-beam Computed Tomography (CBCT)

CBCT, also termed cone-beam volumetric tomography or cone-beam volumetric imaging, has impacted dental practice in the most significant manner since panoramic radiography. While this modality is used in many other areas of medicine, its dental application has been paradigm-changing. It provides 2D and 3D evaluation of hard tissue structures, as well as medical modeling and computer-assisted "virtual" treatment planning. CBCT provides many of the benefits of CT bone-window imaging at less cost and ionizing radiation risk. It is most effective for imaging intraosseous and calcified lesions of soft tissue (Figs. 3, 4, 5, 6, 7, 8, 9, 10). CBCT does visualize soft tissue; however discrimination between different types of soft tissue is not predictable [8]. CBCT is increasingly

Fig. 3 Coronal CBCT. Same patient as Fig. 2 with diagnosis of ameloblastoma. Cortical expansion and tooth displacement are noted (*arrows*)

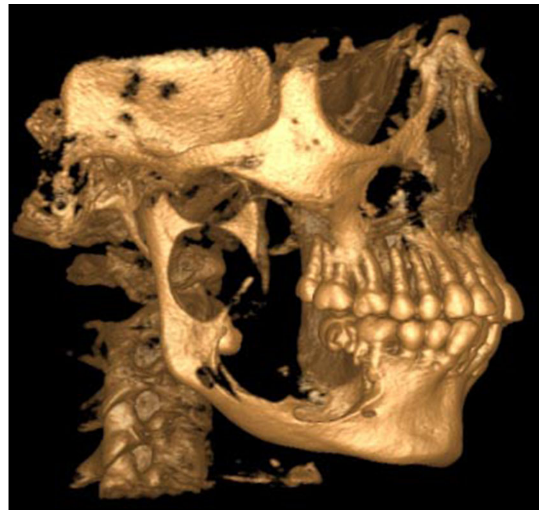

Fig. 4 CBCT 3D rendering. Same patient as Fig. 2 with a diagnosis of ameloblastoma. The cortical borders of the lesion appear perforated due to voxel averaging error in rendering the 3D image

available in private dental practices as well as free-standing imaging centers. The multiplanar reformatted (MPR) 2D images are the basis of most interpretation. Specific areas of interest can be further interrogated with linear or curved image layers, changing the slice widths (limited by the acquisition voxel size), proper application of filters, and selection of appropriate window level and width. Pseudopanoramic and 3D renderings are typically used only as orientation visualizations as they can contain artifacts that mimic pathologic lesions and trauma due to the reconstruction algorithms [9] (Fig. 4). High spatial resolution limited field of view CBCT studies are well adapted to assess individual teeth for fractures and periapical inflammatory lesions. CBCT is also appropriate for soft tissue pathoses that do not require differentiation, such as paranasal sinus disease and airway assessment for sleep apnea. Most CBCT software programs provide tissue density interrogation measured in Hounsfield units (HU), similar to multidetector computed tomography. However, the HU values in CBCT are not calibrated to a tissue density standard and cannot be used to definitively determine tissue type as with CT [10, 11]. Scatter artifacts are often generated from metallic materials and densely radiopaque materials (i.e., dental restorations, surgical plates and screws, some endodontic obturation materials), however only minimal scatter artifact is experienced with dental implants [12]. Advantages of CBCT include generally lower radiation risk compared to multidetector computed tomography, moderate acquisition cost, short acquisition time, excellent bone window renderings, ease of reformatting data volume in multiple 2D planes as well as 3D renderings, moderate accessibility, and ease of data transferability using DICOM algorithms. Disadvantages include greater cost than intraoral and panoramic radiography, moderate accessibility, scatter artifacts from metallic and some endodontic obturation materials, lack of calibrated soft tissue density measurement, and greater radiation risk compared to panoramic radiography depending on the CBCT image acquisition protocol used. Advances include higher spatial resolution, small field-of-view imaging studies, shorter acquisition and reformatting times, further decreases in radiation risk, broader dynamic range through the more common use of flat-panel image receptors, and improved interactive software programs [8, 13].

Fig. 5 Coronal CBCT. Expansile mixed tumor of right mandible with classic "ground glass" trabecular appearance and no displacement of the mandibular canal (*arrows*). The histopathologically confirmed diagnosis was fibrous dysplasia

Fig. 6 Coronal CBCT. Ethmomaxillary sinusitis with opacification and likely obstruction of the right maxillary sinus (*solid arrows*). Fluid accumulation is noted in the left maxillary sinus (*dashed arrow*). Hyperplasia of the left nasal turbinates (rhinitis) is also present (*dotted arrows*). Note thickening of the medial wall and floor of the left maxillary sinus (neo-osteogenesis), which is a diagnostic feature of chronic sinusitis. Horizontal scatter artifact from metallic dental restorations is apparent in lower portion of the image

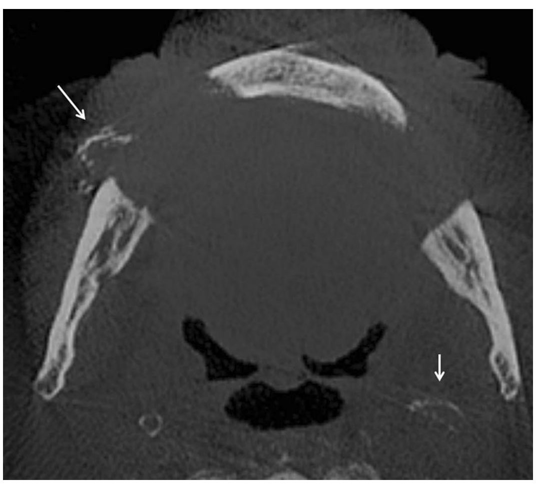

Fig. 7 Axial CBCT. "Pipeline" or "tram" appearance of a calcified facial artery is present (*arrows*). The radiographic impression is Mönckeberg medial calcific sclerosis (arteriosclerosis)

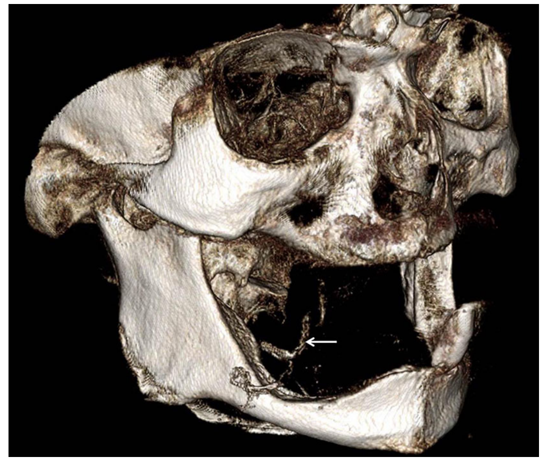

Fig. 8 CBCT 3D rendering. Same patient as Fig. 7. A calcified facial artery is visualized buccal, superior, and lingual to the adjacent mandible (*arrow*). Mönckeberg medial calcific sclerosis has been associated with occlusive or peripheral vascular disease, Sturge-Weber syndrome, and metastatic calcification in hyperparathyroidism

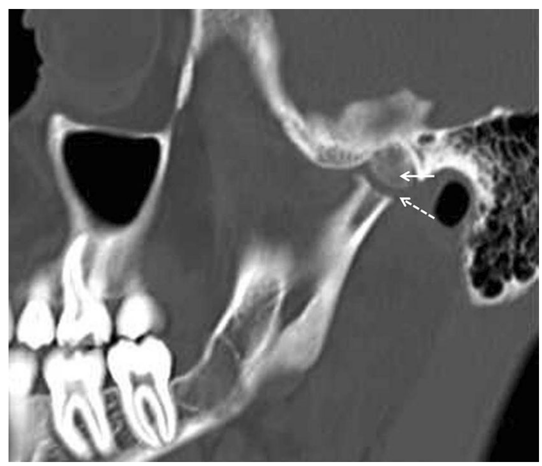

Fig. 9 Sagittal CT in bone window. An osseous mass extends from the temporal bone into the glenoid fossa (*solid arrow*). This section is through the lateral portion of the lesion making it appear as though a displaced fracture is present (*dashed arrow*). The radiographic impression and histopathologic diagnosis was osteochondroma

Other Advanced Imaging Modalities with Maxillofacial Applications

Multi-slice Computed Tomography (CT)

CT acquires an image volume as the X-ray source revolves in a helical pattern around the region of interest. While bone-window CT studies are comparable to CBCT studies, CT has less signal-to-noise ratios, resulting in higher image quality [6]. Soft-tissue window CT allows the discrimination of soft tissue structures of only slightly different densities, as well as accurate assessment of tissue density calibrated in Hounsfield units (−1,000 HU for air, 0 HU for water, +1,000 HU for cortical bone) [6]. Thus, a focus of interest on the image may be interrogated to determine tissue type (i.e., 700–3,000 HU for bone, 40–80 HU for soft tissue, 30–45 for blood, −60 to −100 for fat, and −4 to −600 for aerated lung). Intravenous contrast agents may be employed during CT acquisition to enhance soft tissue and

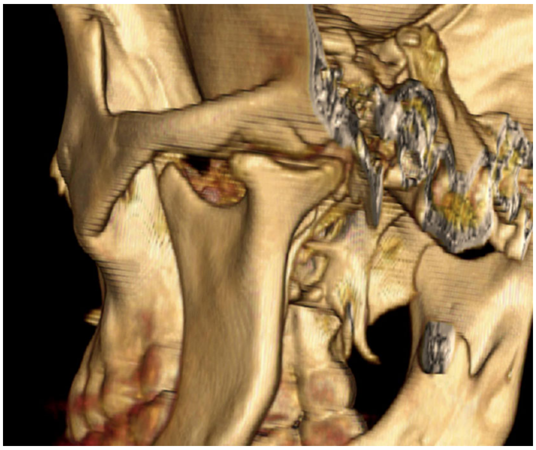

Fig. 10 CT 3D rendering. Same patient as Fig. 9. This rendering depicts the morphology of the osteochondroma in all three dimensions

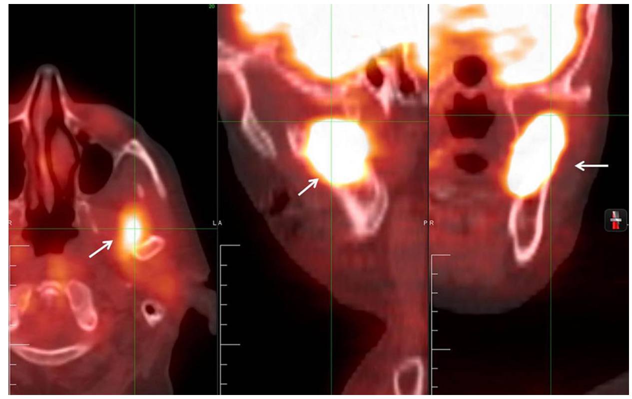

Fig. 11 Fused PET/CT study. These axial, sagittal, and coronal (*from left to right*) images combine the sensitivity of PET with the specificity of CT. The high signal suggest active bone metabolism, a condylar fracture in this case (*arrows*)

vascular image details. Many pathologic entities will be considerably more conspicuous with contrast material. In addition, contrast administration in CT is an essential ingredient for frequently performed CT angiographic examinations. CT is most appropriate for the diagnosis and extent of many infections, cysts, tumors, and trauma while providing key insight into the extent of their involvement [14] (Figs. 11, 12). It is the modality of choice for osseous lesions with soft tissue extension and soft tissue lesions, especially when soft tissue differentiation is requisite. Considerable overlap may exist between CT and MR when soft tissue characterization is necessary. In many cases, these imaging modalities may both be needed to fully characterize soft tissue lesions; in those instances they should be considered complementary imaging modalities [1]. Advantages of CT include data visualization in both soft tissue and bone windows, ease of reformatting data volume in multiple 2D planes as well as 3D renderings, and ease of data transferability using DICOM algorithms. Disadvantages include cost of acquisition, relatively high radiation exposure, limited dental accessibility (except in hospitals or medical imaging centers), and imaging artifacts from metallic materials. Advances include less image noise, increased acquisition speed, fusion images to merge high specificity CT data volumes with high sensitivity nuclear medicine/positron emission tomography data volumes (fused PET/CT study), and improved interactive software programs [6] (Fig. 11). The newest generation helical scanners have reduced acquisition times and increased image quality significantly. The use of low-dose acquisition techniques has also been a great benefit in decreasing radiation risk to patients, especially in children [15].

Fig. 12 T1-weighted sagittal MR image. Same patient as Figs. 9 and 10. The high signal area is from the fatty bone marrow of the osseous mass extending into the glenoid fossa (*arrow*)

Magnetic Resonance (MR)

MR acquires images with a magnetic field and radiofrequency pulses with the image signal of tissues based on hydrogen ion concentration. MR studies provide excellent soft-tissue differentiation [1, 6]. A typical imaging study may include intravenous contrast agents in order to augment the detection of many lesions of the head and neck. Image protocols will include a variety of sequences, each designed to optimize certain tissue characteristics. While virtually all protocols incorporate traditional T1-weighting (fat is high signal) with and without contrast, and T2-

weighting (water is high signal) techniques, current protocols often expand the imaging armamentarium to include short tau inversion recovery (STIR) techniques and fat suppression (Figs. 12, 13). Diffusion weighted imaging (DWI), MR spectroscopy, and MR perfusion are more advanced techniques that may have efficacy in selective cases. Open gantry MR scanners help to minimize the discomfort and claustrophobia experienced by some patients during image acquisition in closed gantry units; however the lower field strength magnets may decrease acquisition speed and limit minimum slice thickness [16]. MR studies experience significant artifacts from metallic materials, but not to the extent of CT and CBCT [17]. Nevertheless, artifacts emanating from non-removable orthodontic appliances will render an examination of the oral cavity and the majority of the suprahyoid neck to be of nondiagnostic quality in most cases. An otherwise innocuous retained pellet or metallic projectile in the face may create sufficient ferromagnetic artifact on MR to defeat any attempt at obtaining diagnostically relevant anatomic detail of the sinonasal, orbital, and oral cavity structures depending on location and the technical nuances of the individual MR pulse sequence performed. The presence of some ferromagnetic materials in the patient are a contraindication to MR, as the relatively strong magnetic field of the unit may cause heating and/or movement of those materials that may risk damage to adjacent tissues. Metallic alloys used in dental restorations are not affected during MR acquisitions but they may significantly distort the image. Orthodontic arch wires (but not stainless steel brackets) and removable dental appliances are ferromagnetic and should be removed prior to MR imaging; dental implants cause only minor image distortions [1]. For soft tissue imaging, MR may be used in addition to CT soft tissue windows. The results of MR and CT (soft tissue window) may differ somewhat due to acquisition principles; MRI distinguishes tissues relative to hydrogen ion concentration and CT distinguishes tissues relative to density. Typical applications of MR are evaluating articular disk position in the temporomandibular joint, neoplasms or masses involving soft tissues, malignant lymph nodes, marrow status, documenting perineural invasion, and salivary gland masses or inflammatory ductal changes using noninvasive MR sialography [18]. Additionally, MR angiography is appropriate for the evaluation of suspected vessel stenoses, occlusions, aneurysms, and vascular malformations. Advantages of MR include excellent soft tissue differentiation and no ionizing radiation risk. Disadvantages include relatively high cost of acquisition, limited dental accessibility (except in hospitals or medical imaging centers), moderate cortical bone visualization, claustrophobia from small closed gantries, movement potential of ferromagnetic materials within the body, and imaging

Fig. 13 Sagittal T2-weighted MR image. Same patient as Figs. 9, 10, and 12. The high water concentration of the thin crescent shaped cartilaginous cap of the lesion presents as high signal (*arrow*). T2-weighted images often provide optimal differentiation of signal intensities as do STIR-weighted sequences

artifacts. Advances include considerably shorter acquisition and reformatting times, open gantry systems to minimize claustrophobia or the ever more common obese patient, and improved interactive software programs. A new technique, sweep imaging with Fourier transformation (SWIFT), has been shown to be useful in assessing the extent of carcinoma into the mandibular cortex [19]. Although still in the research phase, SWIFT MR has been applied to the dentition and adjacent bone which may portend a dental imaging system without ionizing radiation risk [20].

Nuclear Medicine (NM)

NM is a form of molecular imaging that can visualize both physiologic and pathologic processes even when structural anatomic changes are not apparent. Radionuclides are combined with intravenously administered pharmaceutical agents to direct the radiotracer to the tissues of interest. Gamma scintillation cameras are employed to detect emitted gamma rays and create diagnostic images, either as planar images (scintigraphy) or as multiplanar image slices (single-photon emission computed tomography—SPECT). A common maxillofacial imaging study is the bone scan using technetium 99 m as the radiotracer. This may reveal areas of osteolytic and osteoblastic activity. SPECT has been employed to determine the extent of bisphosphonate-induced osteonecrosis of the jaws and documentation of mandibular growth in patients with asymmetries [21].

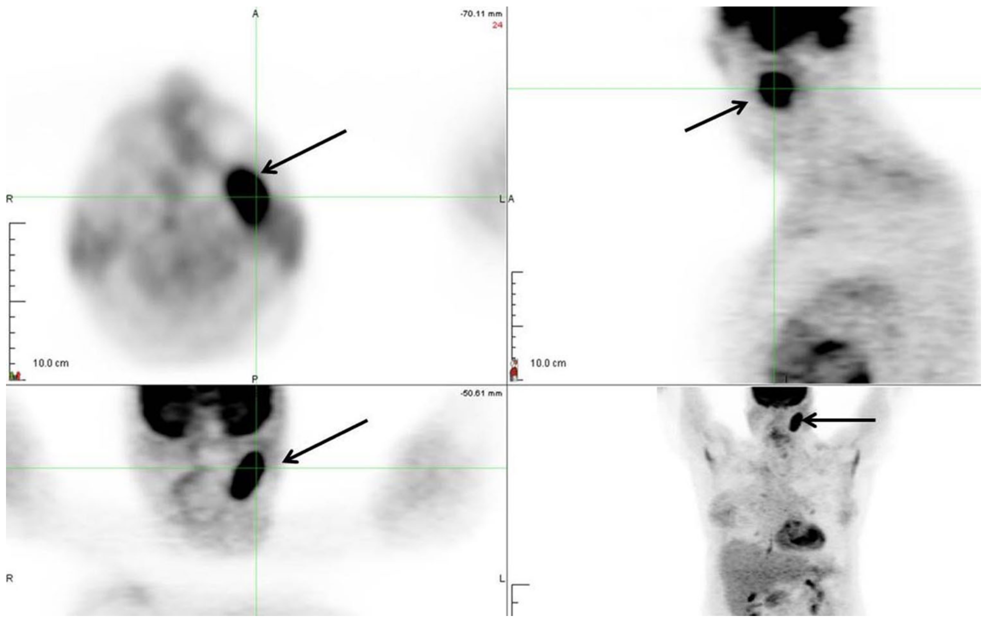

Fig. 14 PET study. Same patient as Fig. 11 imaged from the axial (*upper left*), sagittal (*upper right*), and coronal (*lower image*) planes. The more anterior coronal slice is to the left and the more posterior to the right. Increased radiotracer activity is noted in the left condyle, suggesting ongoing bone lysis or apposition (*arrows*). This is consistent with the radiographic impression of condylar fracture

Positron emission tomography (PET) studies acquire images based on tissue metabolic rates and are helpful in assessing tumors, metastases, and inflammatory disease (Fig. 14). While PET has high sensitivity, it lacks specificity; however, specificity is usually improved by fusing PET images with CT images to enhance anatomic localization (Fig. 13). PET/CT fusion has been reported to be helpful in staging and management planning of head and neck squamous cell carcinoma [22]. Clinically, PET/CT fusion has served a vital role in the diagnosis and treatment of head and neck malignancy. It is especially efficacious in the post-treatment neck for the detection of treatment response and tumor recurrences. Advantages of NM include high sensitivity functional imaging and the ability to increase specificity by fusion with CT. Disadvantages include relatively high cost of acquisition, limited accessibility (except in hospital or medical imaging center), and radiation exposure. Advances include higher spatial resolution studies, fusion with CT for greater anatomic specificity, shorter acquisition and reformatting times, and improved interactive software programs. A significant NM innovation is lymphatic mapping using a hand-held gamma counter with a new radiopharmaceutical (Lymphoseek; Navidea Biopharmaceuticals; Dublin, OH, USA) to assist in the localization of lymph nodes draining a primary tumor site. This diagnostic advancement was originally designed for breast cancer and melanoma, but has recently received U. S. Food and Drug Administration approval for use in mapping sentinel nodes in the spread of squamous cell carcinoma in the head and neck [23].

Ultrasonography (US)

US is useful in assessing the nature of soft tissue masses; however, it is of limited use when the area of interest is immediately adjacent to osseous structures. The image is created by ultra high-frequency sound waves; a hand-held transducer emits the ultrasonic beam and accepts the reflected echoes of the initial beam. Fluid filled masses (cysts) do not reflect the sound waves. Tissues that reflect may do so to different degrees (partially solid or solid masses). US is usually quite useful in characterizing lesion margins [6]. Applications in the maxillofacial region are for muscle thickness, Sjögren syndrome, salivary gland/duct inflammation and calcifications, thyroid, parathyroid, and lymph node pathology (Fig. 15). US may also be employed for image guidance in fine-needle aspiration on the neck. Doppler US allows real time images that are valuable in imaging carotid artery plaques (atheromas) and vascular stenosis or occlusions. As compared to CT, US is usually the preferred modality for the evaluation of thyroid gland and parenchymal lesions. Advantages of US include no ionizing radiation risk, moderate accessibility, and moderate cost. Disadvantages include sensitive acquisition technique and lack of efficacy in soft tissues immediately adjacent to osseous structures. Advances include the application of 3D imaging algorithms which can also render surface images, multiplanar reformatting, and pseudo-colorization. Multiple studies have investigated the application of US for dental caries, dental fractures, periapical inflammatory lesions, selected maxillofacial osseous

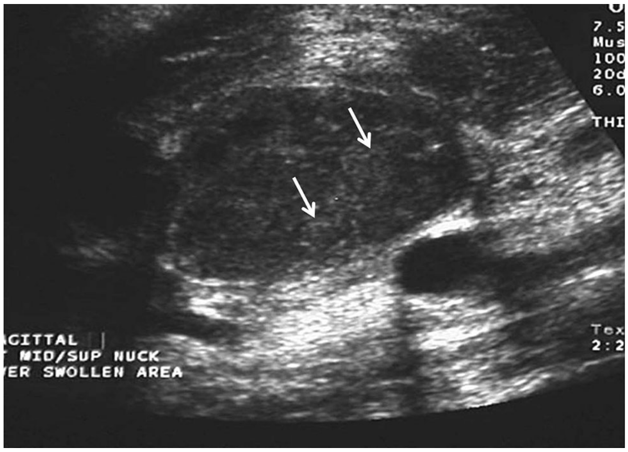

Fig. 15 US study. Gray scale sonography showing a cluster of pathologically enlarged lymphomatous cervical nodes. Intranodal reticulations that obscure the normal fatty hila and other more normal internal nodal architecture are present (*arrows*). (Courtesy: Dr. Christos Angelopoulos; New York, NY, USA)

fractures, internal derangements of the temporomandibular joint, and periodontal osseous defects; while these applications are certainly promising, most are still in the investigational phase [24].

Interpretation of Imaging Studies

Accurate interpretation of advanced imaging studies requires additional expertise to recognize both normal and abnormal processes in a somewhat larger field of view than in traditional dental imaging systems. Additionally, enhanced abilities to appropriately interact with image display software using properly selected spatial resolution, windowing, image slice thickness, and reformation algorithms are keys to an accurate interpretation and diagnosis [8]. While most advanced imaging studies will be interpreted by radiologists, some types of advanced imaging units, like CBCT, may be located in private dental offices or maxillofacial imaging centers. Whether clinical practitioners have CBCT studies performed by such facilities or acquire them in their own offices, many recognize that they will assume liability for reading the scan. The obligation to interpret entire image volumes is the standard [25–27]. Not only will the clinician be responsible for interpreting the scan as it pertains to their area of practice or the particular reason for which the image was acquired, but they will also be responsible for interpreting the entire image volume. There are no known legal cases specifically concerning the matter of the scope of interpreting a dental CBCT study, however CBCT is no different than any other imaging study, i.e., a clinician cannot interpret only a selected portion of a panoramic or lateral cephalometric radiograph [28]. Professional liability insurance companies have suggested that liability waivers signed by patients do not afford protection from less than complete interpretations [29]. When the clinician requires additional expertise in interpretation of a dental CBCT data volume, consultation with an oral and maxillofacial radiologist is appropriate. Fortunately, modern technology has made the electronic referral of imaging studies for interpretation by an oral and maxillofacial radiologist a simple matter, regardless of practice location.

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