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REVIEW ARTICLE

Clinical guidelines for dental cone-beam computed tomography

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Abstract
Dental cone-beam computed tomography (CBCT) received regulatory approval in Japan in 2000 and has been widely used since being approved for coverage by the National Health Insurance system in 2012. This imaging technique allows dental practitioners to observe and diagnose lesions in the dental hard tissue in three dimensions (3D). When performing routine radiography, the examination must be justified, and optimal protection should be provided according to the ALARA (as low as reasonably achievable) principles laid down by the International Commission on Radiological Protection. Dental CBCT should be performed in such a way that the radiation exposure is minimized and the benefits to the patient are maximized. There is a growing demand for widespread access to cutting-edge health care through Japan's universal health insurance system. However, at the same time, people want our limited human, material, and financial resources to be used efficiently while providing safe health care at the least possible cost to society. Japan's aging population is expected to reach a peak in 2025, when most of the baby boomer generation will be aged 75 years or older. Comprehensive health care networks are needed to overcome these challenges. Against this background, we hope that this text will contribute to the nation's oral health by encouraging efficient use of dental CBCT.

Keywords Cone-beam computed tomography · Dentistry · Guidelines · Japan

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What is dental cone-beam computed tomography (CBCT)?

History of development

Intraoral radiography involves placing X-ray film directly into the oral cavity to take photographs of the teeth. This imaging method obtains clear images with high spatial resolution. However, because the images overlap, it can be difficult to diagnose complex conditions affecting the dental and periodontal tissue structures in three dimensions (3D).

In 1972, Hounsfield developed X-ray computed tomography (CT) [1]. Robb et al. performed basic research on cone-beam CT (CBCT) in the late 1970s and early 1980s [2, 3]. In the 1980s, CT imaging became widely used in dental teaching hospitals. This enabled 3D imaging of extensive inflammation and tumors, allowing more precise diagnosis and treatment planning, and contributing greatly to oral health care in Japan. However, these examinations were not optimal for observing fine dental and periodontal structures.

In the early 1980s, basic research to resolve these issues was performed by Toyofuku et al. who demonstrated the effectiveness of dental CBCT in diagnosing disorders of the jawbone in 3D [4]. Nevertheless, several problems remained to be resolved before this examination tool could be put to practical use, including the exposure dose, imaging time, size of the device, calculation time, and image quality. In particular, a smaller voxel size was needed to obtain high spatial resolution, which was considered difficult because of the exponential increase in exposure dose and calculation time needed.

In 1997, Mozzo et al. designed a dental CBCT system specifically for use in the maxillofacial area and the head and neck [5]. This device used an image intensifier to image the entire maxillofacial area with the patient in a supine position and was useful for preoperative diagnoses, implant planning, and treatment of traumatic injuries, such as fractures. In the late 1990s, Arai et al. developed a dental CBCT system in which the area to be imaged was reduced [6]. This method was found to provide high image quality with low radiation exposure, and clinical trials were launched at the Nihon University School of Dentistry Hospital in 1998.

Dental CBCT received regulatory approval in Japan in 2000 and has become widely used since being approved for National Health Insurance coverage in 2012. In 2016, approximately 16,000 dental CBCT devices were operating nationwide in Japan (R&D Co., 2017 Yearbook of Dental Equipment and Products) and are now used to perform around 220,000 examinations per year (2015 Survey of Medical Care Activities in Public Health Insurance).

Characteristics of dental cone-beam CT

Dental CBCT is optimized for imaging of the teeth, jaws, and face, and provides tomographic images from a variety of directions. An X-ray tube and two-dimensional sensor are rotated 180°–360° around the head to collect imaging data, which are reconstructed into tomographic images by a computer [7]. Voxels are rectangular cuboids with sides that range in length from 0.08 to 0.4 mm. The width of the field of view (FOV) can range from 4 to 20 cm and its height from 3 to 20 cm. The tube voltage can range from 60 to 120 kV and the tube current from 1 to 10 mA. Each imaging session takes 5–40 s. These factors vary greatly depending on the device and when it was released [8, 9].

Imaging is performed while the patient is sitting or standing with most devices, although some devices require the patient to be photographed in a supine position. Devices that can perform both panoramic radiography and dental CBCT are now available.

Dental CBCT is optimized for imaging of the teeth and surrounding bone structures, which have high X-ray absorptivity, and provides increased spatial resolution, which allows the fine details of these structures to be visualized. However, because of the significant impact of noise and scattered radiation, dental CBCT provides poor spatial resolution in low-density structures, so it is unsuitable for diagnosis of conditions affecting the soft tissue. Therefore, multi-detector row CT or magnetic resonance imaging (MRI) is used when a soft tissue diagnosis is needed.

The exposure dose varies widely depending on the imaging conditions. The effective dose from one imaging session can vary in the range of 10–1000 μSv. Caution is needed with large-diameter FOVs, because the exposure dose may be greater than that for CT under low-dose conditions [10–20]. The exposure dose is essentially proportional to the lateral area of the FOV, i.e., the product of its height and width, so it is important to select the smallest FOV that meets the imaging objective.

In theory, dental CBCT voxel values are unstable in that the diameter of the FOV is generally smaller than that of the head [21, 22], meaning that a complete set of image data cannot be obtained. Therefore, mathematically correct CT values cannot be calculated for image reconstruction.

Moreover, while the effective doses for conventional intraoral, panoramic, and cephalometric radiography are in the range of 1–8 μSv [23], the exposure dose from dental CBCT can be more than ten times this amount, even under low-dose conditions, so caution is needed.

It is important to take these factors into account, so that patients are selected appropriately for dental CBCT, images are acquired under optimal conditions, and the entire FOV can be interpreted after imaging.

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Imaging features needed for dental CBCT

The following imaging features need to be available so that dental CBCT can be performed safely and reliably.

Adjustable FOV

The FOV should be adjustable so that an optimal FOV can be selected to meet the imaging objective. A small FOV can be selected to visualize a few teeth [24, 25], and a much larger FOV can be selected when imaging the entire head [26–28].

Positioning the patient and fixing the head

It should be easy to place the patient in the device, and there should be a mechanism to securely fix the head in place.

Mechanisms to reduce radiation exposure

Mechanisms to reduce radiation exposure should allow the exposure dose and irradiation area to be optimized according to the age of the patient, the indication for imaging, and the FOV.

Positioning function

Reliable positioning mechanisms are needed when a small FOV (≤ 5 cm diameter) is selected. Such mechanisms are equipped with three-directional laser guide beams and scout view functions to ensure that the area in the FOV is the one being irradiated. Simple positioning mechanisms allow the FOV to be placed rapidly and accurately. However, positioning mechanisms that require movement of the head for placement of the FOV require the patient's cooperation, so may be unsuitable for use in patients who may not be able to cooperate sufficiently, such as those with headache, trismus, or a movement disorder. Care must be taken when moving the head, because repositioning may cause the head to rotate, which can result in inclination of the Frankfort horizontal plane or the midsagittal plane and failed imaging.

Short imaging time

The irradiation time should be as brief as possible to prevent artifacts caused by patient movement. Twenty seconds or less is recommended, although 10 s or less is preferred [29].

Tunable radiation conditions

The tube voltage and current should be able to be adjusted, particularly if the patient is a woman or a child [30–35].

Demo mode

Demo mode is a mechanism that allows the device to operate normally but without irradiation, and can be used to explain important points to the patient before imaging.

Emergency stop button

An easily identified emergency stop button should be located somewhere on the device.

Infection control measures

Structures that come into contact with patients should be easily sterilizable for prevention of infection, and the mechanisms used for fixing the patient's position should be as simple as possible.

Adjustable voxel size

It should be possible to modify the voxel size from about 0.1–0.4 mm to suit the imaging objective. Note that a reduction in the voxel size will increase noise [36, 37], so caution is needed when making changes.

Small cone angle

It should be possible to make the cone-beam angle (the angle of the X-rays incident from top to bottom when the surface of revolution is horizontal) as small as possible. The cone angle decreases as the distance between the X-ray focus and the sensor increases, and when the height of the FOV decreases, so the height of the FOV should not be unnecessarily large. The main X-ray beam should enter the center of the FOV perpendicular to the axis of revolution.

Tunable angle of rotation

During imaging, it should be possible to change the angle of rotation from 180° to 360°. Although 180° imaging causes more noise and streak artifacts than 360° imaging, the exposure dose is lower and the imaging time is shorter, which may decrease the frequency of artifacts caused by patient movement. The angle that best suits the imaging objective should be selected [7, 29, 38–40].

High definition

If the objective is to diagnose fine structures, such as the pulp cavity or periodontal ligament space, small radiation fields of no more than 5 cm in height and 5 cm in width should be selected. When assessing spatial resolution using a modified

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transfer function, the 2-line pair/mm should be 0.1 or higher, both horizontally and vertically [41–44].

A DICOM output

A digital imaging and communications in medicine (DICOM) output should be available so that the images can be used for diagnostic purposes remotely.

Image data back-up

Data should always be able to be backed up in the event of computer failure.

Dose management

The parameters for each imaging session should be automatically recorded in a database.

Effective use of CBCT

Effective use of CBCT requires careful selection of valid cases so that limited human, material, and financial resources can be used efficiently to improve the health of the public while minimizing radiation exposure by following the ALARA principles [45].

In general, dental CBCT involves low radiation exposure; however, the exposure dose can vary 100-fold depending on the size of the FOV, the irradiation conditions, and the type of equipment used [18, 46–49]. The exposure dose when imaging the entire head can be similar to that of medical CT [20], and when imaging small radiation fields, the exposure dose can be several times that of the latest digital radiography devices. Even when the latest methods of reducing radiation exposure are used, the dose from dental CBCT of the head and neck may still be more than ten times that of conventional cephalometric radiography [23, 33].

The Japanese Ministry of Health, Labour, and Welfare has made training mandatory for the operation of new medical devices. Therefore, dental practitioners who use CBCT must allow sufficient time to develop an understanding of the structure of these devices, and learn the procedures required for imaging and interpretation.

The following sections describe the training required, along with other important aspects of dental CBCT.

Dental CBCT training

Practicing imaging methods

Before using dental CBCT for imaging of patients, the operator should understand the structure of the device and the imaging principles involved. Practical training on manikins and other objects is required to learn the different imaging methods.

The operator should practice selecting an appropriate FOV and correctly positioning the patient, particularly when imaging small radiation fields, such as around the upper and lower anterior teeth, canine teeth, molars, horizontally impacted wisdom teeth, and right and left temporomandibular joint.

Training should include checking that the device operates in demo mode without irradiation, checking the emergency stop button, and learning how to lower the exposure dose when imaging children.

If the device can also perform panoramic radiography, this imaging method should be learned at the same time.

Practicing with the viewer

Dental CBCT images are observed using a dedicated viewer, which is a software application that runs on a computer. The operator should practice starting the viewer; displaying cases; adjusting brightness and contrast; displaying axial, sagittal, and coronal sections; displaying tomographic images of the desired direction and position by rotating the axes; zooming in and out on images; measuring distances; saving images; changing the section thickness; using the DICOM output; and changing the voxel size if available.

Practicing interpretation and diagnosis

All the basic anatomic structures in the area of observation should be confirmed on an actual viewer. Images should be checked for artifacts caused by body movement and, if found, additional imaging should be considered. The images should be checked for the presence of metal and, if found, for metal-related artifacts. Not that when imaging small radiation fields, metal outside the FOV can create overlapping artifacts.

The operator should confirm the following anatomic structures in the area of observation [49–57]: enamel, dentin, roots, pulp, periodontal ligament spaces, lamina dura, alveolar bone, jawbone, mental spine, mental foramen, lingual foramen, mandibular canal, incisor branch, nutrient canals, mandibular foramen, mandibular fossa, coronoid process, mandibular notch, mandibular neck, mandibular condyle, articular tubercle, pterygoid process, external auditory foramen, styloid process, greater palatine foramen, lesser palatine foramen, palatine groove, maxillary tuberosity, maxillary sinus, natural ostium, infraorbital canal, alveolar foramen, anterior superior alveolar canal, posterior inferior alveolar canal, nasolacrimal duct, orbital cavity, turbinate bone, base of nasal cavity, piriform aperture, anterior nasal spine, median palatine suture, incisive canal, alveolar

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process, hyoid bone, and airways. Finally, it is important to check for bone deficits, anatomic structural changes, inflammatory osteosclerosis, or other findings that may accompany pathology.

Practicing creating reports

The operator should practice recording the patient's name and other identifying information, date of examination, the area and purpose of the dental CBCT, and the findings observed on dental CBCT images, in particular those for tomographic images orthogonal to the teeth. Pathologic morphologic abnormalities should be recorded in detail, as well as the normal anatomic state, even in the absence of pathologic abnormalities. Tomographic images that contributed to the diagnosis should be included in the report. The diagnosis indicated by the findings should be recorded, along with any necessary comments and the operator's name and signature, either physical or electronic.

Procedure for imaging with dental CBCT

The operator should undertake a detailed interview and record the patient's medical history. If the lesions are thought to be limited to the teeth, jaw, or other dental hard tissue, intraoral radiography or panoramic radiography should be performed if these would provide the information needed for an accurate diagnosis.

If the information gained from intraoral radiography or panoramic radiography is insufficient to make a diagnosis, and the patient does not require irreversible emergency surgery, such as tooth extraction or radical pulpectomy, palliative treatment should be provided, and the course observed carefully. At this point, dental CBCT should not be performed unless its results would alter the treatment plan [26, 46, 58, 59]. However, if symptoms with unclear causes do not improve or if irreversible treatments are considered necessary, and having 3D anatomic information about the teeth and periodontal tissue would help to provide safe and reliable care, dental CBCT may be justified. It would certainly be to the patient's disadvantage if a necessary dental CBCT was not performed because the risk from radiation exposure was overestimated.

Note that to diagnose soft tissue pathology, other imaging techniques, such as medical-grade CT or MRI, should be considered instead of dental CBCT.

During imaging, the smallest possible FOV should be selected to minimize the exposure dose. Methods for reducing the exposure dose, such as shortening the imaging time and appropriately lowering the tube voltage and tube current, should always be considered, particularly in children [32, 34, 46, 60].

At this point, the reasons why dental CBCT is necessary should be clearly recorded. The 3D images obtained should be examined in detail, and the diagnosis and treatment plan should be recorded and fully explained to the patient.

A dental radiologist may be consulted to increase the diagnostic accuracy when imaging a large area, and also when a lesion suspected to be a tumor is found with small-field imaging [61–83]. The recent advent of telediagnosis has made it easier to obtain an opinion from a dental radiologist. It is expected that telediagnostic tools will be used more frequently in the future.

Important points during dental CBCT imaging

Consider other examination methods

When regular examination methods are insufficient for making a diagnosis, information on the soft tissues surrounding the teeth and periodontal tissues may be needed. Because dental CBCT is not optimized for diagnosis of soft tissue disorders, an alternative examination method such as medical-grade CT or MRI should be performed instead [84].

Select the optimal FOV for the diagnostic objective

If information is required about a specific localized area, such as a gutter-shaped root of the second mandibular molar, a small FOV equivalent to a digital film of no more than 5 cm wide and 5 cm high should be selected [85–87]. This would expose the patient to a lower dose than if an FOV measuring 6 cm × 8 cm was selected. A smaller FOV would also reduce scattered rays and increase the clarity of the images. An extensive FOV should be selected if imaging is needed over a wide area, such as when a jaw fracture is suspected. However, if the head also needs to be investigated, medical-grade CT may be more effective than dental CBCT.

Select the appropriate voxel size

When a small FOV equivalent to digital film of 5 cm or less is selected, choosing a small voxel size of around 0.1 mm may help differentiate fine structures such as root canals. However, care is needed because this also increases noise. Depending on the mechanical motor precision of the device, the size of the focus of the X-ray tube, the voxel size of the sensor itself, and the magnification of the subject, reducing the voxel size beyond a certain point will not increase definition, but will only increase noise. Therefore, extremely small voxel sizes should not be selected. For example, high resolution is not considered necessary for diagnosing supernumerary teeth in children, so a voxel size of 0.2–0.3 mm is

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sufficient. This lowers the amount of noise compared with a voxel size of about 0.1 mm, which makes it possible to lower the tube voltage and tube current, thereby lowering the exposure dose.

When imaging an extensive area at a low dose, increased noise can hinder the diagnostic process. In such cases, choosing a large voxel size of 0.3–0.4 mm will reduce noise [36, 88]. This would lower the resolution, but because it also reduces noise, it would be effective for low-dose imaging.

Observation at the appropriate contrast and brightness

Voxel values in dental CBCT can become unstable, depending on the size of the area being imaged or the size of the FOV. Therefore, unlike medical-grade CT, it is difficult to automatically display images on the monitor at a stable brightness. The practitioner must adjust the contrast and brightness of each section to suit the objective of the examination. In general, a light contrast, in which air is the darkest "black" and metal is colored "white", is used for overall observations. The window width is then narrowed to match the window level and the contrast is increased so the area that needs to be interpreted has moderate saturation and the image can be inspected again.

Observe all imaged areas by moving through cross-sections in three directions with six degrees of freedom.

When observing cross-sections over a large area with regular medical-grade CT, differences between left and right morphology are usually examined. Therefore, the basic observations are of axial sections, with sagittal and coronal sections also examined.

When dental CBCT is added, sections along the teeth, mandibular canal, and roots are usually reconstructed and observed. To achieve this, the section is rotated around the x, y, or z axes so the section matches the direction of the area to be observed. Additionally, it is possible to move to cross-sections that are parallel or orthogonal to the reconstructed section, to be able to observe contiguous tomographic images. Thus, being able to move among sections with six degrees of freedom (i.e., cross-sections of the x, y, and z axes and rotating around each axis) enables observation of the entire imaged area.

The area to be observed is imaged in three orthogonal cross-sections, so all three images should be examined. Finally, sufficient time should be allowed for repeated examination of the entire region that was imaged.

Confirming all anatomic markers

The images obtained by dental CBCT are extremely thin. Therefore, unlike the overlapping images from intraoral radiography, anatomic structures must be checked by changing between sections with six degrees of freedom. The area for diagnosis should be examined after confirming the anatomic structures inside the FOV.

Depth (optical) illusions

Volume rendered 3D images displayed on two-dimensional screens do not provide information on depth. However, a sense of depth is created by an optical illusion, which occurs when the eye is tricked into seeing something that is not actually there. Caution is needed because it is easy to reverse the direction of depth when observing images.

Care is also needed with axial sections because the image may transpose between right and left depending on whether the view is looking down on the apex or up from underneath. Further, when operating the viewer to rotate a section, care should be taken not to lose track of the anterior–posterior, left–right, and superior–inferior directions.

It is impossible to avoid these optical illusions completely. Therefore, when observing CT images, it is important to reference other images, such as intraoral or panoramic radiographs and intraoral photographs, as well as study casts.

Changing section thickness

If the viewer allows the section thickness to be changed, increasing the thickness may reduce noise, so the recommendation is to adjust the images appropriately before inspecting them. When observing fine structures such as dental pulp, a section thickness of 0.25–1 mm is considered appropriate. When observing thicker structures, such as the periodontal ligament space, a section thickness of 1 mm is more suitable.

Imaging time and motion artifacts

Motion artifacts created when the patient moves during imaging can sometimes make it impossible to secure a diagnosis. Therefore, the head must be securely fixed in place. These artifacts are more likely to occur with long imaging times, so modes with short imaging times should be considered. If possible, choose 180° imaging, because the imaging time is about half as long as for 360° imaging, which may help prevent motion artifacts. This is particularly effective in small children, whose movements may affect the examination [7, 29, 34].

Artifacts caused by the cone angle

The X-ray beam in dental CBCT is cone-shaped, meaning that the X-rays enter the upper and lower edges of the FOV at an angle. Larger cone angles create artifacts. Therefore, areas around the upper or lower edges of the FOV may appear swollen or less bright. This type of artifact does not

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occur in the center of the FOV, where the main X-ray beam is perpendicular to the axis of rotation, so areas that need to be examined closely should be positioned close to the center of the FOV.

When using a multifunction device that can perform both dental CBCT and panoramic radiography, the position at which the main X-ray beam is perpendicular to the axis of rotation may be at the bottom of the FOV. In some devices, the incident angle increases at the top of the FOV, which creates artifacts. Therefore, areas that need to be observed closely should be positioned towards the bottom of the FOV, and the upper regions should be avoided as far as possible when a precise diagnosis required.

Root fractures and artifacts

The presence of metal posts and gutta-percha points in a root canal can cause radiating artifacts [89] that may resemble root fractures. The diagnosis of root fractures should be based not only on dental CBCT images, but also on a comprehensive assessment of pocket depth and current medical history. If a diagnosis still cannot be made after considering these factors, there should be no rush to extract the tooth. The final diagnosis may best be made after a conservative approach over a long period of follow-up.

Metal artifacts

Metal inside (and even outside) the area of observation can generate a variety of artifacts, which may resemble dental caries, root fractures, or bone resorption. When examining CT images, refer to intraoral radiographs and panoramic radiographs to confirm the presence or absence of metal, and take into account any artifacts in the area.

Brightness in the observation room

In general, dental examination rooms are brightly lit because of the work environment. However, when viewing dental CBCT images on a monitor, the surroundings should be dim enough so the light does not inadvertently appear on the monitor. However, care is needed to avoid eye fatigue.

Use of protective aprons

The use of protective aprons in dental CBCT does not reduce the exposure dose, so they are not considered necessary, especially considering that if the protective apron touches the sensor or X-ray tube during imaging, the process may have to be repeated. However, if a patient wishes to use one and it will not hinder the examination, doing so is not problematic. If an extensive FOV is selected, use of a thyroid protector has been reported to effectively reduce exposure to the thyroid gland. The thyroid glands are located close to the jaw and are highly sensitive to radiation, particularly in children [90, 91].

Rely on a dental radiologist for interpretation if necessary

When the entire jaw is imaged, various unexpected findings or lesions may be discovered when interpreting the large area involved. Asking a dental radiologist to interpret the images may improve diagnostic precision [80, 92]. For images with a small FOV of 5 cm or less, a dental radiologist should be consulted to interpret the images if a tumor is suspected or a definitive diagnosis cannot be reached.

Improving image quality by increasing irradiation time

Extending the dental CBCT imaging time to improve image quality [40] should be undertaken with caution, because patient movement can cause artifacts that worsen image quality and may increase the exposure dose.

Stitch imaging

A large area may be imaged by moving the FOV multiple times to expand the area imaged. Another method of enlarging the FOV is to continuously move the center of the FOV during imaging. In most cases, this extends the irradiation time, so care is needed to avoid body movement-related artifacts and an increased exposure dose.

Combination with occlusal radiography

When accurate diagnosis of midline supernumerary teeth and impacted wisdom teeth is not possible using intraoral or panoramic radiography, occlusal radiography may be added. However, dental CBCT should also be considered as a superior alternative.

Combination with eccentric projection

Intraoral radiography or panoramic radiography may be inadequate for diagnostic purposes if numerous roots are present. In such cases, additional imaging with eccentric projection may be performed. Artifacts could have a major impact, particularly on dental CBCT, if there are metal or gutta-percha points adjacent to the area being observed. If such artifacts are expected to render appropriate observations impossible, addition of eccentric projection is recommended.

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Regular maintenance of the device

Dental CBCT uses precision equipment that requires regular maintenance and servicing. This technique also lacks the stable pixel values found on medical-grade CT and produces large artifacts, so it can be difficult to notice when performance degrades. Therefore, maintenance should be performed at set intervals according to the procedures outlined in the manual, by taking images of the test items that come with the device. Every 6 months, a dedicated staff member should check basic performance items, including spatial resolution, subject contrast, noise, collimators, exposure dose, and radiographic quality, and readjust the device as necessary. Basic performance should be able to be maintained for 6 years or longer, but the manufacturer should be notified if there is a marked decrease in image quality.

Indications for small-field dental cone-beam CT

Dental CBCT should be performed when a diagnosis cannot be made using intraoral radiography or panoramic radiography. The following sections describe specific cases when small-field imaging is indicated.

Mandibular wisdom teeth and mandibular canal

When the mandibular wisdom teeth are impacted and the pathway of the mandibular canal is seen to overlap with the impacted teeth on intraoral radiography or panoramic radiography, dental CBCT using a small radiation field is effective for confirming the positional relationship between the impacted teeth and the mandibular canal [93, 94].

Impacted teeth

When an impacted mandibular wisdom tooth is embedded deeply, extraction can be facilitated by shaving a portion of bone. The mandibular canal is sometimes split into two branches, which can make bone shaving problematic [8, 94]. Careful examination with dental CBCT using a small radiation field can alleviate this problem. This technique is also effective for examining the positional relationship between the maxillary sinuses and impacted teeth in the maxilla [73].

Impacted supernumerary teeth

Supernumerary teeth occur in a variety of impaction positions, most typically in the midline. Dental CBCT provides information about the positional relationships in 3D to facilitate safe and reliable tooth extraction. It also allows assessment of the degree of apical closure of adjacent teeth. It may be advisable to delay extraction until the apices of the adjacent teeth are closed to protect their pulps. However, if existing images reveal incomplete closure of the apices, surgical extraction should not be undertaken, and thus dental CBCT is not indicated.

Assessing excess roots or pulp and gutter-shaped roots

Dental CBCT with a small radiation field is effective for diagnosing complex root and root canal morphology [86, 95], such as excess roots in the maxillary molar and premolar region, excess roots and gutter-shaped roots in the mandibular molar and first premolar region, and double roots in the mandibular lateral incisor.

Apical lesions

Dental CBCT can improve treatment outcomes for surgical resection of apical lesions, such as radicular cysts, apical granulomas, and alveolar abscesses, by helping surgeons to understand preoperatively the extent of the lesions and the relationships with adjacent bones and teeth. Dental CBCT with a small radiation field is particularly effective for lesions that are located on the lingual (palatal) side where there is a blind spot beside the tooth root in the surgical field and for assessment of the presence or absence of cortical bone [86]. Using a microscope during surgery may also improve the treatment outcomes.

Identifying causative roots

Dental CBCT with a small radiation field is effective for assessing which root is the cause of apical periodontitis in multi-rooted teeth [86, 96, 97]. It can also help detect which roots require repeat root canal therapy in multi-rooted teeth, such as the second mesiobuccal canal in maxillary molars [24, 25, 44].

Odontogenic maxillary sinusitis

When diagnosing odontogenic maxillary sinusitis, it is important to understand the relationship between the causative teeth and the maxillary sinus, the presence of bone defects or the dome-like elevation of the base of the maxillary sinus, and the extent of mucosal hypertrophy [73–75, 79, 83]. Dental CBCT with a small radiation field can assist in identifying causative teeth. However, if odontogenic maxillary sinusitis is widespread, it must be differentiated from other diseases, so medical-grade CT or MRI is indicated [84].

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Root fractures

Root fractures are caused by excessive occlusal force, but may also occur with aging, so the number of cases has been increasing. Dental CBCT with a small radiation field is effective in diagnosing root fractures, but because the diagnosis can be influenced by artifacts from metal posts and gutta-percha points, clinical symptoms should also be considered [43, 89, 98, 99].

Furcation lesions

It can be difficult to detect furcation lesions in molars on conventional radiographs because the lesions may be surrounded by multiple roots, and inserting a probe may be difficult. Dental CBCT with a small radiation field is effective for diagnosing such cases.

Fistula

Dental CBCT with a small radiation field is effective in identifying the causative tooth or root when a fistula forms on the gingiva.

Osteoarthritis of the temporomandibular joint

Dental CBCT is useful for diagnosing deformities of the bone structure of the temporomandibular joint [40, 65, 76, 78, 82, 100, 101]. However, because it cannot depict articular discs, MRI should be used instead.

Fenestration

Openings from cortical bone deficits in the root area (fenestration) can occur on the buccal side of any tooth, but are particularly common in the maxillary incisors and premolars. Dental CBCT with a small radiation field can be effective for diagnosing discomfort of unknown cause.

Nasopalatine duct cysts

Nasopalatine (incisive canal) duct cysts may cause malalignment of the maxillary anterior teeth. Understanding the positional relationships with the adjacent incisors and the bases of the sinuses is important [102]. Dental CBCT with a small radiation field is useful for diagnosing these cysts.

Tooth transplantation

For tooth transplantation to be successful, it is important to understand in advance the 3D morphology and the size of the roots of the donor teeth. It is particularly important to know the number of roots, root morphology, and root length, and to measure the mesiodistal and buccolingual widths. Dental CBCT with a small radiation field is useful for performing these measurements.

Benign odontogenic tumors

Dental CBCT can be useful for diagnosing strictly limited odontogenic tumors and examining internal calcification in detail. However, in most cases, differentiation from other tumors is necessary, which requires medical-grade CT or MRI.

Implant planning

Dental CBCT can be an effective preoperative examination to create a plan for placing implants in a small number of teeth. It allows the anatomic structures inside the imaged region to be examined in 3D to check for lesions and other issues [103–107]. Unexpected findings, such as osteomyelitis, osteopetrosis, inflammatory osteosclerosis, osteoporosis, and maxillary sinusitis, should be treated before placement of the implants.

If no lesions are found, implant placement can be planned, taking into account the position of the mandibular canal and the lingual foramen (where blood vessels enter the mandibular canal), the pathways of the submental artery and sublingual artery (with regard to the recessed morphology of the inferior margin of the mandible on the lingual side), the pathway of the posterior superior alveolar branch along the incisive canal and the base of the maxillary sinus, and the pathway of the anterior superior alveolar branch near the maxillary incisor. These details are particularly relevant when placing implants at an angle.

Orthodontic anchor screws

Dental CBCT can help to determine the optimal approach when placing orthodontic anchor screws [107] if damage to adjacent roots is possible or if the cortical bone is thin. Dental CBCT should be performed cautiously in such circumstances and with the patient's consent.

Adhesions, external resorption, and internal resorption

Dental CBCT with a small radiation field can be useful for assessing the condition of the periodontal ligament spaces and external and internal root resorption [108]. It is particularly useful for impacted teeth and teeth that have not been moved with orthodontic force.

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Follow-up

After a diagnosis is secured using dental CBCT, radiography can be performed for follow-up as needed. This is particularly helpful in patients with chronic diseases that are likely to recur. Follow-up is generally performed using intraoral radiography or panoramic radiography, although dental CBCT may be justified if recurrence or another issue that would significantly change the treatment plan occurs, and new diagnostic information is needed.

Regardless of the imaging method used, follow-up examinations should generally be performed at least 6 months apart, with 3 months being the minimum interval. Unless the patient's condition is changing rapidly, frequent imaging is not performed because it would not provide new diagnostic information.

Pumping and manipulation of the temporomandibular joint space

Dental CBCT is effective for confirming the direction and depth of needle insertion in advance, so pumping and manipulation of the temporomandibular joint space can be performed safely and reliably [109, 110]. Dental CBCT is considered particularly effective in shortening procedures and preventing complications.

Indications for extensive FOV (≥ 8 cm diameter) of all jaw areas or the entire jaw

Dental CBCT may be added when a diagnosis is not possible on intraoral or panoramic radiography. Specific examples in which dental CBCT with an extensive FOV is indicated are outlined below.

Jaw deformity

Dental CBCT with an extensive FOV is effective for determining orthodontic therapy in cases of jaw deformity. However, the exposure dose may be similar to that of medical-grade CT, depending on the imaging conditions. In general, imaging is performed with a voxel size of ≥ 0.3 mm and under low-dose conditions [10, 26, 88, 111, 112]. Moreover, the top-to-bottom incident angle increases when the height of the FOV exceeds 8 cm, which can generate overlapping artifacts in the tomographic images and may affect the diagnostic precision for certain factors such as distance. Diagnosis of soft tissue disorders is also important when surgery is necessary. Medical-grade CT should be performed instead of dental CBCT in this situation.

Cleft alveolus and palate

Cleft palate surgery is usually performed in infants, so dental CBCT is not indicated, given the difficulty of keeping infants still [113]. If imaging is necessary, a medical-grade CT device that allows imaging in a supine position should be used, and the exposure dose should be minimized. In older patients who require imaging, dental CBCT should be performed carefully after considering its likely effectiveness.

Implants

Dental CBCT is an effective preoperative examination for creating a plan for implant placement in the whole jaw or in multiple teeth [103, 104, 106, 114–116]. It allows the anatomic structures in the imaged region to be fully observed in 3D to locate sites for the implants. Other details available from dental CBCT include information about the entry point of blood vessels into the bone (important when implants are placed at an angle), and the pathways of the submental and sublingual arteries with regard to the recessed morphology of the inferior margin of the mandible on the lingual side.

Unexpected findings such as osteomyelitis, osteopetrosis, inflammatory osteosclerosis, osteoporosis, and maxillary sinusitis may be discovered, requiring implant placement to be delayed.

Contraindications to dental cone-beam CT

Cases with soft tissue involvement

Dental CBCT is not indicated in cases involving soft tissue, such as malignant tumors, phlegmon, and other forms of extensive inflammation.

Follow-up

Generally, follow-up is performed using intraoral radiography, panoramic radiography, or cephalometric radiography rather than dental CBCT. However, dental CBCT may be justified in some cases, such as if the course does not proceed as expected or if there is a recurrence. However, these cases are rare. If a patient's treatment needs to be repeated, but diagnosis is not possible because of the involvement of soft tissue or other factors, consider referral to a more advanced medical institution for examination with medical-grade CT or MRI.

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Observation of the airways

Observing the airways in a supine position is important in the diagnosis of sleep apnea syndrome. Because dental CBCT is usually performed in a sitting position [117–119], it is not indicated for diagnosis of this condition. Regular imaging should be performed in a supine position or using medical-grade CT optimized for a low-exposure dose if necessary [120].

Suggestions for reducing radiation exposure

Exposing humans to high doses of radiation is known to cause malignant tumors, infertility, cataracts, and other impairments [121]. However, radiation cannot be detected by any of the five senses, and the units used to express the radiation dose are complex and difficult to grasp, which hinders its understanding by most patients. In statistical terms, 3% of malignant tumors that occur in Japan are believed to be caused by medical CT [122], and medical CT of the brain is reported to be a cause of brain tumors in children [123].

Japan has the highest penetration rate of medical CT in the world [124], and because of its universal health insurance system, about 20 million scans are performed each year (2015 Survey of Medical Care Activities in Public Health Insurance). The exposure dose per examination is in the range of 1–4 mSv. This is equivalent to 6 months to 2 years of the annual dose from natural radiation in Japan. The annual exposure dose allowed for the general public is 1 mSv, so the dose from medical-grade CT is roughly equivalent to or even greater than this.

Meanwhile, the 5-year survival rate for cancer in Japan is 62%, which is much better than that in other OECD countries, and is expected to rise further. With our increasing ability to overcome the sequelae of debilitating conditions such as stroke, an increasing number of these patients are returning to live in the community. One result of this is that the average lifespan in Japan is now among the highest in the world. This is partly because of the spread of medical CT, which allows malignant tumors and brain infarctions to be definitively diagnosed and treated early and appropriately. Accordingly, the benefits of medical radiation exposure are thought to greatly outweigh the risks, and there is no doubt that it has contributed to the health of our nation.

Rapid diagnosis and treatment increase the benefits of therapies, which overall have contributed greatly to public health [121]. Nevertheless, practitioners must strive to lower these risks by reducing exposure doses as much as possible.

If technologic advances can further reduce the exposure dose from medical CT, the statistical probability of medical radiation causing malignant tumors could be significantly lowered. Radiation doses can also be decreased by avoiding nonessential examinations, and modifying the irradiation conditions to reduce the exposure dose when imaging is performed. However, excessively lowering the exposure dose can cause image quality to deteriorate, making it impossible to achieve the original objective of the examination, i.e., securing a diagnosis. Therefore, doses should be lowered only to the level at which diagnostic capacity is not affected.

Children are more sensitive to radiation than adults, and because their remaining lifespans are longer, the risk of development of a malignant tumor in the future as a result of radiation exposure is higher. Therefore, examinations need to be performed carefully, and alternative examinations should be actively considered. If radiation is used, it should be kept to the minimum level necessary.

Radiation exposure associated with dental CBCT is basically thought about in the same way as medical CT. However, the following considerations are necessary because of the characteristics of dental practice and dental CBCT [8, 10, 12, 14–19, 21, 22, 30, 31, 33–35, 39, 48, 102, 105, 125–127].

It is important that only essential dental CBCT is performed [60]. When examinations are performed, the smallest possible FOV should be selected [87, 88]. The exposure dose for children should be about half that used in adults. The X-ray tube voltage and the tube current should be reduced by 0–10% and by 40–60% of the values used in adults, respectively. Additionally, selecting 180° imaging instead of 360° imaging effectively halves the image acquisition time (Table 1) [7, 60].

Although dental CBCT excels at depicting hard tissue, it cannot be used to evaluate soft tissue, which has low contrast, so is not indicated for diagnosing widespread inflammation or tumors. In such cases, medical CT or MRI should be used instead.

Caution is warranted if the radiation field extends over the entire head, because the exposure dose may be equivalent to that of medical CT. When imaging a large area, the procedure should be performed under low-exposure conditions by increasing the voxel size and reducing noise as much as possible. For details, refer to the important points already described in this text. However, reducing the exposure dose too much will reduce image quality and make it impossible to achieve the diagnostic objective. Therefore, only lower the dose to the extent at which it does not reduce diagnostic capacity.

When dental CBCT is applied in orthodontic therapy, the dose for an FOV that covers the entire head, even under low-dose conditions, can be tens of times that of cephalometric radiography, so it should only be applied with caution. Therefore, dental CBCT is not used routinely in orthodontic therapy [10, 26, 112].

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Table 1 Measures to reduce radiation exposure

Measure	Adult	Child	Result
Shorten imaging time	17.5 s	9 s	Reduces artifacts arising from body movement
Select 180° imaging	360°	180°	
Lower tube voltage 0–10%	90 kV	80 kV	Reduces dose rate
Lower tube current 40–60%	5 mA	3 mA	
Increase voxel size	0.125 mm	0.25 mm	Reduces noise
Reduce relative absorbed dose	100%	25%	Reduces dose to one quarter

Carefully determine if imaging is essential. Do not perform if not justified. Select the smallest field of view according to the diagnostic objective. Conditions using 3DX Multi Image Micro CT (Morita, Kyoto)

Compliance with ethical standards

Conflict of interest Yoshinori Arai has received royalties from J. Morita MFG Corporation (Kyoto, Japan). Takafumi Hayashi, Toru Chikui, Sachiko Hayashi-Sakai, Kazuya Honda, Hiroko Indo, Taisuke Kawai, Shumei Murakami, Masako Nagasawa, Munetaka Naitoh, Eiji Nakayama, Yutaka Nikkuni, Hideyoshi Nishiyama, Noriaki Shoji, Shigeaki Suenaga, and Ray Tanaka declare that they have no conflicts of interest.

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