Computed Tomography: Principles and Applications

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ABSTRACT: Computed tomography (CT) is gradually becoming more widely available in veterinary referral practices and has advantages for the investigation of patients with a variety of lesions affecting most parts of the body. The cross-sectional depiction of anatomy in CT images eliminates the problem of superimposition of body parts, which significantly limits conventional radiography. Therefore, CT has a higher sensitivity for detecting disease and enables more accurate assessment of the extent of lesions, which is important in surgical planning.

Computed tomography (CT) has been in clinical use in humans since 1973. Although CT was originally developed for imaging the brain, CT scanners are used today for a wide range of examinations of most parts of the body, particularly the head, thorax, and abdomen. CT is gradually becoming more widely available in veterinary referral practices; therefore, it is important that practitioners be aware of this imaging modality.

PRINCIPLES

Image Formation

In conventional radiography, a broad x-ray beam is emitted from a stationary tube and passes through the patient, casting a shadow on a flat screen that absorbs the x-rays and then re-emits their energy as light, which affects photographic film. In CT, a narrow, fan-shaped x-ray beam is emitted from a tube as it moves around the patient, and x-rays that pass through the patient are counted by a series of small electronic detectors; signals from the detectors are then passed to a computer, which reconstructs the data into a two-dimensional image representing a cross-section of the patient (Figure 1). A CT scanner represents a high-quality piece of engineering that includes a high-output x-ray tube, a gantry that supports the x-ray tube, detector array, and a patient bed. Operation of the scanner is controlled by computer. CT images are viewed as they are acquired on a monitor. Other scans can be viewed or manipulated on a remote workstation without interfering with the scan in progress. CT images may be printed onto film so that they may be viewed on a light box.

During a scan, the x-ray tube normally revolves continuously through 360° around the patient as the patient is moved through the aperture of the scanner; the patient is moved either in a series of small increments (axial scan mode) or continuously (helical scan mode; Figure 2). The size of the region to be scanned and the thickness of tissue represented by each image can be precisely selected by the radiographer. Images representing thin slices (i.e., 1 to 2 mm) of the patient may be acquired when maximal resolu-
tion of small, high-contrast structures is required (e.g., when examining the bones of the middle and inner ear). As an alternative, thicker slices (i.e., 5 to 8 mm) can be used when it is important to distinguish between tissues of similar attenuation (e.g., parts of the brain, abdominal organs). Thicker slices are necessary because recognition of small differences in attenuation (i.e., low-contrast resolution) depends mainly on minimizing statistical variations (i.e., “noise”) in the images; this is achieved by using thicker slices with a correspondingly higher radiation dose.

CT scans have properties similar to those of conventional radiographs because both are produced via the absorption of x-rays by tissues of different density; thus low-density tissues (e.g., lungs) appear black or dark gray, and high-density tissues (e.g., bone) appear light gray or white. The major differences between conventional radiographs and CT images are:

- Each CT image represents a thin section of the patient; thus multiple images are required to cover a particular anatomic structure or body cavity (Figure 3).
- CT images are digital and composed of many pixels, each with a number that describes the attenuation of the tissue within that pixel (Figure 4).
- Because CT images display the attenuation directly assigned to each pixel, whereas conventional radiographs present the sum of attenuations within all superimposed structures within the thickness of the patient, CT can detect differences in tissue density that are too small to be visible on conventional radiographs.

Image Interpretation

Each pixel in a CT image is assigned a number that describes the amount of attenuation of the x-ray beam by that part of the patient. These numeric values, known as CT numbers or Hounsfield units (HU), encompass a wide range (e.g., –1,000 HU for air, 0 HU for water, 3,000 HU for compact cortical bone; Figure 5). The CT image observed on the computer monitor may be adjusted so that the potentially wide range of attenuation values in the tissues being examined (known as the window) can be displayed using the relatively few gray levels that the monitor produces. A wide window is used to display a wide range of attenuation in air- or bone-containing structures (e.g., in the head or thorax), whereas a narrow window must be used to display the more limited range of attenuation associated with soft tissues (e.g., in the brain or abdomen; Figure 6). It is normal practice to view images using multiple windows to thoroughly examine different tissue types. CT can distinguish different soft tissue and fluid types (e.g., blood may be distinguished from transudate based on their CT numbers) as well as differentiate between soft tissues and some fluids.
The principles of interpreting CT images are the same as those for interpreting conventional radiographs. For example, the same radiographic signs (i.e., number, position, size, shape, margination, opacity) are used, with tissue density replacing opacity. The terms hyperdense, isodense, and hypodense are used to describe the relative attenuation of structures in CT images, although tissue density may also be described precisely according to its CT number.

CT images are often easier to interpret than conventional radiographs because the cross-sectional depiction of anatomy eliminates the problem of superimposition of body parts; however, to recognize and describe structures correctly, it is necessary to learn cross-sectional anatomy in detail. CT images are usually acquired in the transverse plane, although it is possible to reprocess the data after acquisition to produce sagittal, dorsal, or oblique images and three-dimensional reconstructions (Figure 7). Depending on the slice thickness used to acquire the original data, reconstructions can have a coarse appearance and, although they may sometimes look impressive, do not add any information to the original format.

Practicalities

Just as with conventional radiography, accurate patient positioning is important in obtaining optimal CT images. For example, oblique positioning can complicate the interpretation of CT images just as it does in radiography. Although the exposure time for a CT scan of a body region such as the thorax may be as little as 30 seconds, the patient must remain perfectly still for an initial “pilot” image (used to select the position of CT images), the scan, and sometimes a repeat scan after intravenous injection of contrast medium. Therefore, CT scans usually take several minutes and patients are usually sedated or anesthetized. For most scans, we prefer to position patients in sternal recumbency.

Anesthetized animals are usually monitored from outside the room while CT is conducted. Animals are not manually restrained for CT scans; however, for critically ill patients requiring constant monitoring, it may be necessary for a person (wearing a lead apron and
period of hyperventilation of anesthetized animals can induce apnea for up to 1 minute, which is enough time to complete the scan while personnel are out of the room.

Contrast studies such as intravenous urography\(^7\) (Figure 8), myelography\(^8\), and portography\(^9\) can be combined with CT. Intravenous contrast medium tends to accumulate in vascular, hemorrhagic, or edematous lesions, which aids in their identification. Contrast medium accumulation may also enable lesion margins to be defined more precisely (this is discussed later).

CT scans can be affected by various artifacts that degrade image quality and make interpretation more difficult.\(^10\) Movement of the patient during the scan causes blurring (Figure 9). Highly attenuating structures such as metallic implants or positioning sandbags can cause streak artifacts (Figure 10).

APPLICATIONS
CT enables more detailed examination of a wider range of structures than does conventional radiography or ultrasonography. Thus CT may be used:

- As an alternative to a multiple-view radiographic study
- Following normal results of radiography or ultrasonography
- To gain more information about a suspected abnormality observed via radiography or ultrasonography
- To guide biopsy of a known lesion
- To determine the extent of a lesion before surgery or radiation therapy

In practice, the selection of cases for CT depends partly on an assessment of the individual patient’s needs and partly on various local factors, including the cost, convenience, and availability of other imaging facilities. CT is generally more expensive than ultrasonography and less expensive than magnetic resonance imaging (MRI).

Head
CT is particularly well suited to examinations of the head because of the high contrast provided by bone and air-containing structures and because cross-sectional images eliminate problems associated with superimposi-
tion that affect radiography of the head. Therefore, CT is useful in assessing animals with head trauma (Figure 11). Although MRI is generally considered the optimal modality for imaging the brain, CT can be a useful alternative when there is limited access to MRI or costs must be minimized. CT scans of the brain have less anatomic detail than MRI scans but may nevertheless enable detection of intracranial hemorrhage \(^{11}\) (Figure 11), hydrocephalus, and intracranial masses \(^{12-14}\) (Figure 12). When the brain is examined, CT scans are typically obtained before and after administration of intravenous contrast medium. The blood–brain barrier normally prevents contrast medium from reaching the neural tissues; however, many inflammatory or neoplastic lesions damage the blood–brain barrier, thereby allowing accumulation of contrast medium and facilitating detection of lesions affecting the brain.

Other indications for CT of the head in small animals include exophthalmos \(^{15}\) (Figure 13), suspected otitis media \(^{16}\), and chronic nasal discharge. CT scans clearly show the fine detail of the turbinates and nasal conchae; thus small intranasal lesions or sites of bone invasion by nasal neoplasms that could be missed on conventional radiographs are seen on CT scans. \(^{17,18}\) Accurate assessment of the extent of a nasal lesion aids in determining the prognosis and treatment options. Rhinitis and nasal neoplasia may be reliably distinguished using CT \(^{19}\) (Figure 14). The frontal sinuses are normally included in a nasal CT study because fluid accumulation, mucosal thickening, and bone lesions often occur secondary to nasal disease. Postcontrast CT scans can be used if invasion of the brain is suspected. The retropharyngeal lymph nodes can be included in the study to look for signs of local spread of disease.

**Thorax**

For the thorax, a helical CT scan technique is preferred to minimize scan time, which reduces the likelihood of movement artifacts resulting from patient breathing. CT is used for imaging all thoracic structures except the heart, which appears blurred. CT images of the lungs are...
particularly useful, often revealing lesions (e.g., metastases) that are not visible on survey radiographs or enabling detailed assessment of the extent of a lesion, which aids in surgical planning. Suspected pulmonary metastasis\(^\text{20}\) (Figure 15), thoracic mass\(^\text{21,22}\) (Figure 16), and nontraumatic (“spontaneous”) pneumothorax\(^\text{23}\) are frequent indications for thoracic CT.

**Abdomen**

At most institutions, abdominal CT studies are relatively infrequent compared with abdominal ultrasonography because of the convenience and lower cost of the latter; however, CT is useful for the examination of abdominal structures that are difficult to examine via ultrasonography, such as the pancreas,\(^\text{24,25}\) mesentery, and pelvic canal. There is evidence that CT is a more accurate method of determining the extent of abdominal lesions, which may be important when resection is planned (Figure 17). Reports have described the use of CT for investigation of portosystemic shunting,\(^\text{9}\) adrenal gland disease\(^\text{26}\) (Figure 18), and ectopic ureters.\(^\text{27}\)

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**Figure 12.** CT scans of a dog with an intracranial mass resulting from granulomatous meningoencephalitis. Although the initial CT scan (left) appears normal, a repeat scan (center) after administration of intravenous contrast medium shows focal accumulation in the left lobe of the cerebellum (arrow). A postgadolinium T1-weighted MRI (right) of the same dog more clearly shows the anatomy of this region and the mass lesion (arrow). MRI is preferred in imaging the brains of dogs and cats; although CT produces lower-quality images, it does have other advantages, including lower cost and shorter scan time, which may enable scanning without anesthesia in critically ill patients.

Initial CT scan. Postcontrast CT scan. Postgadolinium T1-weighted MRI.

**Figure 13.** The use of CT to investigate exophthalmos. Pre- and postcontrast CT images of the head of a dog with left exophthalmos and signs of pain when opening the mouth. In the precontrast scan, there is swelling of the left masticatory muscles (note the convex dorsal contour [arrow on left]). Contrast accumulation in the left temporal muscle (* on right) supports a diagnosis of myositis.

Precontrast CT image. Postcontrast CT image.

**Figure 14.** CT is particularly well suited to nasal cavity examinations because of the high contrast provided by bone and air-containing structures.

A CT scan of a normal nasal cavity. In dogs with destructive rhinitis (e.g., aspergillosis), destruction of the nasal turbinates is readily observed. Replacement of turbinates by a soft tissue mass with destruction of the surrounding bone is typical of a nasal tumor.
**Figure 15.** CT scan of an obese dog with fibrosarcoma between the scapulae. A small nodule in the dorsal left caudal lobe (arrow) is compatible with pulmonary metastasis. A pulmonary nodule (arrow) raises the possibility that the mass has metastasized. Impingement on the esophagus (*) suggests possible invasion, which would complicate resection of the mass. Lack of lesions affecting the ribs and the presence of bronchus within the mass (arrow) support a diagnosis of pulmonary mass.

**Figure 17.** Postcontrast CT images of the abdomen of a dog with pheochromocytoma affecting the right adrenal gland. The tumor (*) is clearly visible between the aorta and caudal vena cava. The margins of the mass are ill-defined, with evidence of retroperitoneal infiltration by the tumor (arrow). The left ureter is encased by the tumor (arrow). Resection of this lesion would require a left nephrectomy.

**Figure 18.** Postcontrast CT images of the abdomen of a dog with adenocarcinoma affecting the right adrenal gland. These images indicate invasion of the tumor into the caudal vena cava, resulting in a blood clot or tumor thrombus. The tumor (*) is visible between the right kidney and the caudal vena cava. In an image just cranial to the one on the left, the tumor merges with the caudal vena cava (arrow). The intrahepatic part of the caudal vena cava is filled with a thrombus, leaving only a thin rim of contrast medium in the surrounding lumen (arrow).
Poorly marginated foci of bone destruction affecting the body of the first lumbar vertebra, floor of the vertebral canal, right pedicle, and base of the transverse process.

Repeat scan showing a hypodermic needle placed as a guide for the biopsy needle, which was subsequently inserted alongside. The streak artifact from the tip of the needle indicates a safe path to the lesion. The histologic diagnosis was plasmacytoma.

Figure 19. CT scan of the elbow of a dog with arthritis secondary to fragmented medial coronoid process (arrow). (R = radius; U = ulna)

Figure 20. Spectrum of CT findings in dogs with incomplete ossification of the humeral condyle.

Figure 21. Images of a dog with a tumor destroying the fifth thoracic vertebra (T5).

Lateral radiograph showing a subtle lucency affecting the base of the dorsal spine (arrow).

CT image more clearly showing the extent of the lesion, which has destroyed the base of the dorsal spine (*), dorsal lamina, and left pedicle (arrowhead). A pathologic fracture (arrow) is also visible. In this instance, the CT scan enables more confident diagnosis of a vertebral lesion and more detailed depiction of the extent of the lesion. This information was used to guide biopsy.

Figure 22. CT-guided biopsy of a vertebral neoplasm.

In a normal dog, there is a relatively uniform trabecular pattern within the humeral condyle.

An incomplete sagittal fissure with surrounding sclerosis.

A complete but nondisplaced fissure.

Pathologic fracture through the middle of the humeral condyle. The dog had a Robert Jones bandage and plastic gutter splint applied to support the injured limb. This support was left in place for the CT scan because it does not adversely affect the images.
Musculoskeletal Structures

The detection of minimally displaced or incomplete fractures using conventional radiography can depend on positioning the patient so that the x-ray beam is parallel to the fracture gap. Without the likely orientation of a fracture being known in advance, obtaining this optimal position may be a matter of luck, and it is possible to make good-quality radiographs that do not show the fracture. Also, in some body parts (e.g., the skull or spine), the shape and complexity of bones create superimposition that can hide lesions. CT is more sensitive than conventional radiography in detecting fractures because CT uses a multidirectional x-ray beam and its cross-sectional images eliminate the problem of superimposition.28

CT is useful in examining the canine elbow, particularly in dogs with suspected fragmented coronoid process (Figure 19)29 or incomplete ossification of the humeral condyle30 (Figure 20) because these conditions are difficult to detect using conventional radiography. Finding signs of incomplete ossification of the humeral condyle can help explain the occurrence of a condylar fracture or may enable prophylactic treatment in animals at risk for fracture.

CT is often used to examine the spine, mainly in animals with suspected intervertebral disk prolapse, fracture, or neoplasia11 (Figure 21). Biopsies of lesions may be obtained with CT guidance, even if that was several hours earlier. As an alternative, dilute contrast medium (e.g., iohexol [80 to 100 mg/ml of iodine]) may be used.

REFERENCES

ARTICLE #2 CE TEST
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1. Which is a major advantage of CT compared with conventional radiography?
   a. CT is much quicker to perform than radiography.
   b. CT results in a much lower radiation dose to patients than does conventional radiography.
   c. Anesthesia or sedation is rarely required in CT.
   d. The cross-sectional depiction of anatomy in CT images eliminates the problem of superimposition of body parts.

2. CT scanners produce an x-ray beam in the shape of
   a. cone. c. fan.
   b. pencil beam. d. rectangle.

3. Each pixel in a CT image is assigned a number that describes
   a. its width and thickness.
   b. its position relative to the center of the x-ray beam.
   c. the attenuation of tissues in that pixel.
   d. the radiation dose to the patient.

4. When CT is used to scan the brain of a dog with a suspected intracranial mass, which protocol should be used?
   a. thick slices; narrow window
   b. thick slices; wide window
   c. thin slices; narrow window
   d. thin slices; wide window

5. Which statement regarding the use of contrast medium in CT is correct?
   a. Intravenous contrast medium normally penetrates the blood–brain barrier.
   b. Intravenous contrast medium tends to accumulate in hemorrhagic or edematous lesions.
   c. Larger doses of intravenous contrast medium are necessary for CT than for conventional radiography.
   d. Intrathecal administration of contrast medium is not necessary in CT myelography.

6. Which statement regarding the use of CT for investigation of nasal disease is incorrect?
   a. Sites of bone invasion by nasal neoplasms may be missed with conventional radiography but are usually visible with CT.
   b. Rhinitis and nasal neoplasia may be reliably distinguished by CT.
   c. CT can be used to detect signs of brain invasion by a nasal neoplasm.
   d. The retropharyngeal lymph nodes are too small to be examined by CT.

7. CT is more sensitive in detecting pulmonary metastasis than is conventional radiography because
   a. motion blur is not a problem in CT.
   b. the patient’s radiation dose is much higher in CT.
   c. CT eliminates the problem of superimposition by ribs and other structures that could obscure pulmonary lesions.
   d. CT uses a much lower kilovolt peak than does conventional thoracic radiography, making nodules more visible.

8. The CT number (HU) represents the amount of x-ray attenuation of a tissue relative to
   a. air. c. blood.
   b. water. d. bone.

9. Which is the most appropriate window width in examining a sclerotic lesion affecting a vertebra?
   a. 3,000 HU
   b. 1,000 HU
   c. 500 HU
   d. −1,000 HU

10. Which organ is the least well depicted by CT?
    a. the brain
    b. the liver
    c. the heart
    d. the lungs