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CT and MRI for Advanced Practitioners Mini Series

Session One: Basic principles of CT and MRI

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Computed tomography

Computed tomography historical background

The history of computed tomography goes back to 1917 with the mathematical theory of the Radon when he demonstrated that an object could be reconstructed from an infinite number of projections through that object. The CT was invented in 1971 by British engineer Godfrey Hounsfield of EMI Laboratories, England and by South Africa-born physicist Allan Cormack of Tufts University, Massachusetts. Hounsfield and Cormack were later awarded the Nobel Peace Prize for their contributions to medicine and science. The first clinical CT scan on a patient took place on 1st October 1971 at Atkinson Morley's Hospital, in London. The patient, a lady with a suspected frontal lobe tumor, was scanned with a prototype scanner, developed by Godfrey Hounsfield and his team at EMI Central Research Laboratories in Hayes, west London. The scanner produced an image with an 80 x 80 matrix, taking about 5 minutes for each scan, with a similar time required to process the image data. Current CT scanners can produce images with a 1024 x 1024 matrix, acquiring data for a slice in less than 0.3 seconds, and are an integral part of a modern hospital's imaging resources.

Basic CT unit anatomy

A CT system is mainly composed of a scanning unit (i.e., the gantry) with a rotating x-ray emitting tube and a detector system, a patient table, and a console equipped with a sophisticated computer that allows adjusting acquisition parameters and image reconstruction. The rotating x-ray tube is powerful enough to operate for long periods of time without overheating, thus permitting acquisition of large volumes of data. The detector system also plays an important role in image quality. It converts the incident x-rays that traverse tissue into electronic signals. The signal output is proportional to the density of the penetrated tissue. Filters and collimators are also present. Filters remove the low energy photons that contribute strongly to the patient dose and scatter radiation but less to the detected signal. Collimators ensure good image quality and to reduce unnecessary radiation doses for the patient.

Image acquisition and formation

X-ray tube revolves continuously around the patient as the patient is moved through the scanner aperture. X-rays are produced continuously and detectors are sampled approx. 1000 times per 360˚ tube rotation and measurements are taken. The mechanism by which the CT system reconstructs the data measured by the detectors is based on the concept of x-ray attenuation, which mainly depends on the electron density of the medium. X-ray attenuation is quantified by measuring the fraction of radiation removed in passing through the patient's anatomy. The absorption probability is described by the linear attenuation coefficient (μ). Once μ is measured for a signal ray, the μ of each individual voxel composing the image matrix can be determined using a mathematic process called *filtered backprojection*. Practically, for a single image with a 512 × 512 pixel matrix, this represents 262,144 different μ values. For display purposes, these values are transformed into Hounsfield units (HU) or CT numbers, normalized to voxel values containing water (μ_w). HU for other tissues are then calculated using the flowing formula:

$$\text{HU of a tissue} = [(\mu_{tissue} - \mu_w)\ \mu_w] \times 1000$$

Based on this formula, the HU of pure water is zero, and any structure or tissue causing more x-ray attenuation than water will have a HU value above zero, whereas any structure or tissue causing less x-ray attenuation than water will have a HU value less than zero (negative). (Fig.1) The fact that liquids and soft tissues can be discriminated based on their HU values confirms the greater contrast resolution of CT over radiography.

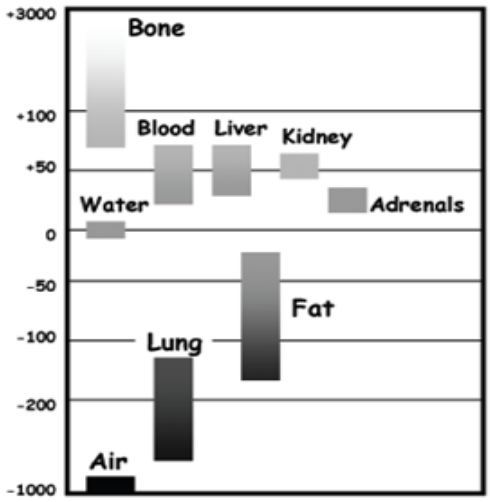

Fig.1

Other important parameters that are set before image reconstruction include slice reconstruction interval, which adjusts the proportion of overlap between adjacent slices of tissues used for image reconstruction, and reconstruction filter, which determines the level of edge reinforcement applied while processing raw data. These parameters must be set carefully according to the region of interest. For example, a low-pass filter, commonly known as "standard or soft tissue filter" is recommended when soft tissue contrast must be emphasized, such as in brain imaging, with the downside of creating a blurrier image. "Bone filters," conversely, maximize spatial resolution, but introduce more noise, thus reducing contrast resolution. Such images are sharper but grainier. "Detail filters" that offer intermediate pass filtration may also be used for the reconstruction of smaller soft tissue areas to prevent excessive blurring. Hence, reconstruction filter(s) must be selected according to the size of the body part to be imaged and the content to be highlighted (e.g. soft tissue and/or bone).

Image Display

HU values that can be measured with typical scanners range from approximately −1000 to +3095 HU, for a total of 4096 shades of gray (12 bits of grayscale*). This range of values cannot be resolved by the human eye, which cannot differentiate more than 40 shades of gray.5 To visualize and appreciate all tissues composed of variable HU, the window width (W) and level (L) of the image grayscale must be adjusted, according to the median and range of HU composing the area of interest. The viewing software allows adjustment of the extent (maximum-to-minimum) of gray shades (W) displayed (i.e., image contrast) and the HU at the centre of the window (L). W/L must be

adapted to the tissues being evaluated and usually requires adjustments during evaluation of a CT study for all tissues to be evaluated completely.

Contrast medium

The use of iodinated contrast agents is a routine procedure in several CT protocols. After a bolus intravenous injection, the distribution of this hyperattenuating substance can be tracked throughout the body, providing information on the perfusion of tissues and integrity of natural barriers, such as the blood-brain barrier. For non-angiographic studies, postcontrast scans are performed approximately 50 seconds after the bolus injection to allow contrast medium to pass into the extravascular space. Hence, the HU of a tissue will increase in proportion to the concentration of the contrast medium, the volume of its blood space, and the permeability of its capillary bed. Enhancement characteristics are used to complement other morphologic observations and increase both sensitivity and specificity of CT examinations. Contraindications to the administration of iodinated contrast agents includes a previous adverse reaction to an iodinated contrast agent, dehydration and severe renal failure. Heart failure can also be a contraindication because of the administration of a large bolus of fluid. Severe adverse reactions to the administration of iohexol IV, as part of routine CT scans, were described on a recent study. Severe reaction such as spasms, tachycardia, tachypnoea, VPC's were observed in 0,8 of the dogs and mild/moderate reactions like changes in the pulse, blood pressure, cardiac and respiratory rate were observed in 36% of the dogs and cats.

Objectives of the administration of contrast medium:

- Enhancing the ability to see anatomic detail
- Evaluate the integrity of natural barriers (eg, blood-brain, blood vessels)
- Information on tissue perfusion
- Pattern of contrast uptake is complementary to other morphological features to characterize lesions

Technical considerations

Due to the relatively high radiation dose, manual restraint by personnel is usually not an option for small animal CT. General anaesthesia is a common form of patient restraint for CT studies. It is safe and controllable, provides a motionless patient and allows hyperventilation to induce apnoea during thoracoabdominal CT studies. Alternative restraining options includes heavy sedation or patients immobilized or unconscious due to pre-existing medical condition. A new device (VetMouseTrap) made from transparent acrylic (Plexiglas), attempts to take advantage of the typical behaviour of ill cats to provide a clinically and image supportive environment. Most dyspnoeic cats will preferably remain immobile with elbows abducted in sternal recumbency. This natural behaviour provides an opportunity to provide CT imaging of the head, neck and thorax with minimal movement in a physically restrictive device with appropriate clinically supportive aspects are addressed (oxygen and intravenous therapy).

The appropriate reconstruction filters must be selected according to the size and body part to be imaged (see image acquisition and formation).

Slice thickness single most important setting to select for a CT scan. Slice thickness is directly proportional to the magnitude of volume averaging (synonym partial volume artefact) and inversely proportional to the magnitude of image noise. Thus thick-slice CT images are blurry but contain little noise, whereas thin-slice images are sharp but noisy.

Principles of CT Image Interpretation

Scanning planes

- Transverse plane
- Sagittal plane
- Dorsal plane: for the axial skeleton, thorax and abdomen
- Frontal plane: for the appendicular skeleton. The plane cuts along the long axis of both front or hind limbs and is perpendicular to the transverse and sagittal planes.

Basic terminology of location

- Cranial (Cr): directed towards the cranium. It applies to the axial skeleton (head, neck, spine and pelvis) thorax, abdomen and the appendicular skeleton (proximal to the carpus/tarsus).
- Caudal (Cd): directed towards the tail. It applies to the axial skeleton, thorax, abdomen and appendicular skeleton (proximal to the carpus/tarsus).
- Distal (Di): directed away from the body. It applies to the appendicular skeleton.
- Dorsal (D): directed towards the back for the axial skeleton, thorax and abdomen, and towards the head for the distal part of the appendicular skeleton (carpus/tarsus and distal extremities).
- Lateral (L): directed away from the median plane towards the flank. It applies to the axial skeleton, thorax, abdomen, appendicular skeleton and tail.
- Left (Le): directed to the left of the body. It applies to the axial skeleton, thorax and abdomen.
- Medial (M): directed towards the median plane (midline). It applies to the axial skeleton, thorax, abdomen and appendicular skeleton.
- Palmar (Pa)/Plantar (Pl): directed towards the tail. It applies to the distal appendicular skeleton (carpus/tarsus and distal extremities). The term ‘palmar’ is used for the forelimbs and ‘plantar’ for the hindlimbs.
- Proximal (Pr): directed towards the body. It applies to the appendicular skeleton.
- Right ((Rt): directed to the right of the body. It applies to the axial skeleton, thorax and abdomen.
- Rostral (R): directed towards the nose. It applies to the head.
- Ventral (V): directed towards the belly. It applies to the axial skeleton, thorax and abdomen.

Terminology of direction

The terms craniad, caudad, distad, dorsad, laterad, mediad, palmad, plantad, proximad, rostrad and ventrad can be used to describe a direction or motion towards the equivalent location.

Artefacts

A diagnostic imaging artefact can be defined as an appearance on an image that is not representative of a structure within the patient. Artefacts are a common phenomenon in CT, which can result in severe image degradation. In veterinary practice some of those artefacts are particularly marked because of the variance in patient anatomy and the fact that older, less sophisticated CT units are frequently used. Most CT artefacts occur due to interactions between patient and machine, which are all subject to the laws of physics.

- Motion is a frequent artefact in CT. Commonly observed artefact-inducing motions include voluntary movements, respiration, cardiac movement and peristaltic motion. This artefact may occur as streaks, blurring, ghosting and slice mismatch. Remedies to minimize this artefact includes appropriate chemical restraint, minimize the scanning time, hyperventilation prior to scanning to induce transient apnoea and electronic respiratory and cardiac gating.
- Stair step artefact is commonly seen in MPR images created from thick slices of objects obliquely oriented along the Z-axis. The remedy to minimize this artefact is reduce the slice thickness.
- Photon starvation artefact results of an insufficient number of photons reaching the detector at highly attenuating body parts. This artefact is more marked when X-ray beam is in a horizontal position (e.g. shoulders, thighs) and may usually occurs as streaks. The remedies to reduce this artefact includes the use of a higher current, increase the slice thickness and creative patient positioning.
- Undersampling (aliasing) artefact occurs when an insufficient number of projections used in the image reconstruction. This artefact rarely has serious effects on the diagnostic quality of the images and usually occurs as streaks emanating from sharp edges and small objects. Remedies to this artefact includes avoid high-density objects (e.g. ET tube) and increase the tube rotation time.
- Beam hardening artefact results of selective resorption of low-energy photons from the polychromatic X-ray beam by highly attenuating structures. This artefact appears as dark bands or streaks adjacent to highly attenuating structures (e.g. between the temporal bones). Beam hardening artefact cannot be completely remedied but it may be reduced by software and avoid high-density objects.
- Partial volume occurs when an object is partially intruding in the scanning plane. This artifact occurs as blurring of the margins, erroneous attenuation and streaks. Partial volume artefact can be minimized by reducing the slice thickness.

CT safety principles

CT uses x-rays which is a type of ionizing radiation. The x-rays interact with living tissues and produce electrically charged particles which can cause tissue damage. Ionizing radiation have two types of effects on living tissues. Deterministic effects describe a cause and effect relationship between radiation and certain side-effects. They are also called non-stochastic effects to contrast with chance-like stochastic effects (e.g. cancer induction). Deterministic effects have a threshold below which the effect does not occur. The threshold may be very low and may vary from person to person. However, once the threshold has been exceeded, the severity of an effect increases with dose.

Examples of deterministic effects are skin erythema, irreversible skin damage, hair loss, sterility, cataracts, lethality and foetal abnormalities. Stochastic effects occur by chance and which may occur without a threshold level of dose, whose probability is proportional to the dose and whose severity is independent of the dose. Cancer induction and radiation induced hereditary effects are the two main examples of stochastic effects.

The radiation protection regulations and guidelines for veterinary practice can be found at: "Ionising Radiations Regulations (IRR 99)" and "BVA guidelines".

The fundamental aim of radiation protection is to reduce risk of harm by ensuring that any dose received is justified and 'as low as reasonably practicable' (ALARP). Therefore, all the studies involving radiation should be justified, the exposures should be kept as low as reasonably practicable,

exposure to radiation should be monitoring and the CT room should provide radiation shielding for the staff. No individual should be in the room during the CT scan.

Magnetic resonance imaging

Basic MRI physics

MR imaging has become an important diagnostic tool in veterinary medicine because of its inherent high-contrast resolution that allows soft tissues to be characterized more sensitively than with CT. The high contrast resolution of MR imaging fundamentally revolves around the electromagnetic properties of hydrogen nuclei (protons), which are abundant in body tissues. Energy transfer to and from these protons can be localized spatially (i.e., in individual voxels) and is the source of image formation. MR imaging can therefore be compared, in a clinical setting, to mapping the distribution of H+ protons in the water (H2O) and lipid (CH2/CH3) component of tissues.

In the absence of an external strong electromagnetic field, the nuclear magnetic moments point in random directions therefore the total magnetization (M0) is null.

In the presence of a strong external electromagnetic field (B0) like a MRI scanner, the nuclear magnetic moments align parallel or anti-parallel to B0 resulting in a total magnetization (M0) parallel to B0. Additionally, precession of nuclear magnetic moments around B0 also occurs, with a frequency proportional to B0 characteristic of each nucleus (Larmor frequency).

Then we apply a radiofrequency pulse (RF) and the nuclei absorb energy from this pulse by a phenomenon called resonance. This causes the net magnetization vectors (longitudinal and transverse) to rotate in a certain angle. Once the RF current is turned off the nuclei relax, realign with B0 and emit energy (signal) that is picked up by a coil. The two relaxation processes occur simultaneously: longitudinal, T1, and transverse, T2, relaxations. The rate at which T1 and T2 relaxation occurs is tissue specific and exploitation of these differences is the fundamental source of tissue contrast in MR imaging.

MRI sequences

The two main MRI sequences are T1 and T2. In T2 water and fat are bright unlike T1 where water is dark and fat is bright. T2 tend to be superior to detect pathology while T1 is superior to evaluate anatomy. Other sequences commonly used in veterinary MRI protocols includes:

- FLAIR (fluid attenuated inversion recovery). This sequence is similar to T2 but the signal of the free water (CSF) is nulled therefore appears dark. This sequence is useful for the identification of brain periventricular lesions.
- STIR (short tau inversion recovery). This sequence is also similar to T2 but the signal of the fat is nulled therefore appears black. This sequence is useful in musculoskeletal pathology.
- GRE (Gradient Recalled Echo) is very useful to diagnose haemorrhagic lesions. Haemorrhagic lesions appear black on GRE.

MRI contrast

Gadolinium is the contrast agent used in MRI. This is a metal-based contrast and is given IV. Gadolinium affects the relaxation times of protons in their vicinity shortening their T1 and T2 relaxation times enhancing the T1w images. This contrast agent does not cross the blood brain barrier. In humans with renal failure, gadolinium may cause nephrogenic systemic fibrosis. This disease has never been reported in animals.

The MRI scan

MRI scans are performed under general anaesthesia because the study is long and considerable noisy. Typically, an MRI scan takes approximately 45 minutes depending on the number of sequences performed and the area covered.

In a typical brain scan the following sequences are performed: T2w in the sagittal, dorsal and transverse plane, FLAIR and T1w pre and post-contrast in the transverse plane. Other sequences such as GRE may also be performed. Spinal scans are usually shorted and a typical protocol may include T2w images in the sagittal, dorsal and transverse plane. Other sequences such as T1w pre and post-contrast may also be performed when there is a suspicious of a inflammatory/infectious process or neoplasia.

Basic MRI safety

Magnetic Resonance Imaging uses the magnetic properties of hydrogen and its interaction with both a large external magnetic field and radio waves therefore there is no ionizing radiation involved. Most of the MRI scanners are always on even when a patient is not being scanned. The MRI scanner is very noisy, and the scanning time is long therefore an adequate GA plane and adequate monitoring is very important.

Ferromagnetic objects (iron, nickel and cobalt) have high susceptibility to magnetization and cannot be brought into the scanning room. In the scanning room these objects become projectiles and fly towards the magnet with a tremendous force. All the equipment brought into the MRI scanning room should be carefully verified for its MRI safety compatibility (check the presence of the MRI SAFE sticker).

It is important to always go through the MRI safety check list before every scan. This check list should include several items that should checked before the MRI scan such as the presence of collars or other metallic objects, possible ingestion of foreign bodies by the patient, history of previous surgeries and the type of implant placed (Orthopaedic implants generally safe if in situ > 6 weeks and most of the modern implants (pacemakers, joint replacements) are MRI safe).

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