Forensic Radiologic Imaging of Blunt Force Injuries, Penetrating Injuries, and Drowning[1]

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I. Overview of Radiologic Imaging

Immediately upon its discovery in 1895, radiography was used in the courts to document and illustrate gunshot wounds. Since that time radiography has been used to aid in the determination of identity, assist in the evaluation of injury, namely bone injury in blunt and ballistic injury, and to localize metallic fragments and foreign bodies.

Today forensic organizations such as AAFS and NAME specify the use of radiography in their standards and guidelines. Conventional X-ray or whole-body radiographs are used in most centers. However, technological advances in cross-sectional imaging have made it possible for CT to be used routinely with forensic autopsy. Cross-sectional imaging makes the radiologic contribution to forensic autopsy more effective and brings the potential to increase both the speed and accuracy of forensic pathologists and anthropologists.

Radiographs (Conventional, Digital, and Fluoroscopic)

Conventional, two-dimensional radiography is the most widely used radiology technique in forensic medicine. Equipment is less expensive, easier to operate and less expensive to maintain than cross-sectional units. Radiographs are used to document fractures, injury patterns and occult injuries, localize foreign bodies and metallic fragments, and to aid in the identification of human remains when conventional methods such as fingerprinting or DNA analysis are not available or cannot be utilized. Radiography is invaluable in the forensic investigation of gunshot wounds and is universally used to locate the bullet, document the path of the bullet, and to assist in the retrieval of the bullet. Radiography is also the imaging modality of choice to evaluate subtle bone detail such as metaphyseal fractures in child abuse and in the anthropologic evaluation of skeletal remains or dissociated remains.

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We consider radiography to be essential even when CT is available. Because of its excellent resolution and absence of streak artifact, radiographs complement cross sectional imaging when studying metallic fragments. Also, imaging of small dissociated remains mixed with debris is more efficient with radiography.

Conventional radiographic images can be obtained with mobile or fixed units. Some mobile units are fluoroscopic with the X-ray tube and detector mounted in a “C arm” configuration. “C-arm” units are particularly helpful when searching for small metal fragments. If mobile units are employed and radiography is performed in the autopsy rooms, radiation protection measures should be strictly enforced to protect all personnel. Mobile units may also be used as back up when fixed units are non-operational or as the primary unit for isolation or contamination cases and in field or temporary morgues. Fixed radiographic units in dedicated radiography rooms are the optimal choice in a dedicated forensic facility. Older radiography units utilized radiographic film screen systems and equipment for wet or dry processing. Newer state-of-the-art radiography units are digital and the images are viewed on the computer and archived on a picture archiving and communication system (PACS) network. Over the past decade, there has been an increase in the use of whole body digital scan units in forensic facilities. These units allow for the rapid acquisition of a whole body radiograph with little manipulation of the body. In addition, most of the units can acquire images in orthogonal planes as necessary.

Computed Tomography (CT)

Adding CT to forensic autopsy expands the role of radiology in forensic autopsy, allowing the radiologist or forensic pathologist to view anatomy without dissection. The multiplanar and three-dimensional capability makes the anatomic display of the CT similar to that of autopsy. Cross-sectional imaging viewed in this manner directs the forensic pathologist during dissection, allows injury patterns to be visualized in three-dimensions, detects occult disease or injury, and enables thorough evaluation of anatomic areas that are difficult to dissect. In certain causes of death and forensic scenarios, it is possible that cross-sectional imaging may serve as a triage technique to help forensic pathologists decide which decedents should have a limited or complete autopsy. In those cases that do not undergo a complete autopsy, cross-sectional imaging findings add anatomic information to the external examination and toxicology findings that were previously used alone to determine the cause of death.

The first CT scanners acquired a single slice per rotation but these have been replaced by “multidetector” (MDCT) scanners. MDCT data is acquired as a volume of data in a single scan by using a two-dimensional array of detector elements along the long (z-axis) of the body enabling the scanners to obtain 4, 8, 16, 64, or more slices with each rotation of the x-ray tube. MDCT enables rapid acquisition which is not a necessity in the postmortem imaging where motion does not occur, however, its speed in obtaining a whole body scan is advantageous. PACS networks are necessary to store and retrieve the data and post-processing workstations are necessary to view and manipulate the images for interpretation. Note: For the purpose of this presentation, MDCT and CT will be used interchangeably.

A variety of protocols can be used to obtain scans. Protocols specify the technical and anatomic parameters for obtaining scan data, reconstructing scan data into images, and reformatting images into anatomic planes. Scanning protocols can be organized for specific anatomic regions of the body similar to clinical scanning protocols or can be more generalized to obtain full body data. Protocols should be established according to the technical capabilities of the specific scanner used. Older scanners have table travel of 1.5 meters which means that whole body scans usually require repositioning and another overlapping scan to do a complete survey. Newer scanners have a table travel of 2 meters. Thus, repositioning is usually not necessary.

We scan all of our decedents with their arms at their sides. The total body scans are obtained from the skull vertex to distal point allowable by table travel (up to 2000 mm). The scanning parameters for the total body scans are dependent on the machine but since radiation exposure is not a consideration we recommend obtaining isotropic slices for maximum resolution. [Example: our parameters are detector configuration 16 x 0.625, pitch 1.375:1, table speed 13.75 seconds, reconstruction thickness 0.625 mm, and reconstruction interval 0.625 mm.] Clinical CT scanning has parameters for each body region. In whole body scanning a compromise is to use a general soft tissue protocol. We found an exception to this was needed to optimally image the brain and developed a dedicated head CT protocol. [Example: our head scans are acquired axially with a slice thickness of 2.5 mm and a slice interval of 2.5 mm, with the CT gantry angled parallel to the orbital-meatal line.] All scans can be reconstructed and typically two separate series, one using a soft tissue algorithm and one using a bone algorithm and viewed in multiple window and level settings. Special protocols such as CT angiography (contrast injections) have also been used. Images are viewed on the PACS workstations in multiple window settings to optimize depiction of pathology and injury. Three-dimensional workstations are preferred for image manipulation and reformations. The software developed for image processing in clinical radiology is also suited for postmortem imaging; no special adaptations are required.

Magnetic Resonance Imaging (MRI)

MRI has superior contrast resolution compared to CT. Consequently, it is a useful technique to image soft tissue alterations and pathologic processes. Postmortem MRI has been used to assess soft tissue and visceral hemorrhage, ischemia, and tumors. However, the technical complexity and availability of MRI make it more complicated to use as a routine imaging modality compared to CT.

Ultrasound

Although not as commonly used in forensic medicine as CT and MRI, ultrasound has been reported to be an effective imaging modality in autopsy diagnosis. Ultrasound is less expensive and more readily available than CT and MRI. It has the potential to be a useful tool when performing limited autopsy or to guide organ biopsy in a minimally invasive autopsy. A major limitation of sonography is the degradation of images by the artifacts produced by air and gas. Soft tissue gas is a major feature of decomposition and this has the likelihood to limit postmortem use.

Other Considerations

Incorporation of cross-sectional imaging modalities such as CT into a forensic facility requires careful consideration of the impact on daily workflow. In our practice, cross-sectional imaging augments standard radiography. If cross-sectional imaging is performed on every case, consistency in the workflow and imaging protocols is essential to avoid error. Our routine protocol calls for all bodies to be scanned fully clothed, in the human remains pouch ("body bag"), as they arrived at our facility. This protocol minimizes disturbance of the body and movement of forensic evidence. However, we sometimes will re-scan a body with arms raised to improve chest and abdomen resolution or to perform an angiographic study.

State-of-the-art radiography, CT, MRI, and ultrasound produce large quantities of digital data. Incorporation of these imaging modalities into a forensic facility requires careful consideration of the space, power, and personnel requirements to operate and maintain these technologies. In addition, a computer network and PACS network is necessary if digital radiography, CT, MRI, or ultrasound are to be utilized. PACS replaces traditional film and allows efficient storage and rapid transmission of images to computer workstations for interpretation or viewing of images.

II. Blunt Force Injury

Postmortem CT is useful to visualize and reconstruct blunt injury patterns prior to autopsy. In some cases, multiplanar and volumetric reformatted CT images may provide better visualization of blunt traumatic injuries than autopsy. Blunt force injuries may also coexist with other injury mechanisms such as blast and thermal injury. Three-dimensional display of head, spine, and pelvic injuries may facilitate the understanding of the mechanism of injury.

Crainiocerebral Injuries

Scalp lacerations and subgaleal hematomas cause focal soft tissue changes on CT. Closed lacerations or those located on the dependent surfaces of the body are usually not visible. Nondisplaced linear skull fractures appear as linear lucencies in the skull and usually involve both the inner and outer table of the skull. Depressed skull fractures have fragments that are displaced inward toward the brain. Three-dimensional volume rendered CT images are very helpful to display the skull fracture pattern, which is often more difficult to appreciate at autopsy because the fractured skull fragments tend to fall apart when the scalp is dissected away from the calvarium. Epidural hematomas are located between the skull and dura. Epidural hematomas are typically biconvex in shape and have mass effect on the adjacent brain.

Cerebral contusions occur with or without an associated skull fracture. On CT, they appear as focal punctate or linear areas of hyperattenuating hemorrhage. Small cerebral contusions are very subtle and difficult to identify on postmortem CT. Surrounding low attenuation edema may be present if the decedent survived for period of time after trauma.

Acute intracranial hemorrhage is high attenuation (80 to 90 Hounsfield units) on CT because the protein in blood has a high attenuation coefficient. During life, hemorrhage reaches its maximum attenuation in the first 2 to 4 hours at which time clot formation and retraction occur. If a decedent survives beyond the acute phase, hemorrhage becomes progressively lower in attenuation. Intraparenchymal hemorrhage will be surrounded by vasogenic cerebral edema, which reaches its maximum at 4 to 5 days. Overtime, the margins of intraparenchymal hemorrhage become less distinct.

Subdural hematomas are located between the dura and the arachnoid membrane. They are crescent-shaped and do not cross dural attachments. Acutely, they are hyperattenuating on CT but may also be mixed attenuation. Chronic subdurals are typically fluid attenuation on CT because they are composed of serosanguinous fluid. We have found it difficult to detect small subdural hematomas that are thinly layered beneath the dura because on postmortem CT the dura appears denser than the adjacent brain and the relative density of adjacent blood is similar to that of the dura.

Diffuse axonal injury classically occurs in the corticomedullary junction of the lobar white matter, corpus callosum, and dorsolateral aspect of the brainstem. CT may be normal or show petechial hemorrhages in the corpus callosum and at the gray-white junction. Postmortem MRI may be more effective at demonstrating diffuse axonal injury than CT, however the findings of diffuse axonal injury on MRI have not been reported to date.

Subarachnoid hemorrhage is seen as a thin layer of high attenuation in the cerebrospinal fluid spaces, cisterns, and sulci on CT. In our experience, it is often difficult to correlate subtle areas of hemorrhage that is suspected on CT with autopsy because blood enters the subarachnoid space during removal of the calvarium.

Vascular injuries to the carotid and vertebral arteries are difficult to diagnose on routine postmortem CT. Hemorrhage in the adjacent tissues is suggestive of an underlying laceration, but the location and extent of laceration is not detectable on cross sectional imaging unless intravascular contrast is administered.

<u>Thoracoabdominal Injuries</u>

Pre-autopsy imaging in blunt chest trauma is useful to show pneumothorax, tension pneumothorax, and the placement of tubes and lines if resuscitation was attempted. Pneumothorax can usually be distinguished from early decompositional gas in the pleural space. The presence of an associated rib fracture, hemothorax, and pulmonary contusion supports the diagnosis of traumatic pneumothorax.

Pulmonary contusions most often occur at the site of impact. Airspace consolidation and opacification in a nonsegmental distribution is a characteristic finding. Consolidation in the contralateral portion of the chest is indicative of a contracoup contusion. Pulmonary lacerations may appear as focal consolidations or cavities on CT. They may have surrounding opacity from contusion. Linear tracks of gas through the lung may also indicate communication with a bronchus and an associated tracheal or bronchial laceration. Tracheal or bronchial lacerations may also produce pneumomediastinum.

Hemorrhage in the mediastinum is indicative of a major vascular injury. Aortic lacerations are one of the most common major vascular injuries in blunt trauma. Radiography may show widening of the mediastinum from a periaortic hematoma, blurring of the aortic contour, or thickening of the paratracheal stripe. On CT, mediastinal hematoma is the most indicative finding of aortic laceration. Injuries to the aortic arch branches, pulmonary artery, and vena cava may also produce mediastinal hematomas. Pericardial and cardiac lacerations usually result in pericardial hematomas, which may cause cardiac tamponade. Cardiac contusions and lacerations are usually not evident on postmortem CT.

Diaphragm elevation should raise concern for diaphragm laceration or rupture. Intraabdominal organs may protrude into the thorax when there is laceration or rupture of the hemidiaphragm. Laceration or rupture of the liver, spleen, and other visceral organs may be difficult to identify on routine postmortem CT because of the non-contrast technique. Hemoperitoneum usually has a higher attenuation that simple ascites, which is water attenuation. Focal collections of blood adjacent to an organ or major vascular structure are indicative of injury. The site of injury may not specifically be identifiable on CT. Extraluminal gas within the abdomen is very commonly observed on postmortem CT because the earliest signs of decomposition are observed in the abdomen.

Spine, Pelvic, and Extremity Injuries

Abrasions, contusions, and minor hemorrhages into the soft tissues may not be evident on postmortem CT. Significant hemorrhage into the soft tissues increases the attenuation and thickness of the involved soft tissue. With increasing hemorrhage into the soft tissues, the fat planes become distorted and focal asymmetry develops.

Diagnosis and interpretation of fractures is generally straightforward on radiography. Vertebral body compression fractures and abnormalities in alignment are best viewed on sagittal CT images. Axial images are useful to view the pedicles and posterior elements of the vertebral bodies. Intervertebral disc injuries and spinal cord contusion or hematoma cannot be reliably assessed on CT. We have found CT very useful to screen the bony structures of the spine, particularly the cervical spine because this region is difficult to dissect at autopsy. Three-dimensional images provide an excellent depiction of the anatomic distribution of spine fractures, which can be difficult to appreciate at autopsy.

Complex, comminuted, and open fractures of the extremities are generally simple to diagnose. Fractures of the extremities, hands, and feet are best evaluated with conventional radiography. However, CT has the added benefit of providing soft tissue information that may be valuable in the assessment of the extent and volume of an associated hematoma.

III. Gunshot Wounds

In the evaluation of gunshot wounds, radiography can be used to document the presence or absence of bullets, location of bullets, skeletal injuries, and additional findings such as air in the right atrium and pulmonary outflow tract in an individual with a gunshot wound to the head. As long as the bullet or bullet fragment is radiopaque, there is excellent edge detail of its borders. It must be noted that precise measurement of the dimensions of the bullet is limited by geometric and physical factors during the capture of the image. Although tempting, the caliber of the bullet cannot be determined on radiography. It can only be determined when it is recovered. In determining the location of the bullet using radiography, orthogonal views are necessary to determine the location of the bullet in all three planes of the body. The location and extent of long bone skeletal injuries caused by a bullet is usually readily apparent. However, without orthogonal views, it is often difficult to determine the exact location and extent of axial skeleton injuries. The main limitations of radiography are the inability to determine the location of wound tracks and to detect soft tissue injuries. Additionally, radiographs may not detect non-metal fragments such as plastic or paper wadding which can be projectile components.

Similar to radiography, CT can be used to document the presence or absence of bullets or bullet fragments. In contrast to radiography, the location of these projectiles relative to adjacent anatomical structures can be determined in any plane. Even minute bullet fragments can be located. When there is embolization of a bullet or bullet fragments, the precise location of these projectiles can be demonstrated as the entire body has been scanned. Non-metal fragments such as paper or plastic wadding from a shotgun shell can be visualized with CT. A disadvantage of CT is that metallic objects create a streak artifact and the edge detail of the projectile's borders is blurred. This may make it difficult to determine the shape of the projectile prior to recovery. This is why we continue to perform radiography in conjunction with CT.

CT is effective in documenting skeletal injuries caused by gunshot wounds. The characteristics of the fracture pattern may help with the determination of trajectory of the bullet through the body. Three-dimensional images can be reformatted to demonstrate the extent of skeletal injury where there are complex fractures such as in the case of a contact gunshot wound to the head. Caution must be taken when creating these images as the 'smoothing' software can mask injury. It is our opinion that these reformatted images are best suited for demonstrative aids and that the planar views are used for the diagnoses.

The ability of CT to detect soft tissue injury due to gunshot wounds depends on the organ and the ballistic characteristics of the projectile. In soft tissue, gas ("air") and hemorrhage are the principal markers of injury. However, gas in blood vessels, organs, and body cavities is also a common feature of decomposition. Careful selection of the optimal CT window and level setting is necessary to observe all of these critical findings. In the brain, decomposition decreases the tissue attenuation and provides contrast to the adjacent hemorrhage which has high contrast. Thus, a gunshot wound that has significant hemorrhage around the bullet path due to the permanent and/or temporary cavity will be readily detected. Similarly in the lung, hemorrhage is higher in attenuation compared to the normal surrounding aerated lung. However, organs such as the heart, liver, and spleen are usually isoattenuating with hemorrhage. In these organs, linear collections of gas within the organ and disruption of the outer contours are the markers of injury. The gastrointestinal tract is difficult to evaluate for injuries due to a gunshot wound because the intestines are often collapsed and the presence of pneuomatosis is an unreliable sign. As described in the section on blunt force injury, additional findings such as a hemothorax due to injury of a major vascular structure, are usually readily apparent. However, it is usually not possible to discriminate the specific vascular injury. A technique to overcome this limitation is post-mortem angiography where radiopaque contrast material is injected into a vessel and images obtained.

In terms of determining the path of the bullet through the body, the radiographic wound track is the "visible" remnant of the temporary and permanent cavities caused by the bullet. In many cases, the path of the bullet through the body can be determined using CT. As stated above, the principal markers for injury to soft tissue (including major organs) are gas and hemorrhage. For bone, fractures and bone fragments in adjacent soft tissue are the principal markers of the wound track. In some cases, the direction of the wound track can be determined based on the location of bone fragments in adjacent soft tissue and/or the pattern of fractured bone. The beveling of the skull that has been used for decades by forensic pathologists to aid in the trajectory of the bullet through the skull can be demonstrated on CT images. Since the images can be viewed in any plane, it is possible, in select cases, to view the track of the bullet on a single image. However, it must be understood that many factors affect the trajectory of a bullet within the body and this may not always be a linear path. In addition, the body position at the time of injury maybe completely different from position at the time of imaging. As a consequence, individual injuries such as fractures of different bones may not form a straight line even though the trajectory of the bullet through the body was linear. One limitation of CT is the difficulty in determining the location of the entrance and exit wounds on the surface of the skin. Optical surface scanning and the placement of radiopaque markers on the skin surface at the location of the wounds have been used to overcome this limitation. Another limitation of CT is the determination of the range of discharge of a firearm. Even with surface rendering, it is not possible to definitively visualize soot deposition or abrasions caused by gunpowder.

IV. <u>Postmortem Changes and Artifacts</u>

Postmortem change and decomposition are always present at autopsy and on postmortem CT because they begin to occur immediately upon death. Consequently, the appearance of postmortem change and decomposition on postmortem CT can be considered normal and should not be mistaken for a pathologic process or injury. Postmortem change and decomposition are important findings on MDCT because they may obscure soft tissue injury or pathology, thereby limiting the CT assessment of soft tissue for hemorrhage, laceration, and wound tracks in cases with suspected trauma. Putrefactive gas should not be mistaken for pathologic gas collections that may have contributed or causes of death such as air embolism, pneumothorax, pneumoperitoneum, or gas forming infections. Gas in anatomic spaces and in blood vessels can generally be considered putrefactive when it is present symmetrically throughout the entire body. However, asymmetric or focal gas collections should be viewed as suspicious and related to an underlying pathologic process or injury unless there is an explanation for focal or asymmetric decomposition.

Livor Mortis

Hemoconcentration from postmortem livor mortis results in increased attenuation of the affected organs, vasculature, and tissues on CT. This finding is easily observed in large caliber arteries and veins as well as the cardiac chambers. In these structures blood separates into serum and erythrocytic components due to the effect of gravity. This produces a fluid level on CT. High attenuation erythrocytes layer dependent to plasma in the cardiac chambers and when supine, in the posterior aspects of the great vessels. The vessel wall on the nondependent side appears relatively dense because of the attenuation difference between the vessel wall and serum component of the blood. This is most noticeable in the aorta and is also frequently observed in the posterior dural sinuses of the cranial fossa. Small caliber blood vessels such as the cerebral arteries may also have higher attenuation; hyperattenuation should not be mistaken for cerebral or pulmonary thrombosis.

Visceral livor mortis is most commonly identified in the lung parenchyma on postmortem CT because of the inherent attenuation differences between aerated lung and the pulmonary vasculature. It causes an increased attenuation in the dependent lung. There may be a vertical gradient with increasing attenuation from the nondependent to the dependent portions of the lung parenchyma with increasing degrees of livor mortis. Dependent settling of pathologic pulmonary venous congestion and edema within the lungs and pulmonary consolidation from an infectious or neoplastic process must be differentiated from livor mortis. The cutaneous and subcutaneous manifestations of livor mortis are much less profound on CT when compared to gross examination of the body. There is increased attenuation of the dependent subcutaneous fat and dermis and dependent dermal tissue thickening.

Rigor Mortis and Algor Mortis

Postmortem CT shows no specific findings for rigor mortis or algor mortis. Rigor mortis is most important in positioning the body on the CT scanner table and in some cases may be an obstacle to positioning and passage of the body through the CT gantry. It is possible to physically overcome or “break” rigor and this can be considered in cases in order to permit CT to be accomplished, however, this must be done in conjunction or by the forensic pathologist since rigor status is a forensic finding and iatrogenic injury can be produced if the procedure is not done properly.

Decomposition

We have found it helpful to classify the spectrum of decomposition observed on MDCT as early, moderate, and advanced. This is specifically helpful when there are injuries or pathologic processes suspected that might be associated with the findings of gas in internal organs or vasculature.

One of the earliest signs of decomposition on CT is cerebral autolysis. There is usually some evidence of cerebral autolysis by CT in the majority of bodies that are scanned and autopsied more than 24 to 48 hours after death, even if a body has been stored in the mortuary cooling chambers. The CT features of cerebral autolysis include blurring and loss of definition of the grey-white matter junction, decrease in cerebral attenuation, and effacement of the sulci and ventricles. Within 2 to 3 days, there is progression of autolysis and complete loss of grey-white matter differentiation on CT and the cerebral ventricles and sulci become effaced. As the brain softens, it settles in the gravity dependent portion of the calvarium and gas fills the nondependent portion of the calvarium. At this stage, putrefactive gas may be present within the vascular structures and intracranial spaces. However, putrefactive gas may also be seen within the vasculature before brain settling is evident on CT. Finally, with complete cerebral liquefaction, the brain is water attenuation on CT and there is a fluid level within the calvarium.

The intestinal wall and mesenteric and portal venous systems are generally the first sites of putrefactive gas on CT in addition to the small and large intestine, which may be distended with gas from proliferation of intestinal bacteria. Body cavities such as the pleural and peritoneal spaces may contain a small amount of fluid. The fluid may be putrefactive fluid (purge fluid) or liquefied fat. The latter is more common in the abdominal cavity from liquefied omental, mesenteric, and retroperitoneal fat. Small volumes (10 to 20 ml) of pleural fluid are considered normal at autopsy and are typically easily differentiated from pathologic collections of fluid in the pleural cavity. As putrefactive decomposition progresses, gas enters all vascular structures and potential anatomic spaces. Putrefactive gas is normally symmetrically distributed throughout the body unless there is focal or asymmetric decomposition from an underlying injury or a focal cause of warming or cooling of the body.

Although the pancreas and adrenal glands are among the earliest internal organs to undergo autolysis, they generally have a normal appearance on postmortem CT until putrefactive gas is present. With moderate putrefactive decomposition, the pancreas may be observed to have a disproportionate amount of gas compared to other abdominal organs. Gas appears within the vasculature of the visceral organs in the early postmortem period at the same time that gas appears in other vessels throughout the body. The CT attenuation of the solid visceral organs such as the liver, spleen, and kidneys does not change until the advanced stages of decomposition when the organs begin to fragment, degenerate, and liquefy. In moderate stages of decomposition, visceral organs are still normal in shape and contour. Eventually, the connective tissues collapses and the organs are not recognizable in shape and appearance. Gas fills the abdominal and chest cavities as the organs collapse and liquefy.

Insect activity and animal predation are features are usually easily recognizable on gross examination; and to some degree be seen on postmortem imaging. The appearance of insect activity and animal predation should not be mistaken for pathologic processes or injury when interpreting postmortem CT. Larvae are linear and curvilinear soft tissue or surface irregularities on CT. Animal predation is characterized by one or more bite marks in soft tissues and bones. Often there are innumerable marks from small mammals such as rodents or dogs gnawing on the corpse.

The formation of adipocere in severely decomposed bodies preserves the subcutaneous tissues and portions of internal organs. It has a characteristic low attenuation appearance on CT. Because adipocere formation frequently coexists with putrefactive decomposition, both processes may be present revealing a body that has absent or partially decomposed internal organs and intact skeletal structures surrounded by adipocerous subcutaneous fat.

V. Future Directions

Integrating cross sectional imaging into a forensic environment has implications for both the practice of forensic pathology and radiology. We have found that cross-sectional imaging adds objective, reproducible anatomic data to autopsy. The ability to review and reconstruct the anatomic findings at the time of autopsy at a later date is invaluable. When used as an adjunct to autopsy, cross-sectional imaging provides an anatomic overview of the body prior to dissection. Abnormalities are localized more efficiently when the images are reviewed prior to autopsy; anatomic areas that are difficult to access at dissection are evaluated on images; complex fracture patterns are better visualized; and, occult injury may be detected. Our experience has been based upon strict radiologic-parhologic correlation because all of our cases undergo both imaging and forensic autopsy. This model is appropriate for facilities starting to do advanced forensic imaging.

Cross-sectional imaging may potentially serve to augment a limited autopsy or, in some cases, replace autopsy. CT and/or MRI may be very useful tools to exclude occult trauma or disease in a limited autopsy and to triage cases for autopsy in mass casualty scenarios. Ongoing and future study comparing the accuracy of cross-sectional imaging to autopsy is necessary to validate and establish the effectiveness of imaging modalities in the determination of the cause of death. Such material will also needed to support courtroom use of the data. Since radiographs have been accepted and CT is an extension of this technology it is not likely this will be a problem. There could, however, be questions raised about use of CT data to reconstruct 3D images.

The most important limitation in integrating cross-sectional imaging with autopsy is the cost and availability of CT and MRI scanners and personnel. Purchase and installation of state-of-the-art equipment in a forensic facility may be prohibitive for some jurisdictions. As an alternative to an on-site scanner, medical examiners may choose to collaborate with local radiology practices or hospitals in order to obtain imaging studies on decedents. When making the decision to use postmortem CT and MRI, it is important to realize the strengths and weaknesses of each imaging modality because each has unique benefits and limitations.

Workflow

Although the standard practice in forensic facilities is to radiograph and image human remains before physical autopsy begins, the timing and circumstances of the imaging can be varied based on the workflow in a particular forensic facility. All possible options that comply with prescribed forensic guidelines should be considered when establishing a forensic workflow that includes radiography and cross-sectional imaging. The decision on when to obtain radiographs and cross-sectional imaging should be based on the processing scheme of the facility and the physical location of the radiologic equipment.

At our facility, intake photography and identification precede radiologic examinations. After the radiologic exams are completed, the remains undergo forensic dental examination followed by autopsy. While this workflow has advantages of efficiency and maintains an organized chain of custody, radiographs and CT images show external debris, clothing, and personal effects on the body. In some cases, these can be detractors because they may create artifacts on the images. However, the imaging does reflect the physical relationship of clothing, personal effects, and in some cases, medical devices at the time of death. If there is significant artifact from external debris, clothing, or personal effects, re-imaging after the body is cleaned may be necessary.

There are advantages to imaging the body after it has been cleaned and had a preliminary external examination. Some facilities may find that this fits their workflow better, particularly if the imaging equipment is at another location and transport could affect external evidence. Artifacts from clothing and debris are eliminated and metallic markers can be placed on the skin surface to identify wounds so that their precise location appears on the images. If imaging is performed after external examination, medical devices (e.g., tubes, lines, and catheters) should be kept in place so their position and possibly their effectiveness can be assessed on the images. Consideration should be given to separately radiograph clothing and other personal effects to check for metallic evidence or other findings that may have been overlooked. The disadvantage of this sequence is the disruption of the continuity between external examination and dissection.

Cost effectiveness of using expanded imaging in the death investigation process has yet to be established. Will cross sectional imaging allow a medical examiner to do more cases? Can the operation of complex imaging equipment be done by autopsy technicians or will radiology technologists need to be hired? The budgetary issues are certain to impact the speed in which cross sectional imaging gets accepted and adopted. Scientific study will help to resolve the issues but this in turn has to be supported through research grants.

Other Applications of Cross-sectional Forensic Imaging

The documentation of intravascular lines, chest tubes, endotracheal or nasotracheal tubes, airway devices, tracheostomies, and nasogastric tubes, as well as less common devices such as intraosseous infusion catheters is part of the autopsy external examination. CT adds to this assessment by providing multiplanar two and three-dimensional images of the position of these devices since the internal positioning of most tubes and lines are easily established. We emphasize that CT assesses device position at the time the postmortem CT only because devices can shift position during transport and handling of the body. In addition, the clinical effectiveness of a particular device cannot be assessed because there are complex physiologic factors involved in injury and resuscitation sternum.

Second autopsy can be performed before burial or after exhumation. CT facilitates the anatomic evaluation of exhumed bodies by providing a noninvasive anatomic assessment. If no autopsy was performed prior to burial, CT assists in localization of key anatomic organs and skeletal structures that may have shifted position during the decay process. This can be particularly helpful in intermediate to advanced stages of decay.

Anthropologists study found human remains for age, gender, stature, and ethnicity by analyzing anthropomorphic features and osteometric criteria, which may help to establish identity. Reassembly of skeletal remains helps to further identify and classify findings that may help indicate the cause of death. Radiography and CT scanning of the reassembled remains is superior to imaging bones individually or collectively. Images of a partially or completely reassembled skeleton better depict injury patterns and show the relationship of wounds to one another.

Intact human remains and dissociated human remains may be found during the investigation of catastrophic trauma or large-scale disaster events such as hurricanes, floods, mass transit accidents, aircraft accidents, and explosions. Recovery and identification of all human remains is one of the most important objectives of these investigations. In addition, forensic pathologists may be asked to determine if cause of death was related to the event circumstances or was a homicide. CT has been proposed as a means of autopsy triage. On occasion, dissociated remains may be matched when specific bony landmarks or features are identified on CT.

Training and Education

Postmortem forensic imaging draws on two bodies of knowledge: forensic pathology and radiologic imaging. Educationally these have been two separate pathways. It is logical to assume that at some point they will overlap and this likely will be at the fellowship level. At this point radiologists will need to learn forensics and pathologists to learn about acquisition and interpretation of cross sectional images. The opportunity for such training will only be possible where pathology and radiology facilities have incorporated cross sectional imaging into forensic practice. This will probably be Medical Examiner Offices which have acquired equipment or arranged for a nearby radiology facility to perform the imaging. The required time for obtaining the skill set needed to be a "forensic radiopathologist" could be based upon the number and type of cases studied. In this way experienced forensic pathologists and radiologists could supplement their existing skills quickly. Current credentialing bodies like the ACGME might be involved with criteria at the fellowship level but it is also essential that organizations like CAP and NAME become involved so that standards for training and practice have appropriate oversight.

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