Chapter 8
The Use of Radiology in Mass Fatality Events

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History

On December 28, 1895, Wilhelm Conrad Roentgen submitted his manuscript "On a New Kind of Ray" outlining the essential features of X-rays to the Würzburg Physical Medical Institute (Roentgen 1895). The new discovery aroused considerable interest. Roentgen's description of the ability to see through the body was greeted with incredulity by the scientific community, and early descriptions went to great lengths to reassure the public that this was indeed a serious discovery by a respected scientist. Within months of Roentgen's announcement, X-rays were in widespread use for a plethora of medical and scientific applications as well as some more frivolous uses (Burrows 1986).

Roentgenography, or radiography as it is now better known, utilizes the principles of the absorption of X-ray photons to demonstrate differentiations in atomic structure of the subject under examination. To the scientists of the late 19th century, the ability to conduct non-invasive examinations of animate and inanimate objects was nothing short of miraculous and made readily accessible by the fact that such examinations could be achieved with equipment that was relatively simple to assemble from instruments easily available throughout the Western world (Brogdon and Lichtenstein 1998).

It is no surprise then that this new tool was quickly applied to forensic examination and to the examination of the deceased. Within months, X-ray examinations had contributed to the forensic investigation of the cause of death and injury in murder and attempted murder cases in the UK and United States, negligence cases in the UK, United States, and Canada, the examination of suspicious packages, archaeological examination of Egyptian mummies, authentication of oil paintings, and numerous other forensic applications (Eckert and Garland 1984; Evans et al. 1981; Glasser 1931; Halperin 1988).

X-ray imaging techniques are minimally invasive, objective, permanent, and comparatively cost-effective. As a result, radiographic imaging is now in common use throughout many aspects of forensic investigation.

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Uses of Radiology for Analysis and Human Identification

The possibility of applying this new and exciting tool in the field of human identification was soon under discussion. As early as May 1896, Bordas suggested that X-rays be used "... for identification through the visualisation of old fractures, bullets, or other known peculiarities ..." (Brogdon and Lichtenstein 1998). In the same year, Angerer suggested that observation of wrist bone development could be used to measure bone age (Goodman 1995). In 1899, Levinsohn recognized that X-ray images could provide more accurate measurements of the skeleton than the then-popular Bertillon method of anthropological classification, which relied on external measurements and was thus subject to variation (Levinsohn 1899).

Radiology is now widely used to assist in the analysis and identification of human remains, and the applications of the use of X-rays first suggested by Levinsohn, Angerer, and Bordas comprise the main methods by which medical imaging contributes to the identification and investigative process. Radiological imaging has the advantage of enabling the examination of remains in a variety of states of decomposition from fully fleshed to completely skeletonized. As such, it affords the opportunity to obtain a considerable amount of data without the need to clean and completely deflesh the remains. It provides the investigative team with a rapid method of triage and classification by answering a number of fundamental questions:

- Determination of human vs. nonhuman remains
- Recognition of commingling
- Evaluation of the biological profile (age, sex, stature, and ancestry)
- Recognition of embedded/hidden foreign objects
- Interpretation of trauma
- Positive identification of individuals by comparison of antemortem and postmortem radiological data

Human Versus Nonhuman

In most cases involving animal bones that are brought to the attention of forensic investigators, a simple visual examination is all that is necessary for the trained anatomist or osteologist to determine nonhuman characteristics. In some cases, however, the most distinctive parts of the bones, the articular surfaces, may be missing due to fragmentation, decomposition, or animal activity. In such cases, radiographic examination of the bone structure and trabecular pattern can be useful in determining human from nonhuman remains (Brogdon 1998b; Chilvarquer et al.1987).

Recognition of Commingling

In cases involving large amounts of fragmented remains, such as a mass fatality incident, remains may be commingled and mixed with large amounts of debris and artifacts. Physical examination of such remains, particularly in cases of fire damage where there is a uniformity of discoloration of all samples retrieved, is both difficult and time-consuming. In such cases, radiological examination can prove useful in determining the presence of one or more individuals but also in identifying and locating small body parts, especially teeth, which may otherwise be overlooked in the absence of a thorough and time-consuming fingertip search (Goodman and Edelson 2002; Kahana et al. 1997; Viner et al. 1998). The use of radiological methods in this context will be discussed in greater detail later in this chapter.

Age Estimation

The development and maturation of the skeleton from birth through childhood, puberty, adolescence, and early adulthood provides reliable age indicators. The appearance and fusion of primary and secondary ossification centers within the developing skeleton follows a predetermined chronological pattern and, in the same way that a physical examination of the defleshed skeleton can determine age at the time of death, so can skeletal radiography deliver the same information in the case of less decomposed remains. There are a number of radiological standards for determination of bone age throughout the first two decades of life, based upon the appearance and fusion of the secondary ossification centers. The final epiphysis to fuse is the medial end of the clavicle, normally occurring during the mid- to late 20s.

In addition to dental development, one of the most useful examinations in determining the age of children is radiography of the hand and wrist, although examination of the knee, foot, and ankle can also be helpful (Greulich and Pyle 1959; Hansman 1962; Hoerr et al. 1962; Pyle and Hoerr 1955; Scheuer and Black 2004). In the mature skeleton, it is the degenerative changes that begin to appear at the margins of the articular surfaces of major joints at around age 40 that will allow the experienced radiologist to estimate adult age (Brogdon 1998b). Calcification of the costal cartilage associated with the ribs and sternum may be readily visualized in people over 50, although it is sometimes observed in younger subjects (Mora 2001). Although chest radiography demonstrates this calcification, its specificity as an aging method is reduced due to similar amounts of mineralization throughout adulthood (McCormick 1980). It is, however, a quick, inexpensive method to obtain a general age estimate that can be used along with other anthropological examinations (e.g., pubic symphysis morphology).

Sex Determination

Differentiation of sexes by skeletal radiology is unreliable until after puberty, as the features that distinguish male from female are not sufficiently developed until this point (Krogman and Iscan 1986). Although on examination the appearance of the male skeleton is more substantial than the female, being generally heavier and the long bones of greater length, it is the examination of certain specific bones that is most useful in determining the sex of an individual. In particular, the shape, size, and geometry of the pelvis (Kurihara et al. 1996; Rogers and Saunders 1994; Sutherland and Suchey 1991), skull, and mandible (Bass 1990; Kurihara et al. 1996) and patterns of calcification of the costal (Navani et al. 1970), tracheobronchial, thyroid, and arytenoid cartilages (Kurihara et al. 1996) can be used to determine sex from skeletal remains by radiological means (Brogdon 1998b).

Stature Estimation

Physical anthropologists are able to make estimations of stature by direct measurement from unfleshed human remains. The length of the femur is usually used, as this has been shown to be reliable (Trotter and Gleser 1952, 1958). In the case of fleshed remains, the same measurements can be made radiographically, provided that correction for magnification is made. This can be achieved by means of an adapted radiographic technique, applying a simple correction factor, or by utilizing modern imaging techniques.

Adapted Radiographic Techniques

By far the simplest method is to utilize a long focus to object distance (FOD) of 180 centimeters and a minimal object to film distance (OFD), by placing the limb directly on the cassette or nonscreen film packet. This will effectively negate any magnification (Maresh 1943).

Another simple method is to take a series of images of the leg on a single film using a narrow-slit aperture X-ray beam directly above each joint space, so as to use the central ray for each image, avoiding divergence. A ruler with radiopaque markings is positioned adjacent to the leg, and measurements are read directly from the film (Bryan 1979). Alternatively, a scanogram technique can be used. The limb is positioned on the cassette together with the radiopaque ruler, as for the previous method. However, instead of taking a series of images over each joint, the X-ray tube (with narrow-slit aperture X-ray beam) is moved along the length of the limb during a long X-ray exposure (Bryan 1979).

Applying a Correction Factor

By applying a correction factor to the measured size of an object on the film, the actual size of the object can be determined. The correction factor is the distance of the object from the focal spot of the X-ray tube divided by the distance of the film from the focal spot of the X-ray tube (Jenkins 1980). Thus, $\mathrm{CF} = (D - d)/D$ (Fig. 8.1).

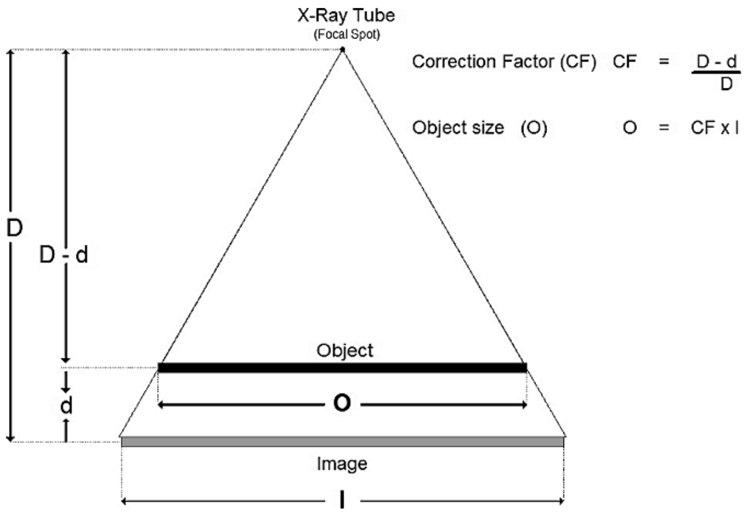


Fig. 8.1 Correction factor to determine the actual size of an object by measurement from the radiographic image

CT Scanning and Digital Radiography

CT scanners and digital X-ray systems can be calibrated to undertake this correction calculation automatically, thus allowing measurements to be made directly from the image. In the case of CT scanning, a scanogram is performed using the scanner to undertake an automated version of the manual process described above (Aitken et al. 1985). Digital X-ray machines using a slit beam can also be used to take direct measurements from the resultant scans, and many other direct digital X-ray machines can be calibrated so as to render accurate anatomical measurements from the resultant images (Beningfield et al. 2003).

Determination of Ancestry

Determination of ancestry is challenging, especially when the remains are badly decomposed or skeletonized. Similar methods to those used by physical anthropologists to determine ancestry from skeletal remains can be applied radiographically with fleshed remains. In particular, examination of the skull and mandible (Bass 1990; Fischman 1985), the distal end of the femur (Craig 1995), and the ratio of long bone length can be useful in determination of population ancestry (Krogman and Iscan 1986).

Recognition of Embedded/Hidden Objects and Interpretation of Trauma

X-ray imaging can be utilized to detect and retrieve hazardous objects, personal effects, projectiles, aircraft parts, and other artifacts and forensic evidence, especially when body fragmentation is extensive (Fig. 8.2). It can assist with determination of the manner of death, document trauma, negate the requirement for invasive autopsy, permit anthropological assessment without the requirement for defleshing, and, of course, establish identification through positive matching of postmortem and antemortem data (Gould 2003; Viner 2001a, b, c). It has proved particularly useful in mass fatality incidents resulting from air disasters (Alexander and Foote 1998; Mulligan et al. 1988; Viner et al. 1998), explosions, and terrorist incidents including suicide attacks (Harcke et al. 2002; Kahana et al. 1997; Nye et al. 1996; Society of Radiographers 2005; Viner et al. 2006). Radiological methods have also been employed extensively in the investigation of war crimes and human rights abuses involving the exhumation of buried human remains (Gould 2003; Tonello 1998; Viner 2001a). In such incidents, the systematic application of radiology has proved essential to the investigation and identification of victims.

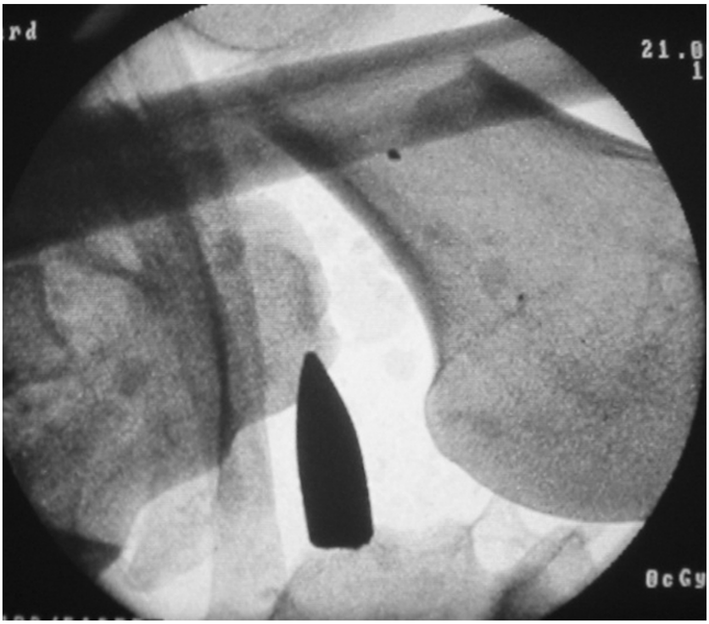


Fig. 8.2 Fluoroscopic image of commingled human remains recovered from a crime scene reveals the presence of ballistic evidence

Positive Identification of Individuals by Comparison of Antemortem and Postmortem Radiological Data

Some of the methods of identification (such as fingerprint analysis) depend upon the integrity of the soft tissues of remains (Brogdon et al. 2003). In some cases involving skeletonization, fragmentation, decomposition, incineration, mutilation, or other disfigurement, identification by means of the skeleton and highly resilient dentition assumes a greater importance; it is here that X-ray imaging comes into its own. Such incidents are often characterized by damage to the soft tissues caused by fire or water or severe disarticulation due to explosion or rapid deceleration injury.

Radiological identification of human remains requires specific and unique findings on postmortem images to be matched exactly with antemortem images of the individual. In some cases, identification can be made from a series of relatively common or nonspecific pathological anatomical changes that appear in identical locations in ante- and postmortem images. In other cases, a single unique feature is sufficient (Brogdon 1998a). In 1927, Culbert and Law (1927) made the first identification of human remains by comparison of antemortem and postmortem radiographs of the frontal sinuses. The degree of human variation in sinus patterns, based on size, asymmetry, outline, partial septa, and supraorbital cells, makes effective comparison for identification possible (Kirk et al. 2002; Marlin et al. 1991; Nambiar et al. 1999).

Medical imaging has long been used for the identification of human remains and is well documented (Binda et al. 1999; Buchner 1985; Craig 1995; Jensen 1991; Kahana and Hiss 1997; Murphy et al. 1980; Sanders et al. 1972; Schwartz and Woolridge 1977). Radiology is used extensively in anthropological and odontological assessment of postmortem and antemortem radiographs, records, or other images for concordance, as they represent an excellent source of data for comparison of anatomical features (Fig. 8.3). Many specific cases have been reported in which radiology has played the leading role in the identification of human remains (Goodman and Edelson 2002; Greulich and Pyle 1959; Kahana et al. 1997; Viner et al. 1998). Binda et al. (1999) even report on a case where radiology proved to be more accurate than DNA

Radiographs taken for medical purposes are often required by statute to be retained for long periods of time. In the UK, for example, the Department of Health requires that radiographs are retained for 8 years, and longer in the case of children (until the patient reaches his 25th year), and 3 years following death (Dimond 2002). In many cases, particularly in privately run clinics, radiographs are routinely given to the patient for safe keeping and thus may be in existence for much longer than the statutory period. With the advent of digital imaging and the decreasing cost of digital storage, many institutions are retaining medical images far beyond their previously applied practice for X-ray film. Records are thus, on the whole, fairly accessible.

The last assessment of the frequency of medical and dental X-ray examinations undertaken by the National Radiological Protection Board (NRPB) in the UK for the year 1997–1998 showed an overall examination rate of 704 examinations per 1,000 head of population per annum. Of this figure, 30% were dental radiography

(a)

Fig. 8.3 (continued)

(b)

Fig. 8.3 A previously healed fracture of the tibia and fibula (2a) offers the possibility of identification by radiology as such trauma will usually have been well documented at the time of the original injury and throughout the healing process. This subject was later identified by comparison of the postmortem radiograph (2b) with an antemortem film

examinations, with a total of 494 examinations per 1,000 head of population being medical X-ray examinations. This figure was almost exactly half of the rate for medical examinations in the United States. The great majority of examinations were conventional X-ray studies (79%), with the majority of these being teeth, chest, and limb radiographs, which accounted for 75% of all examinations. A further 15% were pelvis, spine, and hip examinations. CT examinations represented 5% of the total (9% in the United States), with 50% of these being head and neck, 30% abdomen and pelvis, and 14% chest (Tanner et al. 2001). This position echoes Brogdon's evaluation of the distribution of radiological examinations by body part and modality in the United States undertaken during the same period. As Brogdon asserts, examinations of the chest demonstrate consistency of bony structures over time, and extremities may contain useful radiographic identifiers due to previous injury, degenerative change, or malformation (Brogdon 1998a). All of the above points to a wealth of useful antemortem data being available to the investigator, with the possibility of obtaining a clear and decisive identification if postmortem and antemortem data can be matched.

As demonstrated by the NRPB study, radiographic examinations of the skull have declined dramatically since the advent of CT scanning, and antemortem radiographic data are thus less likely to be available. However, positive identification can be established by CT by comparison either with other CT scans or with some conventional radiographs (Brogdon 1998a; Reichs and Dorion 1992).

Imaging Modalities

Until recently, much forensic examination of the deceased carried out in the Medical Examiner's office or incident mortuary has relied on traditional X-ray technology, which is little changed from the time of Roentgen. In recent years, however, some of the newer technologies that have been available within hospitals and clinics have been used for the forensic examination of the deceased. Most recently, these have included computed tomography scanning (CT) and magnetic resonance scanning (MR) (Bisset et al. 2002; Brookes et al. 1996; Thali et al. 2003).

All of the imaging modalities described in this chapter rely upon the principles of the absorption of X-ray photons to demonstrate differentiations in atomic structure of the subject under examination. In order to achieve a satisfactory result, it is essential that the operator is conversant with the physical principles of X-ray interaction with matter and has a sound knowledge of human anatomy.

Contrast and density on the resultant image are dependent upon the chemical composition of the subject under examination, the energy of the X-ray photons [determined by the peak kilovoltage (kV) applied across the X-ray tube], and the number of photons reaching the film or digital detector [determined by the milliamperage (mA) applied to the coil of the X-ray tube, the time of the exposure, and the distance of the film or receptor from the X-ray source]. It is essential to match the kV applied to the body part under examination in order to achieve an optimum result. Even small variations can enable visualization of anatomical structures that would otherwise be missed, particularly in the juvenile skeleton.

The examination technique, imaging system (be it either film or digital technology), and a number of other factors, including the structure of the examination table, will introduce a number of additional variables that will all need to be taken into account to produce the optimum result. In the case of the photographic image, these factors are also dependent upon the availability of consistent processing conditions that rely upon accurate temperature control, regular replenishment of appropriate chemicals, and control of development time. For these reasons, it is desirable that examinations are conducted by a trained radiographer and are undertaken on equipment that has been regularly and appropriately maintained and is subject to a regular quality control program. As Brogdon points out,

> . . . the person who actually positions and exposes the roentgenograms is absolutely critical to the success of the entire endeavour. The educated, experienced, and sophisticated eye of the radiologist or other professional observer may be required to detect and interpret the subtle nuances recorded on the film, but without adequate technical support, that eye will be blinded. (Brogdon 1998a)

Discussion of all the available imaging modalities is not possible here, and this section will focus on those techniques that may be more commonly used in the examination of commingled human remains resulting from mass fatality incidents.

Film Radiography

The radiograph, as demonstrated by Roentgen, still remains as the method of choice for the examination of the skeleton. It delivers a high-quality image of skeletal structures and can be relatively easily and cheaply acquired and replicated. The radiograph is in essence a "shadow-gram," a still-life image produced by radiation emerging from a subject and striking a sheet of film (Fig. 8.4). The film is developed using a standard photographic process, resulting in a negative image in which the dark areas represent those areas of the subject through which a greater number of X-ray photons have been transmitted.

Since the early days of radiography, it has been common for the majority of the image to be formed, not by radiation, but by light emitted by phosphorescent "intensifying screens" placed on either side of the sheet film in a cassette. These screens emit light in proportion to the number and energy of the X-ray photons absorbed within them. While this considerably reduces the exposure time and thus the radiation dose, it can introduce a degree of unsharpness to the image. For this reason, a wide range of screen types are available, both for general and more detailed skeletal work, where the unsharpness is minimized within the intensifying screens. For optimum trabecular detail, nonscreen film may be used, and this type of examination is favored for the examination of samples in a lead-lined "Faxitron"®machine where such minute detail may prove to be of value. For the majority of examinations, and certainly in the mass casualty situation, the speed and ease of use of a film/screen combination will suffice.

Fluoroscopy

One of Roentgen's earliest observations was that of a fluoroscopic image (Burrows 1986). In fluoroscopy, a continuous "beam" of radiation is directed at and passes through the subject under examination. The emergent rays strike a fluorescent screen that emits light in proportion to the energy of the incident X-ray photons falling upon it. This image, visible to the naked eye, is amplified several thousand times via an "image intensifier" and is recorded and projected onto a computer screen via a closed-circuit TV system (Fig. 8.5).

The resultant image is viewed in "real time." Thus, as the apparatus is moved over the subject, the image seen reflects the movement over the subject, thus allowing rapid coverage of a scene in the same way that a video camera can be panned over a landscape. Alternatively, the apparatus can remain stationary, and any movement of the subject will be detected and demonstrated upon the image.

Fluoroscopy offers significant advantages to the investigator, particularly in the examination of commingled human remains following a mass fatality incident. The real-time nature of the examination makes it particularly suitable for rapid examination of body bags as a triage method. The resultant image, derived from the relative density of objects, rather than their appearance, makes it a simple matter to identify even small fragments of bone and teeth among debris, personal effects, and possible items of evidence from fire, crash, explosion, and other disaster scenes. Employing fluoroscopy as the first stage of the examination process in a mass fatality incident also permits the presence of any hazardous material (sharp objects or unexploded ordnance) to be detected and located, thus reducing the potential hazard at subsequent stages of the process.

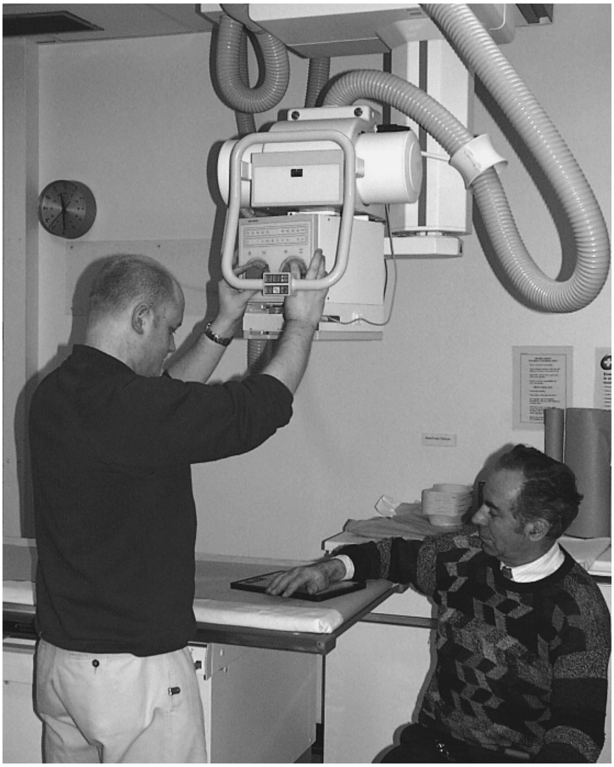


Fig. 8.4 (continued)

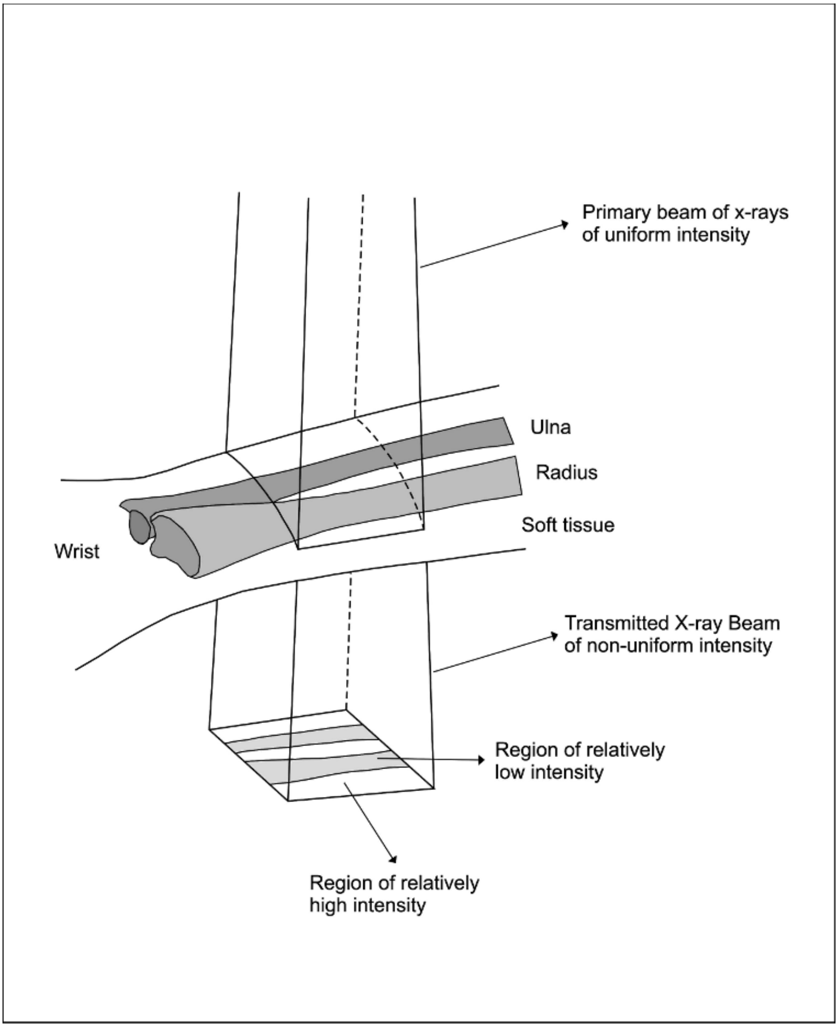


Fig. 8.4 The basic principles of radiography

The use of a mobile C-Arm fluoroscope allows the X-ray tube and detector to be rotated and angled to give better visualization of superimposed structures, which can be particularly useful when examining fragmented, commingled human remains. It is also useful for rapid retrieval of small objects (e.g., ballistic material) under X-ray control. Without fluoroscopy (and appropriate protective equipment), location and removal of these objects would otherwise be difficult and time-consuming (Association of Forensic Radiographers 2004; Tonello 1998; Viner et al. 2003, 2006).

Fluoroscopy does, however, have its limitations in terms of both image quality and the total amount of information that can be permanently recorded on a single image. In this respect, it is best suited for use as an initial triage tool, to be

Fig. 8.5 C-Arm mobile fluoroscopy unit

supplemented by further examination by digital radiography (Association of Forensic Radiographers 2004; Viner et al. 2003, 2006).

Digital Radiography

In recent years, technological advances have allowed the traditional film-/screen-based system to be replaced by digital technology. Digital images offer enormous benefits to medical and forensic applications. They can be relatively easily acquired without the need for use of photographic chemicals and equipment. The recording methods require a decreased radiation dose and have a wider dynamic range than film, resulting in the ability to demonstrate both soft tissue and bony structures from the same image data by altering the display factors. This makes digital imaging an ideal method for detailed examination of fragmented remains with tissue; the same image data can be used to display soft tissue structures, nonmetallic foreign bodies, bony detail, and metallic foreign bodies by simple adjustment of the display parameters.

Digital images can also be superimposed accurately over one another, allowing accurate comparison of antemortem and postmortem data. The fact that digital information can be sent electronically speeds up and simplifies this process dramatically, facilitating rapid identification of the remains of an individual from antemortem data recovered thousands of miles away.

Current systems fall broadly into two categories: computed radiography (CR) and digital radiography (DR). In the process of computed radiography (CR), a photo stimulable phosphor plate replaces the film and screens within the X-ray cassette. The examination is performed in an identical manner to the traditional X-ray examination, and following exposure, the cassette is placed in a CR reader (Fig. 8.6a). The reader withdraws the plate, scans it, and converts the data stored upon it into a digital image. The entire process takes a similar amount of time to the conventional film-based process, but the end result is a digital image (Emerton et al. 2005).

With digital radiography (DR), a flat-panel X-ray detector replaces the X-ray cassette (Fig. 8.6b). The examination is performed in the same way as conventional and CR imaging, but the image appears almost instantly on a monitor following the exposure (Lawinski et al. 2005). Aside from the increase in speed and productivity, this process offers significant advantages for forensic work. First, with DR there is no need to remove the plate following exposure in order to be able to view the image. Thus, with cases that are difficult to position or for commingled remains where structures may overlay one another, making interpretation difficult, the subject can be repositioned immediately, thus improving accuracy and minimizing examination time. Second, where foreign body removal is required (e.g., ballistic material or traces of explosive devices), the same image can be instantly replicated with a radiopaque pointer used to highlight the subject. The item can then be retrieved by the pathologist with the aid of sequential radiographs.

Digital radiography (DR) can successfully be employed as a triage tool in place of fluoroscopy, providing a series of survey radiographs covering an entire body bag. This imaging will allow for the identification of small fragments of bone, teeth, personal effects, and possible items of evidence among debris in the same way as fluoroscopy. However, the static nature of the image and the limitations of the gantry systems currently available reduce its flexibility for identification of superimposed structures and a more complex process for retrieval of items under X-ray control. In cases where it is likely to be a requirement to retrieve small items of evidence from bags containing commingled remains, or when assisting the pathologist to locate and retrieve evidential items from within the soft tissues, a combination of DR and fluoroscopy should be considered to be the gold standard.

Digital X-Ray Scanography

An alternative method, which offers the combined advantages of digital imaging and fluoroscopy, is the use of digital X-ray scanography. The Lodox Statscan® was developed originally for examining suspected diamond smugglers in the mines of South Africa. This machine employs a digital version of the "scanogram" technique described earlier (Fig. 8.7). A narrow-slit beam of radiation passes rapidly over the subject, and the resultant image is recorded using digital technology employing 12 solid-state detectors in a linear array detector. An entire body can be examined from head to toe in approximately 13 seconds, and the gantry can be rotated through 90 degrees (and any angle in between) to give a lateral or oblique image (Beningfield et al. 2003).

The Statscan is a relatively new machine that is currently being employed very successfully for the investigation and management of polytrauma in shock trauma centers in the United States, Europe, and Africa. Due mainly to its high cost, the application of this machine for forensic use is in its infancy but clearly offers significant advantages over conventional X-ray techniques.

Dental Radiography

One of the most useful tools available to the investigator in a mass casualty situation is the use of dental radiography. Identification by odontological means remains one of the major primary methods of identification in mass fatality incidents, despite advances in DNA technology. Comparison of dental radiographs is an important tool for the forensic odontologist. Production of dental X-ray images is rapid, cost-effective, and simple and can be achieved without the need for complex equipment. The principles are identical to those of skeletal radiography and can be accomplished with plain film (without the use of intensifying screens), computed radiography, or direct digital systems.

One of the problems associated with dental comparisons is the postmortem replication of antemortem images. The most common examinations performed by dentists upon their patients are the intra-oral “bite-wing” projections and extra-oral panoramic survey view (Hart and Wall 2002). The bite-wing projection relies on

(a)


Fig. 8.6 Two options for digital radiography. (a) Computed radiography (CR) and (continued)

(b)

Fig. 8.6 (b) direct digital radiography (DR)

the subject's ability to hold an intra-oral film in position in the mouth by biting upon a card support attached to the film. Achieving an exact replication of this view can be very difficult in postmortem analysis for obvious reasons.

The panoramic or "orthopantomographic" technique produces a single film showing the entire dentition, mandible, maxillae, and maxillary sinuses on the same image (Fig. 8.8). The examination is performed using a technique known as rotational tomography in which the X-ray tube and film rotate around a series of fulcrum points that follow the line of the mandible. Structures that are not in the same plane as the fulcrum are blurred out, so that superimposition of the structures is avoided (Mason and Bourne 1998). Since Siemens plc ceased production of its Zonarc®, all currently available orthopantomography equipment operates on the principle that the patient is able to sit or stand in the erect position. This single factor makes replication of the orthopantomograph image very difficult to undertake postmortem and results in the requirement for a series of intra-oral radiographs to be undertaken. An alternative method for achieving a comparable projection to that obtained using orthopantomography that is currently in use in clinical dentistry and under evaluation for postmortem identification is CT scanning (Jackowski et al. 2006; Rocha Sdos et al. 2003; Thali et al. 2006).

CT Scanning

Computed axial tomography (CAT) scanning was developed in the 1970s by a British scientist, Godfrey Hounsfield, working for the EMI Corporation. Hounsfield applied the physics of rotational tomography, going a stage further so that the tube

(a)

Fig. 8.7 The Lodox Statscan (a) gives a full-body digital scanogram (continued)

(b)

Fig. 8.7 (b) in just 13 seconds.

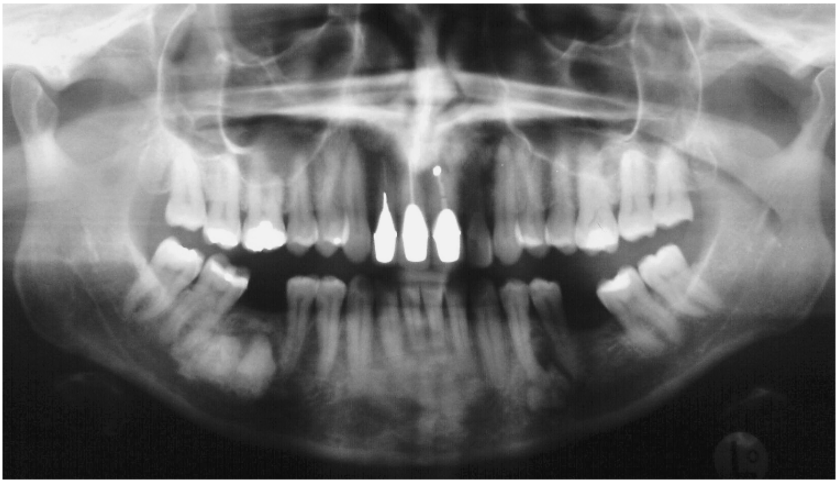


Fig. 8.8 Orthopantomograph: Standard panoramic X-ray view of the dentition routinely performed in general dental practice

and X-ray detector gantry rotate about a single axis in the body. X-ray detectors replaced film and took a series of measurements continuously while the gantry rotated (Fig. 8.9). A computer analyzed the recorded data and reconstructed it as a digital image of an axial “slice” of the subject displayed on an image matrix on a CRT screen. Each pixel was allocated a level on a gray scale that corresponded to the level of radiation transmitted through the body at that location and thus the relative density of the subject. These values are now known as Hounsfield Units and the scale, in which the density level corresponding to 0 is equivalent to water (mid-gray), spans from dense air -1024 units (black) to bone $>+400$ units or greater to dense metallic objects, etc. $+3071$(white). Initially deployed as a tool for imaging the head, it enabled radiologists to examine the brain accurately for the first time without the overlying features of the bony skull obscuring vital soft-tissue information.

CT scanning, as it is now known, has benefited enormously from advances in technology and computer processing power. The entire body can now be scanned in a matter of seconds, and images can be reconstructed in any plane: axial, coronal, saggital, or oblique. While CT scanning is a routine tool in clinical medicine, it is a relatively expensive technique and has only fairly recently been used for post-mortem and forensic examination and is not a widely available resource for the investigator. However, recent studies have shown that it can be a very effective tool at postmortem examination (Haglund and Fligner 1993; Hildebolt et al. 1990; Myers et al. 1999; Riepert et al. 1995; Rocha Sdos et al. 2003; Thali et al. 2003a, b, 2006; Uysal et al. 2005) and may offer the opportunity to gather data that may otherwise be impossible to collect. The ability of CT scanning to undertake 3D and multi-planar reconstructions offers the pathologist and anthropologist the opportunity to examine the underlying skeletal structure of fleshed remains, visualizing trauma, degenerative processes, and articular surfaces and taking accurate measurements (Thali 2000). There are at present a number of studies being undertaken worldwide to evaluate the possibilities of CT for forensic examination and identification, and it was recently announced that a mobile CT scanner has, for the first time, been used in the investigation of a multiple casualty incident (Rutty 2006).

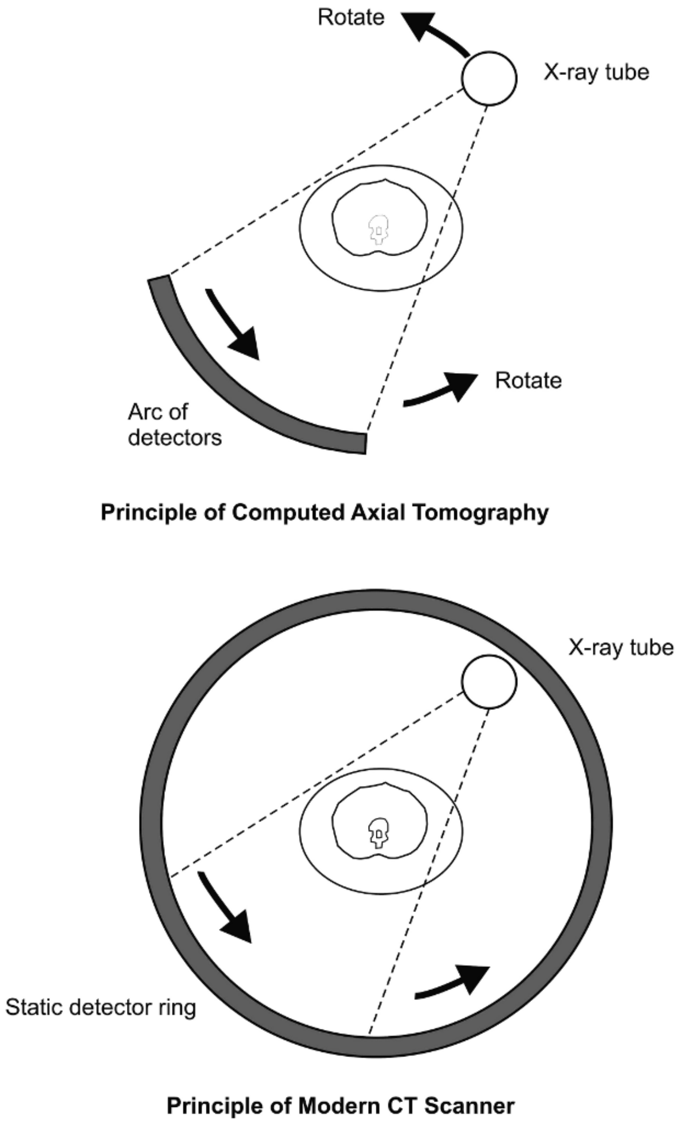
Radiation Protection

Within three months of Roentgen's announcement, reports of the harmful effects of X-rays began to appear in the literature (Burrows 1986). Early experimenters and practitioners, however, took no steps to protect themselves against the effects of radiation. X-ray rooms and X-ray tubes were unshielded and emitted radiation in all directions. It was a common practice among early radiographers and radiologists to test the X-ray tube and determine the exposure required by taking an exposure of their own hand prior to each examination (Burrows 1986). In the UK, documentation of radiation injuries by Dr. John Hall-Edwards and Ernest Wilson led to the publication of a safe code of practice by Dr. Hall-Edwards in 1908 (Hall-Edwards 1908). Both men later died of their radiation-induced injuries.

Adequate protection and codes of practice did not become commonplace until the 1920s, and it was not until 1928 that the International Congress of Radiology in Stockholm adopted the third revised report of the British Radiological Protection Committee as the basis for international regulations (International X-ray Protection Committee 1928). It was not until the 1950s that it was understood that the low levels of radiation exposure used in diagnostic radiology represented a danger to patients. This resulted in the adoption of the radiation protection regulations that are now in use, based upon the risk to patients and operators from late effects of radiation upon patients and radiation workers following low-level exposure (Engel-Hills 2006).

There is no absolute evidence of a threshold below which no damage occurs. Even the lowest doses may cause damage to cells that might later lead to malignancy or hereditary effects if the cells irradiated are the germ cells in the gonads (Engel-Hills 2006). For this reason, radiation exposures should be limited and controlled by appropriate international, national, and state regulations, codes of practice, and schemes of work. X-ray and imaging equipment should be regulated, adequately maintained and inspected, and subject to regular quality control programs. Radiation workers should be appropriately trained in the use of such equipment for the purpose for which it is employed. This is particularly important for fluoroscopy, where the radiation exposure received by the operators can be significantly increased by the use of poor technique and by inexperienced operators using the equipment for longer periods than are necessary to gather the required information.

Provided that the appropriately qualified personnel are involved in planning, commissioning, and operating the equipment, most X-ray techniques can be performed safely in "field" conditions encountered in incident mortuaries following mass fatality incidents or during large-scale criminal investigations. The imaging equipment routinely required in such investigations (fluoroscopy, digital and digital dental radiography, and even CT scanning) is available in mobile or portable form and is routinely employed in military field hospitals or domicillary and veterinary radiological practices. There is therefore no logistical reason why incident mortuaries cannot benefit from the resources required to undertake a thorough investigation.



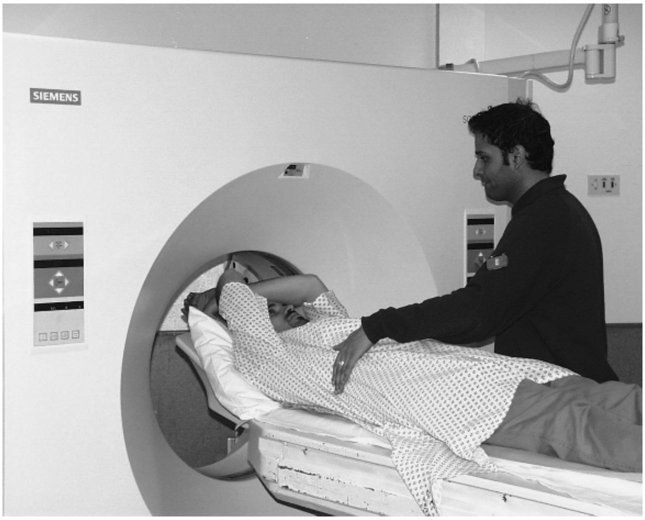


Fig. 8.9 The basic principles of computed axial tomography

Application of Radiographic Methods to Mass Fatalities

Whatever modalities are employed, the examination of commingled fragmented remains, particularly from large-scale incidents, will require systematic application of imaging so as to maximize the information gained while minimizing the time taken and preventing delays in the examination process. In planning the forensic protocol to include the use of radiological imaging, the following principles should be applied (Association of Forensic Radiographers 2004):

- Imaging will be useful as an initial screening tool at triage to determine the nature of the remains. This includes the presence of hazardous material, the remains of more than one individual, the presence of significant material and artifacts (e.g., personal effects and forensic evidence), and to locate and retrieve small, unassociated body fragments (e.g., teeth).
- Aside from dental radiography, the use of radiography for identification is likely to play a relatively small (but important) role in the identification process.
- Comparison views for identification will require accurate positioning and exposure. This is a time-consuming process and cannot be undertaken successfully until after the initial examination/search process is complete (Lichtenstein 1998). It is thus advisable to triage recovered remains so that detailed skeletal radiography for identification is undertaken only when indicated rather than as part of the routine forensic protocol.

Imaging techniques for mass fatalities are thus best deployed along the same lines as for the management of major trauma in the emergency room (Fig. 8.10):

- **Primary survey:** initial triage and assessment
- **Secondary survey:** standard examination of specific body parts (e.g., dentition)

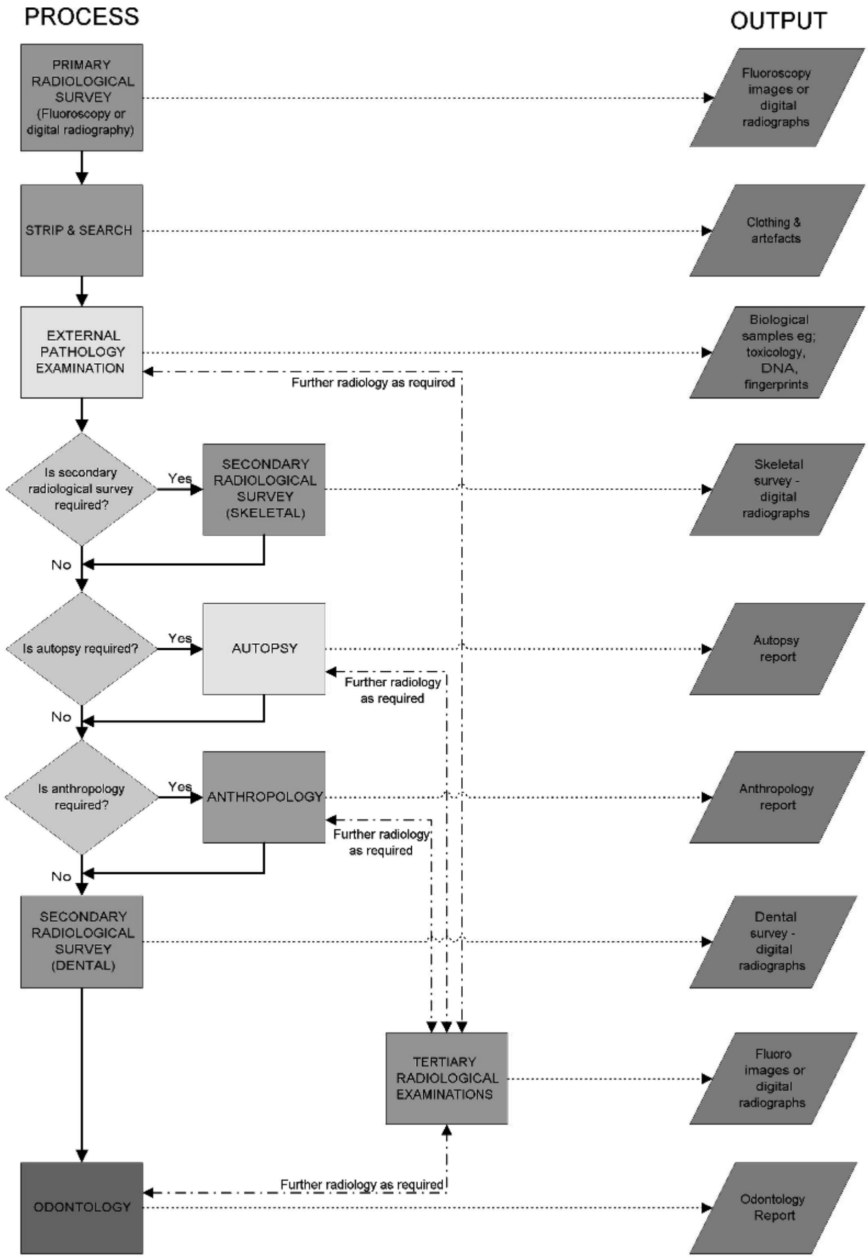


Fig. 8.10 Flowchart showing how radiology contributes to the examination of human remains in mass fatality investigations at each stage

- **Tertiary examinations:** specific examinations performed in response to findings during primary or secondary surveys or during pathology, odontology, or anthropology assessment

Primary Survey (Triage)

The purpose of the primary survey is to undertake an initial assessment of the remains. This should be considered essential in all cases but is particularly important for circumstances involving extensive fragmentation, decomposition, or intermixing with debris. In some cases the use of either computed radiography (CR) or direct digital radiography (DR) will deliver a high-quality image that can be subsequently evaluated by the pathologist, anthropologist, and odontologist without the need for further examination. The digital nature of these images will allow display of both hard and soft tissues, as well as metallic and nonmetallic artifacts and personal effects. In the absence of CR or DR, plain film radiography techniques will offer an alternative, but without the benefits of a digital image. DR has the advantage of being a far more rapid technique than film or CR, and it is particularly suited to use in the mass fatality situation when speed is of critical importance. Direct digital radiography should therefore be considered to be the modality of choice in such cases.

In the absence of DR, particularly in cases where large quantities of remains are recovered and commingled with one another and other evidential material, the advantages of fluoroscopy for mass fatality situations will become apparent at triage. The "real-time" nature of the fluoroscope image will enable rapid location and retrieval of items of interest, and the ability to rotate the C-Arm of the fluoroscope will enable superimposed structures to be more easily identified.

In all cases, the primary radiographic survey should be considered to be the first phase of the investigative process, particularly when examining remains from a crime scene. Imaging examination of the sealed body bag will yield all or some of the following information about the contents of the body bag:

- Recognition of body parts with discernable anatomical landmarks that can be used for body part identification, which is especially useful with cases of fragmentation and decomposition
- An indication of whether the remains of more than one individual are present
- The location and nature (if possible) of any hazardous material—unexploded ordnance, metallic sharps, glass, etc.
- The location and degree of skeletal trauma. This may include the location of any projectile fragments with possible associated bony injury
- The location of unassociated teeth and other small body parts useful for identification
- The location of personal effects, e.g., jewelry, cigarette lighters, keys, wallets, etc. (This may be particularly useful in cases of burned or exhumed remains, where these artifacts may be difficult to locate.)

- The presence of any unique identifying features (e.g., prosthetic hip replacement) that may require further radiographic investigation following autopsy
- The presence of previous healed fractures and other preexisting pathological or anatomical features that may be useful for identification purposes
- The presence of dental work (bridges, crowns, root canal treatments, etc.)

The information obtained from the primary survey should be recorded on a report form to aid subsequent pathology, anthropology, and odontology examinations. Examples of recording forms are shown in Fig. 8.11. If fluoroscopy is used, it is recommended that the entire examination is recorded using video or similar technology. Although hard- or soft-copy images should be taken of significant findings, fluoroscopy is a dynamic real-time examination, and it is advisable that the process is undertaken by a radiographer along with a forensic pathologist or anthropologist and appropriate law enforcement personnel to ensure continuity. The use of DR as a primary survey tool will result in a series of hard- or soft-copy images as a permanent record.

In cases with a large amount of fragmented commingled remains, a primary survey of body bags using digital radiography can be used to construct an image database to aid the identification process. Images can be categorized and filed according to observed anatomical parts, facilitating rapid retrieval for later comparison with antemortem radiographs should this prove necessary. It should be remembered that radiographs produced at the primary survey stage will not be of sufficient quality to permit accurate evaluation by a radiologist, due to the random nature of the anatomical positioning of the body parts within the body bag. Further radiography examinations may be required as part of the investigative process, as detailed below. These examinations, performed subsequent to the primary survey, should in all cases be correctly anatomically positioned so that the resultant radiographs replicate as far as possible the standard views that would be undertaken on a live subject.

Secondary Survey (Standard Radiographic Examination)

The secondary survey should be undertaken after the initial strip and search and external examination so that standard positions can be replicated without overlying clothing and other artifacts. In most cases, examinations can be undertaken following autopsy, but this will be dependent upon the precise nature of the examinations to be performed. Examinations of the skull, for example, are in most cases best undertaken prior to the cranial vault being opened.

The use of imaging to obtain standard projection radiographs as a routine part of the examination protocol should be restricted to those cases that are likely to yield the greatest benefit from the deployment of resources required. In the case of a mass fatality investigation, advances in other identification methods (e.g., DNA) have largely negated the need for the full skeletal survey examination deployed in previous incidents (Mulligan et al. 1988; Nye et al. 1996). In such cases, secondary surveys are now usually restricted to routine dental surveys as a means of collecting postmortem data for later comparison with antemortem films. As the incidence of dental X-ray examinations and the availability of dental records in Western populations are high, the likelihood of such antemortem data availability available makes the routine dental survey worthwhile. In other populations, where dental treatment is either rare or poorly documented, it may be decided that a routine dental radiography survey is not indicated. However, there may be value in routinely taking radiographs of the mandible in the region of the third molar in order to provide data for age estimation.

The precise requirements for dental radiography surveys will be determined by the working practices of the forensic odontologist. In the absence of a presumptive identification with antemortem data for comparison, a full sequence of intra-oral peri-apical films showing the entire dentition, together with bilateral bite-wing examinations, represents a thorough survey from which comparison can be made with antemortem data. In the case of large-scale examinations involving multiple fatalities, the secondary dental survey represents a significant and time-consuming part of the postmortem data collection process. A team approach, involving odontologists and experienced dental radiographers and nurses working together in the incident mortuary, can greatly increase the speed of the identification process and negate the requirement for body parts to be examined elsewhere (Viner et al. 2006).

Similar to the dental images, there may be other indications for including a series of cranial and postcranial projections in the routine postmortem examination protocol. For example, in the case of examining the remains from suspected atrocity crimes, the possibility of systematic antemortem torture and/or beatings may indicate routine examination of body parts, such as skull, limbs, and ribs for evidence of healed or healing fractures at the time of death (Tonello 1998; Viner 2001c).

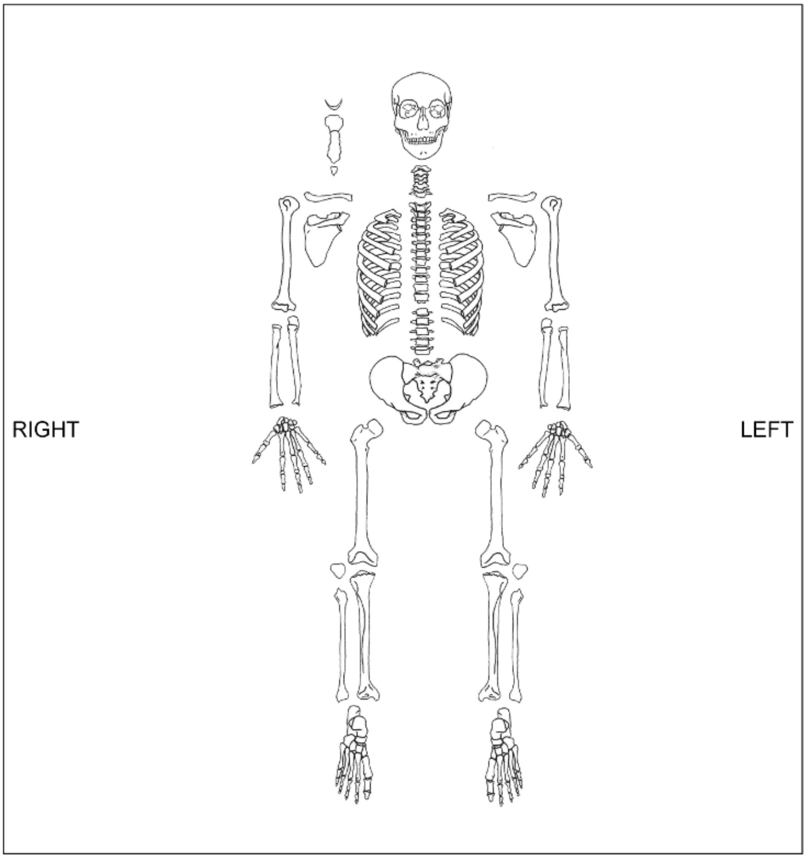
In all events, the precise protocol deployed will be dependent upon a number of factors unique to the circumstances surrounding the death of the individual(s). The protocol will thus need to be agreed upon in consultation with the coroner, medical examiner, odontologist, anthropologist, radiologist, and radiographer in order to achieve the maximum benefit while limiting examination time and resources.

Tertiary Examinations (Special Circumstances)

As described earlier, a range of medical imaging techniques and examinations may be useful in determining the identity of an individual, his anthropological profile, or in determining the cause and manner of his death. The techniques employed will vary from case to case and will be determined by the nature, or suspected nature, of the incident under investigation. In most instances the requirement for further specific imaging will be determined as a result of data obtained at primary radiological survey or from the pathology, odontological, anthropological, or crime scene examinations. It should again be remembered that radiographs produced at the primary survey stage will not be of sufficient quality to permit accurate evaluation by a radiologist due to the random nature of the anatomical positioning of the body parts within the body bag. Examples of possible indications are

(a) RADIOGRAPHIC SURVEY FORM

Artefact/Pathology location diagram



KEY: (#1, #2 etc for multiple examples. Location: →)

A: Intact Bullet	D: Cartridge Case	G: Needle	J: Jewellery	M: Metal (Unknown)
B: Bullet Fragment	E: Whole Round	H: Knife or Blade	K: Key	N: Radio / Remote
C: Shrapnel	F: Razor Blade	I: Glasses	L: Watch	O: Other (describe)

Date

Recorded by

Signature

Site Code & Body #

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Fig. 8.11 (a) Examples of primary survey recording forms designed by the Inforce Foundation and the Association of Forensic Radiographers for use in the investigation of human remains exhumed from mass graves (continued)

(b) inforce

RADIOGRAPHIC SURVEY FORM

Artefact location diagram

For disarticulated remains. For articulated, please use next page.

Top of Bag

Right Side of Bag

Left Side of Bag

KEY: (#1, #2 etc for multiple examples. Location: →)

A: Intact Bullet	D: Cartridge Case	G: Needle	J: Jewellery	M: Metal (Unknown)
B: Bullet Fragment	E: Whole Round	H: Knife or Blade	K: Key	N: Radio / Remote
C: Shrapnel	F: Razor Blade	I: Glasses	L: Watch	O: Other (describe)

Site Code & Body #

Date

Recorded by

Signature

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Fig. 8.11 (b) allow the location of artifacts and pathology to be indicated on a grid system and anatomically as appropriate

- Any unique skeletal features or pathological conditions seen during the primary survey or identified during examination by the pathologist, anthropologist, or odontologist that may be useful for identification.
- To replicate poor-quality antemortem dental radiographs by undertaking subsequent examinations using substandard angulations to facilitate accurate comparison.
- In cases where evidence of trauma identified by the pathologist, anthropologist, or odontologist may indicate further imaging investigations to determine the nature of the injury or weapon used.
- To detect, locate, and retrieve items of forensic evidence seen during the primary survey but not located during examination by the pathologist.
- For those cases that are proving difficult to identify via other means, a full skeletal survey may be useful in determining age, sex, stature, etc., or for detecting unique skeletal features that have been previously documented in antemortem records.
- To document injuries and injury patterns for the purposes of the criminal investigation or as a means of negating the requirement for full autopsy where the cause of death is known.

In the last two cases, imaging examinations may be particularly useful in cases of fleshed remains where anthropological examination is difficult.

Case Studies

United Nations International Criminal Tribunal Investigations of Mass Graves in Croatia, Bosnia, and Kosovo 1996–2002

During the period from 1996 to 2002, the forensic teams of the Office of the Prosecutor for the United Nations International Criminal Tribunal for the Former Yugoslavia (ICTY) exhumed and examined several mass graves in Croatia, Bosnia and Herzegovina, and Kosovo as part of their investigation into alleged war crimes and crimes against humanity. Several mass graves, with wide variations in size and content, were exhumed, and the human remains were examined in mortuaries employing a modified mass fatality protocol. While the exhumation process was generally painstakingly carried out to the highest standards of forensic archaeology, some of the exhumed remains were inevitably commingled, particularly in "secondary" graves containing the remains of previous graves that had been "robbed" and reburied in an attempt to conceal them. Radiography played an important role in the examination of the remains from these graves. Fluoroscopy, radiography, and dental radiography were used, sometimes in "field" conditions, and were employed according to the following protocol.

Primary Survey

The primary survey (triage) was performed using fluoroscopy in all cases. All body bags were examined using a mobile C-Arm fluoroscope by a radiographer and pathologist or anthropologist working together. Fluoroscopy proved invaluable in the location of hazardous material including a number of live hand grenades (Fig. 8.12) and ammunition, razorblades, and other sharp objects. Its primary value was the location of projectile fragments (e.g., bullets and shrapnel), allowing the pathologists to locate and retrieve these at autopsy as well as locating personal effects, many of which carried identifiable markings. The examination of commingled remains using fluoroscopy enabled rapid evaluation of the contents of body bags and facilitated fast separation of human bone from soil, stones, and other artifacts.

Secondary Survey

Secondary surveys were only performed in specific circumstances. The incidence of any dental work among the population was generally very low and did not usually warrant a full dental radiography survey. In most cases, the secondary survey was limited to an oblique projection of both mandibular rami for age determination. In some specific investigations, however (where dental records were known to be available), a full-mouth dental radiography series was undertaken. In other investigations where systematic antemortem assault was alleged, a radiographic examination of the

Fig. 8.12 The use of fluoroscopy for primary survey enables hazards to be identified and located. Fluoroscopy reveals the presence of a live grenade within the body bag (note image on screen in the background)

Fig. 8.13 Secondary surveys may sometimes be used to document perimortem injuries as in this case showing a defensive fracture of the radius and ulna

rib cage and extremities was undertaken to look for evidence of trauma and healing fractures (Fig. 8.13).

Tertiary Examinations

Fluoroscopy

The nature of the exhumed remains often rendered the physical location of items seen at primary survey difficult to locate during autopsy, particularly when these lay in clothing or decomposing tissue. Fluoroscopy was frequently employed during autopsy to locate and retrieve these items under X-ray control.

Radiography

Radiography was undertaken in a number of cases to document identifying features seen during the primary survey or at autopsy or anthropological examination. It was regularly employed to examine epiphyseal plates in young adults to assist with age determination, and, in some cases, it proved possible to establish identity by comparison of postmortem radiographs with ante-mortem films (Fig. 8.14). Generally, however, the incidence of antemortem films being available for comparison proved to be very low. Plain film radiography using high-definition techniques was also employed in some cases to determine whether bony trauma was associated with projectile fragments, particularly in cases where the exact nature of the injury could not be determined simply by physical examination.

Fig. 8.14 Identifying features seen during the primary survey such as this healed fracture of the tibia with two orthopedic screws *in situ* were radiographed in true AP and lateral projections for the purpose of identification as a tertiary examination

July 7, 2005, London Bombings

On July 7, 2005, three terrorist bombs exploded on underground trains and a further bomb on a bus in London. Fifty-six people were killed in these explosions, and several hundred people were injured. Fifty-six cadavers were recovered from the scenes of the explosion together with a large number of fragmented remains.

In accordance with the London Resilience Mass Fatality Plan, the Association of Forensic Radiographers (AFR) mobilized its forensic radiography response team and equipment, some of which was provided on loan by the medical supply industry. A total of 27 radiographers worked in teams of between 6 and 8 for 12 hours per day during the subsequent 11 days (Viner et al. 2006). Two mobile C-Arm fluoroscopy units, a direct digital (DR) unit, a computed radiography (CR) unit, together with plain film radiography and dental radiography, were deployed according to the following protocol.

Primary Survey

Fluoroscopy was employed for the primary survey (triage) of the cadavers. Two radiographers, working together with a pathologist, examined each case documenting any identifying features, injuries, personal effects, and hazardous objects and printing hard-copy images via a thermal printer. The average examination time was 10 minutes.

Both digital radiography (DR) and computed radiography (CR) were employed for the primary survey of the body parts. The use of CR was abandoned after the first day as DR proved to be almost 10 times faster than CR in this application. Two radiographers examined each case using correct anatomical positioning where possible, which was facilitated by the use of transparent body part bags in many cases. Images were stored on a workstation accessible to pathologists and anthropologists for evaluation and written to CD-ROM as a permanent record.

The use of digital technology allowed images to be displayed to evaluate both soft-tissue and bony elements and facilitated rapid triage of commingled body parts for anthropological analysis and DNA testing. In many cases, subsequent radiography for analysis of bony elements was not required due to the high-definition nature of the images and the use of correct anatomical positioning. In this case, due to the rapid identification of victims by other means, it did not prove necessary to utilize the digital image database for comparison with antemortem skeletal radiographs. However, a number of dental fragments were recovered as part of the primary survey, and, in most cases, further radiography of these parts was not required, as the information obtained at primary survey was sufficient for odontological analysis and identification to be made.

Secondary Surveys

Dental radiography was undertaken as a routine part of the identification process using conventional intra-oral film radiography. Teams of experienced dental radiographers worked in conjunction with the forensic odontologists to undertake dental surveys *in situ*, shortening the odontological examination time.

Tertiary Examinations

Tertiary examinations of identifiable skeletal pathology were undertaken as part of the identification process, none of which contributed to a positive identification. A number of further examinations of fragmented remains were undertaken using both CR and DR. These enabled the anthropologists to examine bony elements for purposes of identification and documentation of injuries.

Conclusion

The science of medical imaging has developed rapidly over the last century since Roentgen's announcement of the discovery of X-rays and is continuing to develop at a rapid pace with each leap forward in computer technology. Medical imaging has an important and increasing role in forensic investigation, both in determining the cause of death or injury and in identifying the deceased. There is no one technique that will deliver all the answers, and its contribution to the analysis and identification of commingled human remains will be dependent upon the timely application of the most appropriate techniques. Close collaboration among investigators, pathologists, odontologists, anthropologists, and the radiology professionals (radiologists, radiographers, and physicists) is essential if the maximum benefit is to be obtained.

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References Cited

Aitken, A. G., O. Flodmark, D. E. Newman, R. F. Kilcoyne, W. P. Shuman, and L. A. Mack 1985 Leg length determination by CT digital radiography. *AJR Am. J. Roentgenol.* 144(3):613–615.

Alexander, C. J. and G. A. Foote 1998 Radiology in forensic identification: The Mt. Erebus disaster. *Australas. Radiol.* 42(4):321–326.

Association of Forensic Radiographers 2004 Radiography facilities for temporary emergency mortuaries in the event of a mass fatality incident (unpublished paper). London.

Bass, W. M. 1990 Forensic anthropology. In *CAP Handbook for Postmortem Examination of Unidentified Remain; Developing Identification of Well Preserved, Decomposed, Burned, and Skeletonised Remains*, M. F. Fierro, ed. College of American Pathologists, Skokie, IL.

Beningfield, S., H. Potgieter, A. Nicol, S. van As, G. Bowie, E. Hering, and E. Latti 2003 Report on a new type of trauma full-body digital X-ray machine. *Emerg. Radiol.* 10(1):23–29.

Binda, M., C. Cattaneo, A. Bogoni, P. Fattorini, and M. Grandi 1999 Identification of human skeletal remains: Forensic radiology vs. DNA. *Radiol. Med. (Torino)* 97(5):409–411.

Bisset, R. A., N. B. Thomas, I. W. Turnbull, and S. Lee 2002 Postmortem examinations using magnetic resonance imaging: Four-year review of a working service. *BMJ* 324(7351): 1423–1424.

Brogdon, B. G. 1998a Radiological identification of individual remains. In *Forensic Radiology*, B. G.Brogdon, ed., pp. 149–187. CRC Press, Boca Raton, FL.

1998b Radiological identification: Anthropological parameters. In *Forensic Radiology*, B. G. Brogdon, ed., pp. 63–96. CRC Press, Boca Raton, FL.

Brogdon, B. G. and J. E. Lichtenstein 1998 Forensic radiology in historical perspective. In *Forensic Radiology*, B. G. Brogdon, ed., pp. 13–34. CRC Press, Boca Raton, FL.

Brogdon, B. G., H. Vogel, and J. McDowell 2003 *A Radiologic Atlas of Abuse, Torture and Inflicted Trauma*. CRC Press, Boca Raton, FL.

Brookes, J. A., M. A. Hall-Craggs, V. R. Sams, and W. R. Lees 1996 Non-invasive perinatal necropsy by magnetic resonance imaging. *Lancet* 348(9035):1139–1141.

Bryan, G. J. 1979 *Diagnostic Radiography,* 3rd ed. Churchill Livingstone, Edinburgh.

Buchner, A. 1985 The identification of human remains. *Int. Dent. J.* 35(4):307–311.

Burrows, E. H. 1986 *Pioneers and Early Years: A History of British Radiology*. Colophon Ltd., Alderney, Chanel Islands.

Chilvarquer, I., J. O. Katz, D. M. Glassman, T. J. Prihoda, and J. A. Cottone 1987 Comparative radiographic study of human and animal long bone patterns. *J. Forensic Sci.* 32(6):1645–1654.

Craig, E. A. 1995 Intercondylar shelf angle: A new method to determine race from the distal femur. *J. Forensic Sci.* 40(5):777–782.

Culbert, W. L. and F. M. Law 1927 Identification by comparison of roentgenograms of nasal accessory sinuses and mastoid processes. *JAMA* (88):1632–1636.

Dimond, B. 2002 *Legal Aspects of Radiography and Radiology*. Blackwell Science, Oxford.

Eckert, W. G. and N. Garland 1984 The history of the forensic applications in radiology. *Am. J. Forensic Med. Pathol.* 5(1):53–56.

Emerton, D., I. Honey, A. McKenzie, P. Blake, D. Annett, C. Lawinski, and H. Cole 2005 *Computed Radiography Systems for General Radiography (CR) Comparative Report, Edition 2, Report 05081*. NHS Purchasing and Supply Agency, Her Majesty's Stationery Office.

Engel-Hills, P. 2006 Radiation protection in medical imaging. *Radiography* 12(2):153–160.

Evans, K. T., B. Knight, and D. K. Whittaker 1981 *Forensic Radiology*. Blackwell Scientific, Oxford.

Fischman, S. L. 1985 The use of medical and dental radiographs in identification. *Int. Dent. J.* 35(4):301–306.

Glasser, O. 1931 First Roentgen evidence. *Radiology* (17):789.

Goodman, N. R. and L. B. Edelson 2002 The efficiency of an X-ray screening system at a mass disaster. *J. Forensic Sci.* 47(1):127–130.

Goodman, P. C. 1995 The new light: Discovery and introduction of the X-ray. *AJR Am. J. Roentgenol.* 165(5):1041–1045.

Gould, P. 2003 X-ray detectives turn images into evidence. *Diagn. Imaging* (Special edition).

Greulich, W. W. and S. I. Pyle 1959 *Radiographic Atlas of Skeletal Development of the Hand and Wrist*. Stanford University Press, Stanford, CA.

Haglund, W. D. and C. L. Fligner 1993 Confirmation of human identification using computerized tomography (CT). *J. Forensic Sci.* 38(3):708–712.

Hall-Edwards, J. 1908 On X-ray dermatitis and its prevention. *Arch. Roentgen Ray* (13):243–248.

Halperin, E. C. 1988 X-rays at the bar, 1896–1910. *Invest. Radiol.* 23(8):639–646.

Hansman, C. F. 1962 Appearance and fusion of ossification centers in the human skeleton. *Am. J. Roentgenol. Radium Ther. Nucl. Med.* 88:476–482.

Harcke, H. T., J. A. Bifano, and K. K. Koeller 2002 Forensic radiology: Response to the Pentagon Attack on September 11, 2001. *Radiology* 223(1):7–8.

Hart, D. and B. F. Wall 2002 *Radiation exposure of the UK population from medical and dental X-ray examinations*. National Radiological Protection Board-W4, Chilton.

Hildebolt, C. F., M. W. Vannier, and R. H. Knapp 1990 Validation study of skull three-dimensional computerized tomography measurements. *Am. J. Phys. Anthropol.* 82(3):283–294.

Hoerr, N. L., S. I. Pyle, and C. C. Francis 1962 *Radiological Atlas of the Foot and Ankle*. Charles C. Thomas, Springfield, IL.

International X-ray Protection Committee 1928 International recommendations for X-ray and radium protection. *Br. J. Radiol.* (1):358–363.

Jackowski, C., E. Aghayev, M. Sonnenschein, R. Dirnhofer, and M. J. Thali 2006 Maximum intensity projection of cranial computed tomography data for dental identification. *Int. J. Legal Med.* 120(3):165–167.

Jenkins, D. 1980 *Radiographic Photography and Imaging Processes*. MTP Press Ltd., Lancaster, UK.

Jensen, S. 1991 Identification of human remains lacking skull and teeth. A case report with some methodological considerations. *Am. J. Forensic Med. Pathol.* 12(2):93–97.

Kahana, T. and J. Hiss 1997 Identification of human remains: Forensic radiology. *J. Clin. Forensic Med.* 4(1):7–15.

Kahana, T., J. A. Ravioli, C. L. Urroz, and J. Hiss 1997 Radiographic identification of fragmentary human remains from a mass disaster. *Am. J. Forensic Med. Pathol.* 18(1):40–44.

Kirk, N. J., R. E. Wood, and M. Goldstein 2002 Skeletal identification using the frontal sinus region: A retrospective study of 39 cases. *J. Forensic Sci.* 47(2):318–323.

Krogman, W. M. and M. Y. Iscan 1986 *The Human Skeleton in Forensic Medicine,* 2nd ed. Charles C. Thomas, Springfield, IL.

Kurihara, Y., Y. Kurihara, K. Ohashi, A. Kitagawa, M. Miyasaka, E. Okamoto, and T. Ishikawa 1996 Radiologic evidence of sex differences: Is the patient a woman or a man? *AJR Am. J. Roentgenol.* 167(4):1037–1040.

Lawinski, C., A. McKenzie, H. Cole, P. Blake, and I. Honey 2005 *Digital Detectors for General Radiography: A Comparative Technical Report 05078*. NHS Purchasing and Supply Agency, Her Majesty's Stationery Office.

Levinsohn 1899 Beitraz zur feststellung der identitat. *Arch. Krim. Anthrop.* (2):221.

Lichtenstein, J. E. 1998 Radiology in mass casualty situations. In *Forensic Radiology*, B. G. Brogdon, ed., pp. 189–208. CRC Press, Boca Raton, FL.

Maresh, M. M. 1943 Growth of major long bones in healthy children. *Am. J. Dis. Child.* 66: 227–257.

Marlin, D. C., M. A. Clark, and S. M. Standish 1991 Identification of human remains by comparison of frontal sinus radiographs: A series of four cases. *J. Forensic Sci.* 36(6): 1765–1772.

Mason, R. and S. Bourne 1998 *A Guide to Dental Radiography*, 4th ed. Oxford University Press, Oxford.

McCormick, W. F. 1980 Mineralization of the costal cartilages as an indicator of age: Preliminary observations. *J. Forensic Sci.* 25(4):736–741.

Mora, S. et al. 2001 Applicability of the Greulich and Pyle standards. *Pediatr. Res.* (50):624–812.

Mulligan, M. E., M. J. McCarthy, F. J. Wippold, J. E. Lichtenstein, and G. N. Wagner 1988 Radiologic evaluation of mass casualty victims: Lessons from the Gander, Newfoundland, accident. *Radiology* 168(1):229–233.

Murphy, W. A., F. G. Spruill, and G. E. Gantner 1980 Radiologic identification of unknown human remains. *J. Forensic Sci.* 25(4):727–735.

Myers, J. C., M. I. Okoye, D. Kiple, E. H. Kimmerle, and K. J. Reinhard 1999 Three-dimensional (3-D) imaging in post-mortem examinations: Elucidation and identification of cranial and facial fractures in victims of homicide utilizing 3-D computerized imaging reconstruction techniques. *Int. J. Legal Med.* 113(1):33–37.

Nambiar, P., M. D. Naidu, and K. Subramaniam 1999 Anatomical variability of the frontal sinuses and their application in forensic identification. *Clin. Anat.* 12(1):16–19.

Navani, S., J. R. Shah, and P. S. Levy 1970 Determination of sex by costal cartilage calcification. *Am, J, Roentgenol. Radium Ther. Nucl. Med.* 108(4):771–774.

Nye, P. J., T. L. Tytle, R. N. Jarman, and B. G. Eaton 1996 The role of radiology in the Oklahoma City bombing. *Radiology* 200(2):541–543.

Pyle, S. I. and N. L. Hoerr 1955 *Atlas of Skeletal Development of the Knee*. Charles C. Thomas, Springfield, IL.

Reichs, K. and R. B. J. Dorion 1992 The use of computed tomography (CT) scans in the analysis of frontal sinus configuration. *Can. Soc. Forensic Sci. J.* (25):1.

Riepert, T., C. Rittner, D. Ulmcke, S. Ogbuihi, and F. Schweden 1995 Identification of an unknown corpse by means of computed tomography (CT) of the lumbar spine. *J. Forensic Sci.* 40(1): 126–127.

Rocha Sdos, S., D. L. Ramos, and G. Cavalcanti Mde 2003 Applicability of 3D-CT facial reconstruction for forensic individual identification. *Pesqui. Odontol. Bras.* 17(1):24–28.

Roentgen, W. C. 1895 A new kind of ray. *Phys.-Med. Ges.* (137):132–141.

Rogers, T. and S. Saunders 1994 Accuracy of sex determination using morphological traits of the human pelvis. *J. Forensic Sci.* 39(4):1047–1056.

Rutty, G. N. 2006 University of Leicester Announces World First Forensic Technique: A New Horizon for Mass Fatality Radiology, University of Leicester Press Release, Leicester.

Sanders, I., M. E. Woesner, R. A. Ferguson, and T. T. Noguchi 1972 A new application of forensic radiology: Identification of deceased from a single clavicle. *Am. J. Roentgenol. Radium Ther. Nucl. Med.* 115(3):619–622.

Scheuer, L. and S. Black 2004 *The Juvenile Skeleton*. Academic Press, London.

Schwartz, S. and E. D. Woolridge 1977 The use of panoramic radiographs for comparisons in cases of identification. *J. Forensic Sci.* 22(1):145–146.

Society of Radiographers 2005 Radiographers help identify London Bombing victims. *Synergy* September:1.

Sutherland, L. D. and J. M. Suchey 1991 Use of the ventral arc in pubic sex determination. *J. Forensic Sci.* 36(2):501–511.

Tanner, R. J., B. F. Wall, P. C. Shrimpton, et al. 2001 *Frequency of Medical and Dental X-ray Examinations in the UK, 1997–98*. National Radiological Protection Board.

Thali, M. J. et al. 2000 Improved vision in forensic documentation: Forensic 3D/CAD-supported photogrammetry of bodily injury internal structures to provide more leads and stronger practical forensic evidence. Paper presented at the International Society of Optical Engineers: 3D Visualisation for Data Exploration and Decision Making.

Thali, M. J., T. Markwalder, C. Jackowski, M. Sonnenschein, and R. Dirnhofer 2006 Dental CT imaging as a screening tool for dental profiling: Advantages and limitations. *J. Forensic Sci.* 51(1):113–119.

Thali, M. J., K. Yen, W. Schweitzer, P. Vock, C. Boesch, C. Ozdoba, G. Schroth, M. Ith, M. Sonnenschein, T. Doernhoefer, E. Scheurer, T. Plattner, and R. Dirnhofer 2003a Virtopsy, a new imaging horizon in forensic pathology: Virtual autopsy by postmortem multislice computed tomography (MSCT) and magnetic resonance imaging (MRI)—A feasibility study. *J. Forensic Sci.* 48(2):386–403.

Thali, M. J., K. Yen, W. Schweitzer, P. Vock, C. Ozdoba, and R. Dirnhofer 2003b Into the decomposed body-forensic digital autopsy using multislice-computed tomography. *Forensic Sci. Int.* 134(2–3):109–114.

Tonello, B. 1998 Mass Grave Investigations. Paper presented at the Imaging Science Oncologists, British Institute of Radiology.

Trotter, M. and G. C. Gleser 1952 Estimation of stature from long bones of American whites and Negroes. *Am. J. Phys. Anthropol.* 10:463–514.

1958 A re-evaluation of estimation of stature based on measurements of stature taken during life and of long bones after death. *Am. J. Phys. Anthropol.* 16:79–123.

Uysal, S., D. Gokharman, M. Kacar, I. Tuncbilek, and U. Kosa 2005 Estimation of sex by 3D CT measurements of the foramen magnum. *J. Forensic Sci.* 50(6):1310–1314.

Viner, M. D. 2001a Forensic investigation: The role of radiography. *Eur. Radiol.* Supplement to Volume 11(2):95.

2001b Forensic investigation: The role of radiography in forensic medicine. *ISRRT Newsletter* 37(2):4–7.

2001c The radiographers role in forensic investigation. *Hold Pusten: J. Norwegian Soc. Radiog.* (9/2001).

Viner, M. D., M. Cassidy, and V. Treu 1998 The Role of Radiography in a Disaster Investigation. Paper presented at the Imaging Science Oncolologists, British Institute of Radiology.

Viner, M. D., W. Hoban, C. Rock, and M. T. Cassidy 2003 The Role of Radiography in the Investigation of Mass Incidents. Paper presented at the American Academy of Forensic Science 55th Scientific Meeting, Chicago, IL.

Viner, M. D., C. Rock, N. Hunt, G. Mackinnon, and A. W. Martin 2006 Forensic Radiography: Response to the London Suicide Bombings on 7th July 2005. Paper presented at the American Academy of Forensic Science 58th Scientific Meeting, Seattle, WA.