Science & Justice 62 (2022) 582–593

Contents lists available at ScienceDirect

Science & Justice

journal homepage: www.elsevier.com/locate/scijus

Short Communication

The application of dual energy X-ray soil screening in forensic archaeology

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ARTICLE INFO

Keywords:
Radiography
Search
Human remains
Ballistics
Screening
Disaster Response

ABSTRACT

The need to forensically search soil for small artefacts at a burial site or traces of evidence in a deposition site is a common task shared by investigators and forensic archaeologists. In forensic casework, the importance of finding small pieces of evidence, such as personal effects or ballistic fragments, cannot be overstated as it can assist in the positive identification of the deceased, give an insight into the manner and cause of death, and identify any perpetrators. The soil search methods known as wet and dry sieving, are cumbersome, time-consuming and have limited success for some soil types. This often leads to the decision not to search, resulting in missed opportunities to identify potential evidence.

The primary aim of this study was to investigate if a dual energy X-ray baggage scanner could be used to search for items of potential forensic interest in soil. A trial was conducted using a Smiths Detection ScanTrailer 100100 V-2is mobile X-ray inspection system to establish if it could be used to detect organic, inorganic, and metallic items located within soil. The soil type and natural variables such as water and organic content were adjusted to simulate different environments. The baggage scanner was found to provide a quick and easy way to detect items contained within various soil types, particularly in a sand rich matrix. It is estimated that using this method to search 1 m^3 of soil, when broken down into samples that are < 13 cm in depth, would take around one hour to complete, compared with 100 to 150 person-hours by manual sieving. This is believed to be the first use of dual energy X-ray technology for this purpose and shows the potential for further research and use of this method in forensic archaeology.

1. Introduction

In forensic and humanitarian cases, forensic archaeologists are primarily employed in the search, location and recovery of human remains from clandestine graves [1]. Human remains can become buried following homicide, mass killing, natural disasters, etc.; and while locating the remains is paramount, the recovery of other evidence or associated artefacts from a deposition site will also be of high importance [2]. In forensic casework, elements such as fragments of human bone, teeth or artefacts such as items of clothing, ballistic evidence and personal effects may assist the investigators in identifying the victim and/or perpetrator, as well as hold information on the manner of death and disposal of the body. It is the surrounding area and the soil in which the corpse is buried that has the potential to contain those items. The search and excavation of single or mass graves (those containing multiple bodies) are time consuming and may require the removal of tonnes of soil. With only a limited number of soil search methods currently available, there is a potential that this soil may be largely left unsearched and important items may be missed [3]. Although the use of radiography to examine soil from archaeological contexts has a relatively long history [4], this paper explores how to increase the speed of a search by using a conventional dual energy X-ray baggage scanner, as found at airports and mass transport hubs, to rapidly screen soil from a forensic archaeological excavation.

1.1. Conventional screening

It has long been established that the screening of the grave fill increases the likelihood of locating smaller bones and teeth [5], with one study purporting that sieving increases the number of small finds by 54 % [3]. There are two common methods for screening the grave fill. These methods are known as ‘dry’ and ‘wet’ screening or sieving. Screening or sieving has been well established as good practice in archaeological fieldwork [6].

Dry sieving (Fig. 1a) involves passing the grave fill soil through a mesh sieve. The size of the mesh depends on the sizes of the artefacts to

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https://doi.org/10.1016/j.scijus.2022.08.005
Received 28 April 2022; Received in revised form 20 August 2022; Accepted 28 August 2022
Available online 1 September 2022
1355-0306/

be recovered [5]. Multiple studies have found that mesh sizes of between 3 and 10 mm are generally considered most suitable for forensic casework as these capture small bones and teeth, and most artefacts [3,7].

There are two types of wet screening methods; these are commonly referred to as wet sieving (Fig. 1b) and flotation (Fig. 1c). Wet sieving consists of the washing down of soil through a mesh using water, which washes away finer soil particles through the sieve and leaves behind any larger items. Flotation consists of water being pumped up through the soil and out through a sieve, with the water lifting and carrying away the finer soil particles leaving behind any larger items. Wet screening methods are ideal for releasing items trapped within a damp or compact soil matrix, such as clay [5]. The main disadvantage to the wet screening method is the need for a source of running water which can be difficult to acquire in remote locations. Wet screening methods may also damage

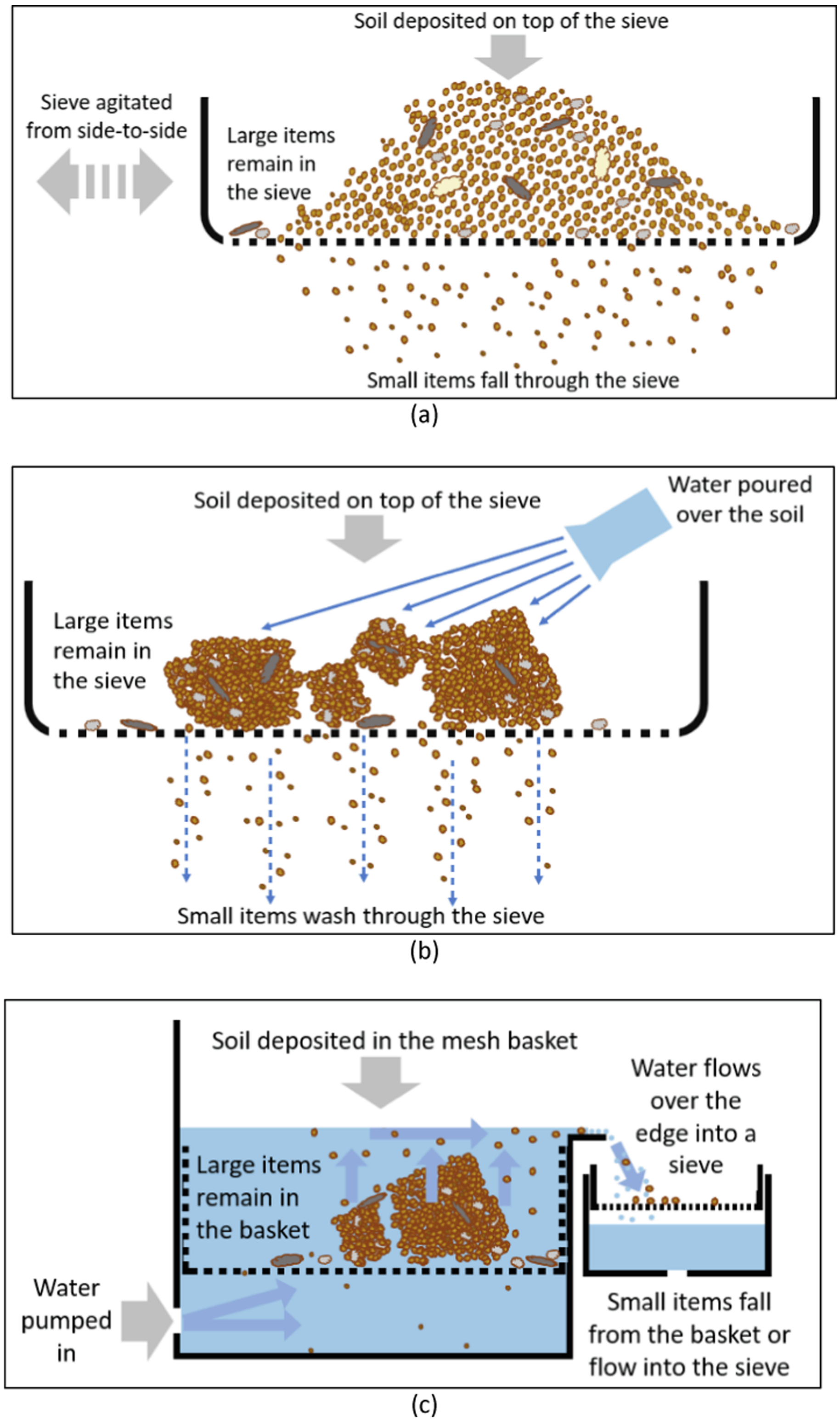

Fig. 1. Conventional soil sieving techniques, (a) dry sieving, (b) wet sieving and (c) flotation sieving.

or destroy fragile items when submerged in water [5].

1.2. X-ray imaging

The application of radiography in an archaeological context tends to focus on the non-invasive post-excavation analysis of items such as mummified remains, cremation urns and heavily corroded artefacts [8,9]. However, its potential for use as a soil screening method has been highlighted by Wessling [10], when radiographic imaging was used as a primary screening method on the site of a large-scale WW1 battlefield excavation at Fromelles, France [11]. Faced with a wet clay soil matrix that was impractical to wet or dry sieve, the decision was made to collect the soil from below each corpse securing it in plastic bags. Initially used as a safety pre-screen for excavated material, to identify any hazardous unexploded munitions or sharp objects, it became evident that radiography allowed archaeologists to find other artefacts within the soil, for example the insignia badges that identified the soldier's nationality [10].

While conventional radiography has good penetrative ability when used during an archaeological excavation [10], its monochrome images are no more than 'X-ray shadows' of the internal structure of an object and give little information about the type of material being observed. This issue has long been addressed for security screening by adopting dual energy X-ray imaging [12,13] that uses the different attenuation of low energy and high energy X-rays to discriminate materials according to their effective atomic number (Z_{eff}). This displays light elements or organic materials ($1 \leq Z_{eff} \leq 9$) as orange, medium elements or inorganic materials ($10 \leq Z_{eff} \leq 15$) as green, and heavier elements or metallic items ($16 \leq Z_{eff} \leq 56$) as blue. This provides a major advantage over traditional monochrome (black and white) radiographic images, where every item within a suitcase would be displayed as a shade of grey regardless of its composition and enables the rapid identification of potential contraband items such as weapons, explosives, and narcotics.

Whilst the use of dual energy X-ray imaging as a search and screening tool is widely recognised by industry [14], its application to searching through debris and soil is a novel one. Previous studies using standard airport baggage scanning equipment, in the support of forensic archaeology and forensic anthropology, have tended to focus on considering it as a direct replacement for conventional medical radiography in a mortuary setting [15]. More recent work has shown it can easily distinguish human remains and other artefacts within body bags both as a pre-screen and to aid both forensic odontologists and anthropologists [16]. It is therefore conceivable that it may also be able to discriminate items contained within bags or buckets of soil recovered during a forensic investigation.

This study aimed to evaluate dual energy X-ray scanning as a new and alternative method for forensically searching for evidence (bone and other material) in different types of soil. This study used the Smiths Detection ScanTrailer 100100 V-2is, which is the in-service equipment utilised by the Royal Air Force Police on behalf of the UK Armed Forces. This mobile scanner was designed in conjunction with the military for checking luggage, freight, or mail; and enables rapid deployment of this technology at short notice anywhere around the world. It would also be well suited to deployment to the scene of any type of (forensic) archaeological excavation or in response to a natural disaster. It is the mobile version of the Smiths Detection HI-SCAN 100100 V-2is that is used for security screening and is found at major transport hubs, postal sorting offices and cargo distribution centres around the world.

2. Materials and methods

The study was divided in two phases. The first explored how the soil matrix and variables such as moisture and organic content affected the scan image. The second focused on a 'real-world soil' matrix and assessed the practicalities and limitations of using a dual energy X-ray scanner as a method to search through soil.

2.1. The dual energy X-ray scanner

A Smiths Detection ScanTrailer was used for this study [12,13], see Fig. 2. This inspection system features two X-ray generators set at 90° to each other and positioned opposite an L-shaped line of photodiode detectors. The first X-ray generator is located at the side of the conveyor belt and scans items diagonally. The second X-ray generator is positioned below the conveyor belt and scans items vertically. This dual aspect scanner creates two separate images and allows the operator to accurately pinpoint where something is located within a scanned item. Each X-ray generator is operated at a constant anode voltage of 160 kV, higher than that typically used in medical radiography, giving the inspection system the ability to penetrate much larger and denser objects.

The Resolution of freight inspection systems are measured by their ability to detect thin copper wires. The sensors fitted to this system are designed to capture images of wires, in clear air, that are 0.09 mm (39 AWG) in diameter. This is likely to be reduced if surrounded by another dense material. Designed for the rapid scanning of luggage, freight or mail, the conveyor belt and scanning tunnel can accommodate items that are 1 m in width and 1 m in height. The conveyor belt can carry an evenly distributed load of 220 kg and moves at 0.2 m/s.

As with most inspection systems, the user interface enables a simple zoom feature along with a range of image display modes to assist with the search for items of interest (see Table 1). In addition to the ability to discriminate materials according to Z_{eff}, the baggage scanner was also equipped with threat detection software (X-ACT, X-ray Advanced Contents Tracking) that uses Z_{eff} to automatically highlight explosives with a red box, narcotics with a green box, and dense or radiopaque areas with a blue box. The correct operation of the scanner was confirmed using an International Civil Aviation Organisation (ICAO) Standard test piece [17].

Unlike static inspection systems, this equipment is fitted on a roadworthy trailer and can easily be transported to where it is required. The trailer provides an IP54 rating (IEC/EN Standards 60529:2018), which provides protection from limited dust ingress and water spray from any direction.

2.2. Test objects

A test object was created to simulate the smaller types of evidence that could be missed during the excavation of a (clandestine) grave. These items were sealed together to form a single reusable sheet (see Fig. 3a). Sealing items side-by-side in a thin layer of plastic prevented their loss and maintained their position to ensure repeatability between all scans and provided comparable items for detection between soil matrices. The same test object was used throughout all testing phases and consisted of the items discussed below and summarised in Table 2.

2.2.1. Weapons

Firearms tend to fall into three categories: handguns, rifles, and shotguns [18]. Handgun ammunition tends to be the smallest type of ammunition and consists of a copper and lead bullet and brass casing. The most common handgun ammunition calibre is 9 mm × 19 mm [19,20], which was added to the test object. Rifle ammunition tends to be larger and again consists of a copper and lead bullet and brass casing, with the most common rifle ammunition calibres being 5.56 mm and 7.62 mm [21,22], both of which were added to the test object. Shotgun ammunition (or shells) are quite different and consist of steel or lead balls (shot) and a brass and plastic cartridge (case) [19]. The size of the pellet-like projectiles contained within the shell varies, but the most common sizes are between Size 8 Lead Shot (2.29 mm diameter) and No.0 Buck Shot (8.13 mm diameter lead balls), both shot sizes were added to the test object. Additionally, mid-sized Size 2 Steel Shot (3.81 mm diameter) were also added to the test object. The shot was distributed across the test object to simulate the spread of pellet-like projectiles after firing [20,21].

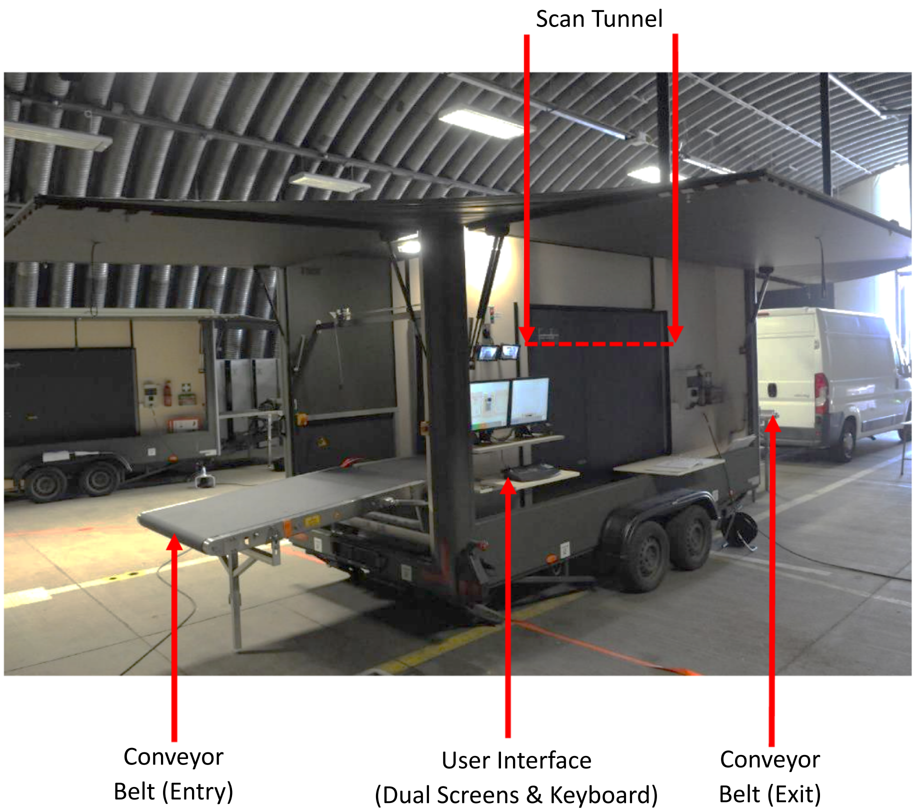

Fig. 2. Smiths Detection ScanTrailer HI-SCAN 100100 V-2is in operation.

Table 1
X-ray scanner image display modes.

Default image (HI-MAT):	Displays materials according to their effective atomic number (Z_{eff}), showing organic items ($Z_{eff} < 9$) as orange, inorganic (Z_{eff} 10 to 15) as green, and metallic items ($Z_{eff} > 15$) as blue, with thin or low-density materials appearing brighter.
Organic only (O^2):	This highlights the organic (orange) items by making the non-organic and high absorbing items appear grey. This makes explosives and drugs easier to visualise.
Organic stripping (OS):	This highlights the non-organic and high absorbing objects and makes the organic items appear grey. This makes metal objects such as weapons and tools easier to visualise.
Black and white (BW):	Similar to a traditional X-ray image displaying all materials in grey levels based on the absorption of the material due to either its thickness or density. Thinner or low-density materials appear brighter.
Negative image (NEG):	Reverses the intensity ranges for the HI-MAT, O^2, OS and BW imaging modes, making smaller or thinner objects (e.g. wires) easier to visualise.
Super-enhancement (SEN):	Optimises the contrast for the HI-MAT, O^2, OS and BW imaging modes. This makes low absorbing items (e.g. plastics and fabric) and items concealed behind metal plates easier to visualise.
High penetration (HI):	Adjusts image contrast from HI-MAT and BW modes to allow any dark higher absorbing items to become easier to visualise. Allows items hidden behind highly absorbing objects to be revealed.
Variance of absorption range (VAR):	This mode allows the image to be shifted between 5 degrees of absorption from high to low. Each level provides enhanced contrast, by retaining the number of brightness levels but progressively reducing the number of absorption range levels.

Bladed items such as knives are commonly used too, especially in countries with tighter firearms regulation or where the ease of access to firearms is restricted. Knife crime is on the increase in the UK where bladed items have become the weapon of choice for use, for example in gang-related violence [22]. When a knife is violently thrust into the body of a victim the tip of the blade could impact on hard tissue (bone) possibly causing the blade tip to fragment. These small metal fragments can be retained in the body after death [23]. During decomposition and skeletonization, these foreign bodies may fall clear of the corpse into the surrounding soil. Two fragments of a steel kitchen knife blade were therefore also included in the test object.

2.2.2. Bone and teeth

Human skeletal remains can be found in forensic casework as fleshed, wet (but unfleshed) and dry bone [24], the latter stages in particular the focus of forensic anthropology. During another study of dual energy X-ray scanning [16] the authors observed that these different states produced a different colour response on the dual energy X-ray scan image, with the fleshed and wet bone appearing orange, and dry bone appearing green. This latter was likely due to the gradual loss of organic material within the bone during decomposition. A selection of fleshed, wet, and dry porcine (*Sus scrofa*) bones was incorporated into the test object in this study, as analogues to represent the small bones in human hands and feet. Fleshed bone was represented by a fresh cut section of pig trotter. The wet (unfleshed) bone was obtained by simmering a pig trotter in water for 1 h to soften and remove the flesh and connective tissues and removed manually. The dry bone state was created by gently boiling a trotter for 1 h to remove the flesh and connective tissue, before soaking the bones in a biological-based detergent for a period of 1 week before letting them dry naturally. Pig teeth were also added to the test object as the tooth composition, density and structure differs from bones.

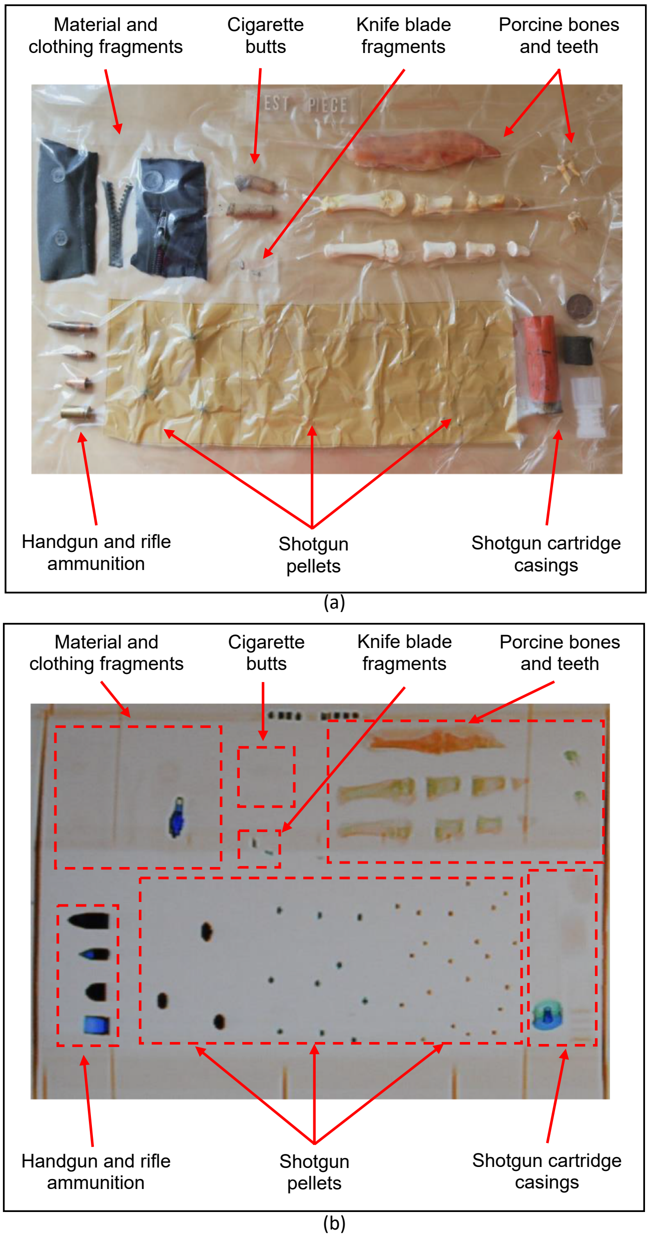

Fig. 3. (a) Standard test object used in this study (see Table 2 for contents) and (b) scan of standard test object in the absence of soil (setting: HI-MAT), both images have the items labelled.

Table 2
Components of the test object used throughout this study.

Item	Details
Material and clothing	Fragments of clothing with buttons and zippers
Cigarettes	Cigarette butts
Knife blade fragments	Tip fragments from a steel knife blade
Porcine bones and teeth	11 × porcine trotter bones (fleshed and defleshed) and 2 × teeth
Handgun and rifle ammunition	One 9 mm × 19 mm bullet and bullet casing One 5.56 mm bullet and one 7.62 mm bullet
Shotgun pellets	Lead shot: Size 8 (2.29 mm diameter) and No. 0 Buck Shot (8.13 mm diameter balls); Steel shot: Size 2 (3.81 mm diameter)
Shotgun ammunition	Components of a shotgun cartridge case including both plastic and fibre wadding

2.2.3. Other items

The grave may often contain the clothing of the victim as well as anything used to wrap or conceal the body during transport prior to deposition. It can also contain anything used as a blindfold, gag, or ligature, such as rope or cloth. Small samples of fabric were added to the test object including manufactured (synthetic) material, natural (cotton) material, as well as pieces of both metal and plastic zipper and buttons.

Two cigarette butts were added to the test object. On occasions at crime scenes, cigarette butts may be found, providing vital DNA evidence. Due to their light paper construction, they would be very difficult to find in the soil. However, the plastic cellulose acetate filter is slow to biodegrade [25] and could persist in the grave fill for some years after burial, hence why two were used in this experiment.

2.2.4. Soil

In the first phase of experiments, the most prevalent constituents of soil, sand and clay, were used in isolation to observe and understand the effect that the soil had on the dual energy X-ray image. Off-the-shelf building sand (Tarmac, UK, BS EN 13139) and modelling clay (Air Drying Modelling Clay (stone), Scola, UK) were used and were combined to create a consistent and repeatable soil composition. Chopped organic material (Meadow Hay Bedding, Tesco, UK) and water were then included as required.

The purpose of the second phase of experiments was to test the X-ray scanner's performance on a real soil matrix. A single clay-rich garden soil (collected from a domestic garden in Henlow, Bedfordshire, UK) was selected as this soil type would naturally prove difficult to sieve. It is recognised that clayey soil is only one type of soil that archaeologists would normally find difficult to sieve and it does not represent all challenging soil matrices [26,27].

The major elemental composition of each material and the garden soil was established using a Bruker Tracer 5i handheld X-ray fluorescence spectrometer and the water holding capacity (WHC) was measured using a modified saturation and drain method [28,29], see Table 3.

2.3. Imaging procedure

Scans were conducted on quantities of soil ranging from 5 kg to 20 kg in weight. Each scan was conducted using two plastic trays. The outer scanning tray was the standard type normally supplied with the scanner, used to transport loose items through the scanning tunnel. A smaller, inner plastic tray was also used to hold the test piece and soil matrix. This was placed inside the other tray with the test piece located underneath the soil unless stated otherwise. The internal measurements of this inner tray were 41.5 cm × 23.5 cm. The location of the X-ray generators and the shape of the detector in the baggage scanner introduces geometric image distortion that is strongly dependant on the position of the scanned object on the conveyor belt. This was minimised by placing the trays off-centre on the conveyer belt on the side furthest away from the X-ray generators. Each sample was scanned 3 times to monitor any variations and ensure the repeatability of results. During each run the sample was paused in the scanner and the image was cycled through

Table 3
Composition of the 3 different soil matrices used in this study.

*Concentration (wt%)	Sand	Clay	Garden Soil
Al_2O_3	4.2	25.0	11.0
SiO_2	91.7	65.7	70.1
K_2O	0.4	5.3	5.5
CaO	0.2	0.6	6.2
TiO_2	0.1	1.3	1.0
MnO	0.1	0.1	0.2
Fe_2O_3	3.3	2.0	6.0
WHC (10^{-4} m^3 kg^{-1})	2.8	1.2	5.2

every possible scan setting, as detailed in Table 1, and the image was recorded. The most successful setting was deemed the one which allowed the visualisation of the most test object items without any further image processing (see Table 4).

2.4. Ethical approval

This study was approved by Cranfield University Ethics committee (CURES).

Table 4
Matrix of scan results including the detectability of each test piece object.

Scan Description	Image	Material and clothing fragments	Cigarette butts	Knife blade fragments	Porcine bones	Porcine teeth	Handgun and rifle ammunition	Shotgun pellets	Shotgun cartridge casings
Standard test object (no soil)	Figure 3 (b)	P	N	V	V	V	V	V	P
Clay-rich garden soil (test object low)	Figure 4 (a)	P	N	N	N	N	V	V	N
Clay-rich garden soil (test object mid)	Figure 4 (b)	P	N	N	N	N	V	V	P
Clay-rich garden soil (test object high)	Figure 4 (c)	P	N	N	N	N	V	V	P
Sand (No Organic)	Figure 5 (a)	P	N	P	V	N	V	V	P
Sand (plus 5% Organic)	Figure 5 (b)	P	N	P	V	N	V	V	P
Sand (plus 20% Organic)	Figure 5 (c)	P	N	P	V	N	V	V	P
Clay (No Organic)	Figure 5 (d)	P	N	V	V	N	V	V	P
Clay (plus 5% Organic)	Figure 5 (e)	P	N	V	V	N	V	V	P
Clay (plus 20% Organic)	Figure 5 (f)	P	N	V	V	N	V	V	P
Sand (Dry)	Figure 6 (a)	P	N	P	V	N	V	V	P
Sand (plus 50% WHC)	Figure 6 (b)	P	N	N	V	N	V	V	P
Sand (plus 100% WHC)	Figure 6 (c)	P	N	N	V	N	V	V	P
Clay (Dry)	Figure 6 (d)	P	N	V	V	N	V	V	P
Clay (plus 50% WHC)	Figure 6 (e)	P	N	V	V	N	V	V	P
Clay (plus 100% WHC)	Figure 6 (f)	P	N	V	V	N	V	V	P
Clay-rich garden soil (Dry)	Figure 6 (g)	P	N	N	N	N	V	V	P
Clay-rich garden soil (plus 50% WHC)	Figure 6 (h)	P	N	N	N	N	V	V	P
Clay-rich garden soil (plus 100% WHC)	Figure 6 (i)	P	N	N	N	N	V	V	P

Key: V = Visible, P = Part Visible, N = Not Visible

3. Results

A dual energy X-ray scan of the test object without soil is included in Fig. 3b, where the geometrical distortion introduced by the scanning procedure is immediately apparent. This was not considered important as the aim when scanning was to locate items rather than accurately record their positions. This image was taken under optimum conditions using the HI-MAT setting. Close examination showed all metallic items (ammunition, knife blade fragments, metal zipper) were clearly visible and showed up as blue or black, indicating a high Z_{eff}. The bones and teeth were also clearly visible and appeared in a range of colours from deep orange to light green, indicating that these were of low to mid Z_{eff}. The clothing, cigarette butts and non-metallic parts of the shotgun shell were all very faint and difficult to see. The outer scanning tray and inner sample tray were also visible and appeared orange in colour as would be expected for plastics.

3.1. Position of test object within the soil

To establish if the images that the scanner produced were significantly affected by the position of the test object within the soil matrix, three locations were examined, with the test object either located at the bottom, middle or top of 8 cm (10 kg) of soil. The best quality images were obtained using the HI-MAT plus HI scanner setting, see Fig. 4. While the change of location introduced a slight shift in the position of the objects due to the geometry of the baggage scanner, the quality of the image was largely unaffected, and only the heavier metallic items were visible. It was noted that the outline and clarity of the thinner metallic objects (shotgun shell and 9 mm casing) appeared only marginally better the higher the test object was located. Overall, the soil appeared green and blue in colour, with a different texture in each image because the soil had to be moved to relocate the test piece for each scan.

3.2. Phase 1 scans – Sand and clay

Fig. 5 presents the dual energy X-ray scans with the test object located below 10 kg of either sand or clay with the addition of up to 20 % organic material (chopped straw). Under these conditions the optimal setting were found to be HI-MAT for sand and HI-MAT plus SEN for clay. All the metallic items were visible; however, the smaller shotgun pellets and knife blade fragments were difficult to see against the 'blue' sand/ clay matrix. While the teeth were not visible, the outline of the fleshed, wet and dry bones could be seen on the scans, although these looked similar in colour to the soil matrix, making them more difficult to see. Overall, both the clay and sand resulted in a mixture of colours with all scan images showing areas of orange, green and blue. While at the higher organic level of 20 %, the area of blue in the image appeared to be slightly increased in intensity, changes in the organic content did not affect the quality of the image or the ability to detect items.

The effect of increasing water content on the dual energy X-ray scans for the test object located underneath 10 kg of either sand or clay are given in Fig. 6 (a-f). Here, the optimal setting was found to be HI-MAT for sand and HI-MAT plus SEN for clay. Overall, increasing the water content in the sand resulted in a marked change to the image, increasing the size of the blue area and triggering the threat detection software indicating that the material was becoming too dense for the X-rays to penetrate (blue box). A similar change was also observed in clay; however, the colour change was not as noticeable. This increase in blue made it difficult to see smaller metallic items of the same colour (knife blade fragments and the steel shotgun pellets). It did however make the bones easier to see, as the blue silhouetted the bones which remained green in colour.

3.3. Phase 2 scans – Garden soil

Fig. 6 (g-i) and Fig. 7 present the dual energy X-ray images from test samples constructed using garden soil. The HI-MAT setting was found to be optimum when varying the water content of the soil (see Fig. 6 g-i), although this soil matrix made it difficult to see many of the items within the test piece, and only the larger metallic items were clearly visible. This was because the garden soil produced a very granular green and blue coloured scan image. Increasing the water content markedly increased the amount of blue in the background, significantly reducing the contrast with the smaller metallic objects that previously had presented in this colour, and triggering the threat detection software.

The effect of altering the amount of garden soil is given in Fig. 7, where the HIMAT plus HI image setting appeared to be best. At a soil depth of 4 cm (5 kg), the garden soil appeared green on the scanned image. As more soil was added, the image started to turn blue in colour, with a notable change occurring around 12 cm deep (15 kg). At this depth the scanned image was mainly blue, with some black areas starting to appear (again triggering the threat detection software). At 16 cm (20 kg) large black areas significantly obscured the centre of the image. This change in the colour of the background meant the test piece

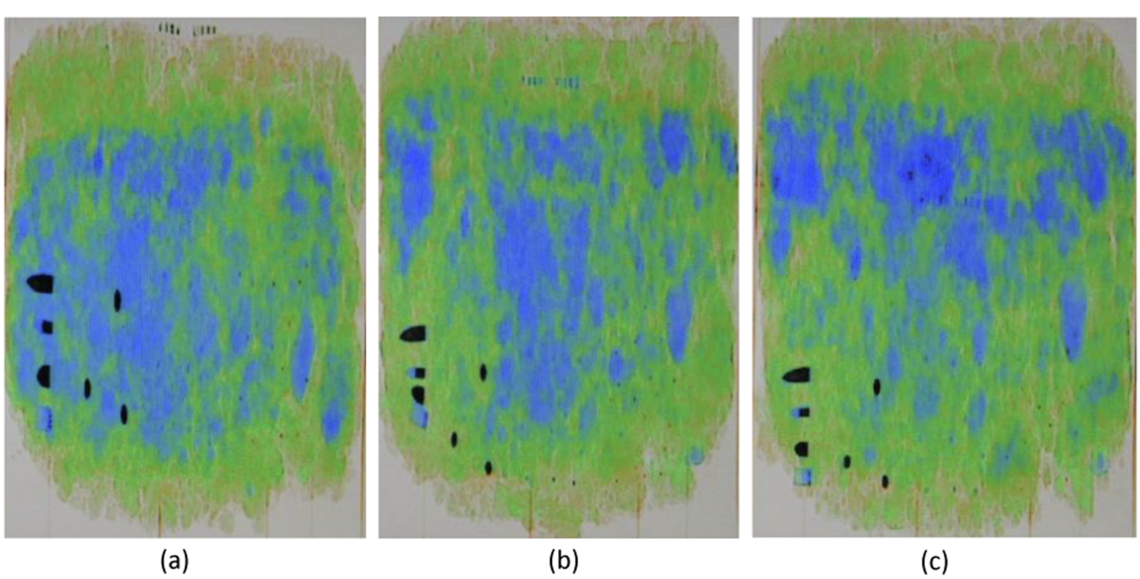

Fig. 4. Altering the location of the test piece in 10 kg of clay-rich garden soil (setting: HIMAT + HI), (a) test object low – 0 cm, (b) test object middle – 4 cm, (c) test object high – 8 cm.

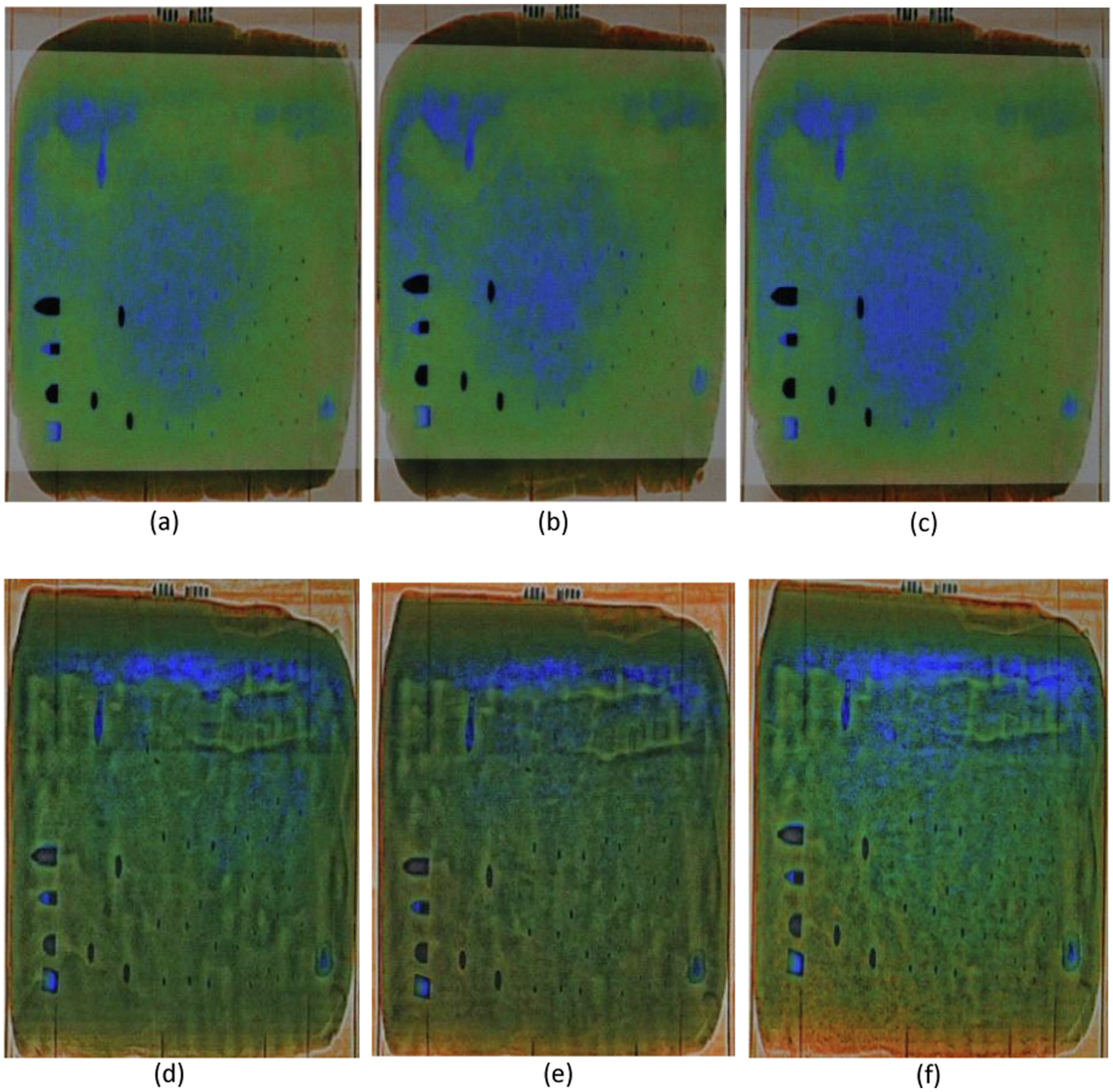

Fig. 5. Altering the organic content in 10 kg sand or clay (setting: sand HI-MAT, clay HI-MAT + SEN). (a) sand without organic, (b) sand plus 5 % organic, (c) sand plus 20 % organic, (d) clay without organic, (e) clay plus 5 % organic, (f) clay plus 20 % organic.

items were most visible in the 4 cm and 8 cm scans. As the thickness of the sample increased to 12 cm and 16 cm, most items were significantly obscured. As normally seen with heavy metallic items, the blackness of the image indicates that at these depths the soil was becoming too dense for the X-rays to penetrate. The optimal soil thickness would be < 12 cm. This coincides with observations made by Wessling [10], where the radiographer found that reducing the amount of soil increased the ability to successfully detect items.

4. Discussion

4.1. Image quality

As in any type of imaging, the ability to detect an object depends on the contrast between the object and its background. The appearance of the background in these experiments depended on how X-rays were absorbed or scattered by the soil matrix and how the resulting images were displayed. When considering this, it is important to remember that the settings for the baggage scanner only relate to how it displays images, not the hardware which was operated consistently throughout all exposures.

In the absence of soil, the image of the test object (Fig. 3 b) had low noise and a uniform orange background ($Z_{eff} < 9$) that is consistent with the plastic of the trays. The introduction of sand, clay or soil changed the background to varying degrees of orange, green and blue indicating a range of and an increase in Z_{eff}. Although the soil matrices were used in field condition, i.e were not artificially dried in an oven before use, the adding of water introduced a further change in image colour for all soil matrices, with increasing amounts of blue within the image as the amount of water was increased, implying $Z_{eff} > 15$. This was unexpected as the addition of water reduced the soil's average Z_{eff} and should have resulted in a move towards an orange image, rather than the colour blue which is normally associated with heavier metallic elements. This anomaly may be related to how the X-rays were scattered by the additional water that occupied the gaps between the grains of the soil matrix scattering low energy X-rays away from the image sensor arrays and reduced the X-rays to a level where they could no longer be reliably recorded, giving an inaccurate indication of Z_{eff}. In practice the operator is unlikely to be interested in the nature of the soil matrix, however the incorrect assignment of Z_{eff} does affect image contrast and how easily metallic objects can be resolved from the background. This made it more difficult to visualise lighter metallic items, such as the knife blade fragments which appeared the same colour. However, the increasingly blue image helped highlight the bones within the sand and clay samples,

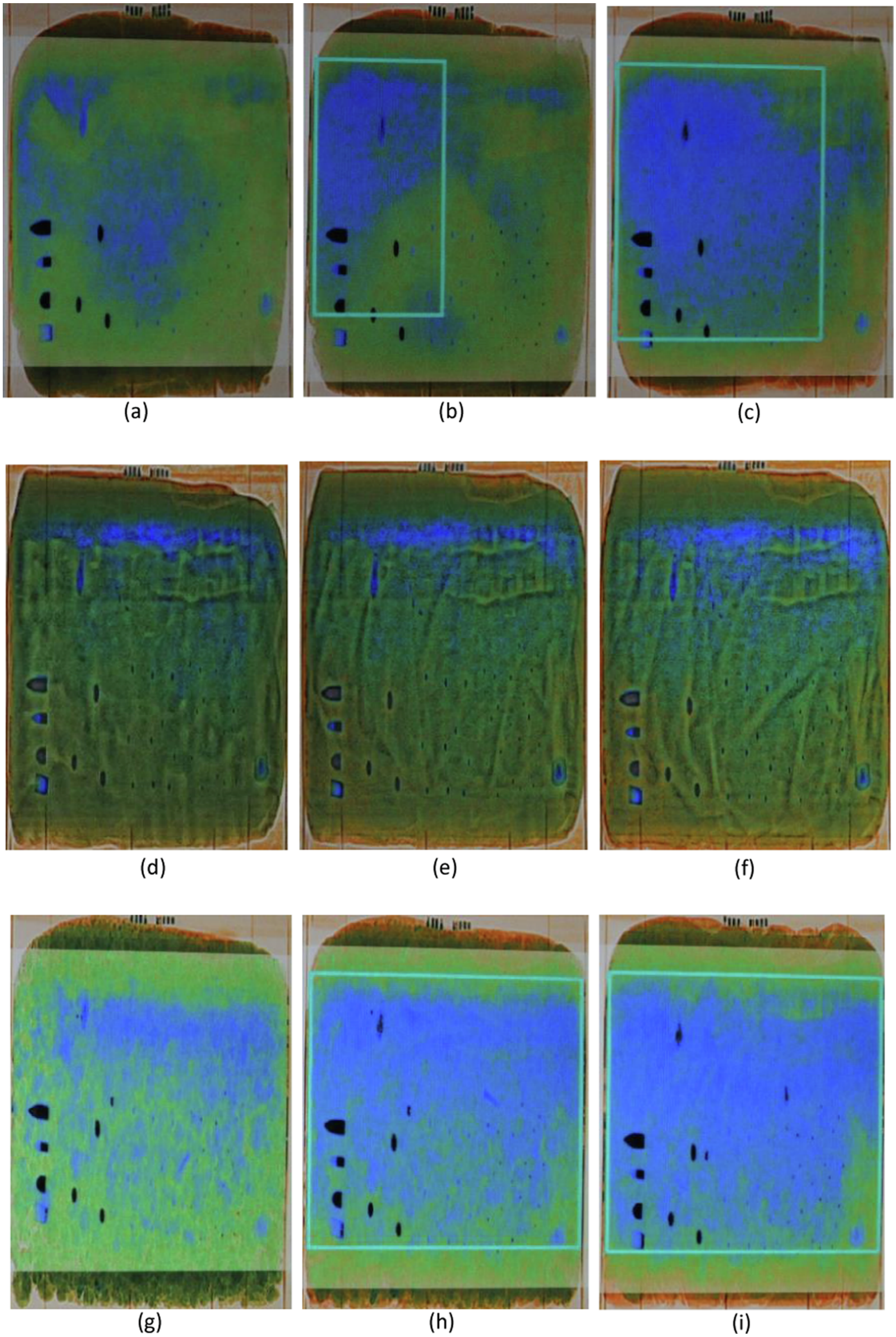

Fig. 6. Altering the water content in 10 kg sand, clay, clay-rich garden soil (setting: sand HI-MAT, clay HI-MAT + SEN, clay-rick garden soil HI-MAT). (a) dry sand, (b) sand plus 50 % WHC, (c) sand plus 100 % WHC, 1(d) dry clay, (e) clay plus 50 % WHC, (f) clay plus 100 % WHC, (g) dry clay-rich garden soil, (h) clay-rich garden soil plus 50 % WHC, (i) clay-rich garden soil plus 100 % WHC. The blue boxes indicate the threat detection software has detected dense areas.

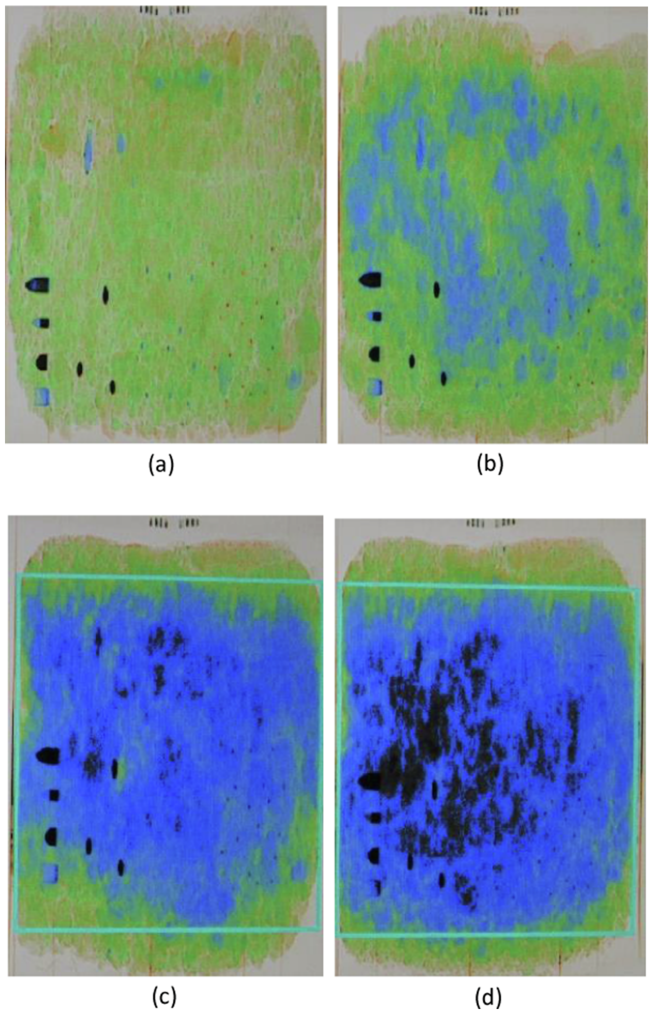

Fig. 7. Altering the amount of garden soil (setting: HI-MAT + HI). (a) 5 kg soil (4 cm depth), (b) 10 kg soil (8 cm depth), (c) 15 kg soil (12 cm depth), (d) 20 kg soil (16 cm depth). The blue box indicates that the threat detection software has detected dense areas.

with the bones remaining greener in colour.

The heavier metallic items, such as the ammunition bullets and casings, were easily visible across all scans. These items consist of metallic elements, such as lead and copper, which are much denser than the surrounding soil matrix. This result was expected as this technology was designed to easily identify this type of material within passenger baggage. Only the metallic parts of the shotgun ammunition were visible, with the non-metallic parts (plastic and cardboard wadding) remaining undetectable, likely due to their low density. The knife blade fragments were largely visible, however, due to their small size, they could easily be missed.

Organic items, such as the bones, appeared to vary in colour between the fleshed, wet, and dry stages of decomposition. The fleshed bone appeared deep orange in colour, indicating a high organic content, a low Z_{eff} material. The wet and dry bones appeared light green in colour, indicating a medium Z_{eff} material. This colour variation between bone types was expected, as previously observed by D'Arcy, Márquez-Grant, and Lane [16]. Due to the light nature of this material, it was difficult to detect as the surrounding soil matrix was generally presented as a similar colour and density.

Inorganic items, such as the clothing fragments, were difficult to detect with only the metal zipper being consistently visible throughout all scans. Cigarette butts were not detectable in any of the scans, likely due to their small size and light paper and plastic construction.

4.2. Application in the field

Once on-site, the X-ray scanner took approximately 30 min for a team of two experienced operators to set up. The scanner required no warm-up or calibration time, other than a cursory test scan of the standard test piece to ensure it was operating correctly. The only technical requirement was the availability of an electrical power supply. This could either be in the form of a connection to the local grid or by way of a portable generator. It is conceivable that many gravesites are in remote locations where connection to a domestic power supply may be limited. The provision and transportation of the scanner, generator and fuel supply to the site is a logistical challenge that would need to be considered.

The scanner used in this study is IP54 rated (IEC/EN Standards 60529:2018), which should provide protection from limited dust ingress and water spray from any direction. The concern when using this equipment was contamination from loose soil during scanning. As the soil moves along the conveyor belt and through the lead curtain at each end of the tunnel, there was a potential for spillage. To mitigate this, the soil would need to be contained in either sealed plastic bags or a container (crate, box, bucket) with a closable lid. The outer bag or container would need to be kept relatively clean to prevent fouling up of the conveyor belt and scanning tunnel. This may be difficult to manage on-site. This equipment would be better suited located on a hard standing, away from the excavation where a decontamination/clean working area could be established. Additionally, if used in inclement weather it would be difficult to prevent the scanner from being damaged during heavy rain. A temporary structure could be used (large tent or marquee), but the ideal location to protect the scanner would be under hardcover, in a garage or warehouse.

During operation the baggage scanner was found to offer significant time savings compared to conventional sieving. The scan time was very quick, with each sample taking 18 s to travel the length of the conveyor belt. Assuming an additional time of around 30 s was required for the operator to pause and observe the image and optimise settings; this gives a total of around 50 s per scan. Even with time for image analysis, this is potentially a much faster process than traditional wet and dry sieving. Indeed, this study showed the optimal amount of garden soil that the dual energy X-rays could successfully penetrate was the 15 kg per sample scan, equivalent to a depth of 12.0 cm in the inner tray, giving a volume of 11,703 cm^3. Scanning 1 m^3 of soil would therefore take just over 1 h compared to between 100 and 150 person-hours by manually sieving [30]. If the typical single grave contains approximately 0.5 tonnes of earth [31], then this scanning method would take slightly under half an hour to search the same quantity of soil, assuming a bulk soil density of approximately 1,280 kg m^3 [32].

Although much quicker than manually sieving the soil, extra time would be needed to separate and package (bag or bucket) the soil for scanning. Additionally, any samples that are found to contain potential items of interest would also need to be opened and searched by hand. This process would likely work well in conjunction with a traditional sieving method, where bulk soil can be scanned relatively quickly, and any samples of interest could be segregated for further search by hand. This would alleviate the need to manually sieve all the soil. The dual screen view provided by this scanner (showing both a horizontal and vertical view pane), would also help the user target a location within the sample, making discovery of any items a much quicker process. It is worth noting that traditional hand sieving may not even be attempted due to the time it would take, or the associated cost in person-hours. This scanning method could provide a middle-ground solution, allowing a search of the soil to be conducted, where previously it would have been left unchecked.

It is feasible that this equipment could be utilised at various points during the excavation and recovery of human remains. If used during the excavation, this methodology would be much quicker than other types of sieving. In a humanitarian or mass grave scenario it could also offer instant identification of a group of individuals. As evidenced during the X-ray screening conducted in the Fromelles excavation [10,11], this X-ray scanning would be capable of easily highlighting the regimental military pin badges of a certain group of soldiers for example. It would also provide the excavation team with a way of safely screening excavated material to identify any potential weapons, live ammunition, and unexploded ordnance without the need to employ a radiographer.

Notwithstanding the issues raised with use on an excavation site (transport, setup, and soil ingress), the optimal time to employ this methodology would be post-excavation where the soil is retained for searching. This equipment could be used as a primary screening method to search any soil or grave fill that was routinely recovered during the investigation, especially where it would be deemed too time-consuming or expensive to sieve by hand. Its use as a post-excavation tool could be opportunistic, to identify other unknown evidence, or directed by the anthropologist or pathologist/coroner to locate something specific. During an examination of the human remains, it could be that some bones are missing; likewise, the identification of ballistic trauma could prompt the search for bullet fragments that have fallen free of the corpse.

5. Conclusion

This study aimed to test a novel application of a dual energy X-ray technology, typically used for security screening, to scan soil to detect objects of forensic interest. Although this study focused on the practicalities of using a Smith Detection ScanTrailer, the observations made highlight the broader potential of dual energy X-ray scanners as a viable soil screening alternative to the conventional manual sieving methods.

In the tests detailed in this study, the X-ray scanner could penetrate the three soil matrices of sand, clay, and clay-rich garden soil, with varying success in the detection of test object items. The results gained showed that soil matrix does have an impact on X-ray digital image quality. Whilst digital imaging was easy for the homogenous sand and clay, the stone content and variability of garden soil hindered the detection of some test object items. Its ability to detect metallic items was clear throughout all scans. Limited success was seen with the visualisation of bones as detectability depended on a homogenous soil matrix and higher water content, which relied on the background substrate to highlight the bones. Lighter inorganic items such as clothing, plastic and cigarette butts were difficult to observe across all soil types deeming this method unsuccessful at consistently detecting them. The optimal soil matrix would be one with a low stone content. The most important factors were water content and the thickness of the soil. Low water content aided detection of metallic objects, whereas the higher water content enhanced the outline of bones. Ideally the soil thickness should be kept below 12 cm when passing through the scanner. Overall, this screening method would not be recommended solely as a reliable way to detect bones or light inorganic material within a complex soil matrix.

The rapid scanning capability and ease of detecting these items would make this ideal for use on some domestic homicide or human rights' cases. Additionally, this technology may also assist in WW1 and WW2 mass grave excavations where the identification of regimental, unit or country insignia badges would be of great assistance.

Like all X-ray equipment, the Smiths Detection ScanTrailer is a sophisticated and sensitive piece of equipment. Some logistical issues were identified, such as the transportation and power supply requirements. It was also identified that the prime location and use of this equipment would be off-site, on a hard standing or in a hard shelter, where the potential ingress of dust or dirt can be controlled. This makes it better suited for use after the excavation has concluded, when the screening of soil can be done in a controlled environment.

CRediT authorship contribution statement

Daniel Kent: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Nicholas Márquez-Grant:** Methodology, Writing – review & editing, Supervision. **David Lane:** Methodology, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

One of the authors (DK) would like to thank the Royal Air Force Police for their continued support throughout the project, including providing access to the ScanTrailer X-ray baggage scanner.

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