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The role of micro-computed tomography in forensic investigations☆

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ABSTRACT

The use of micro-CT within forensic practice remains an emerging technology, principally due to its current limited availability to forensic practitioners. This review provides those with little or no previous experience of the potential roles of micro-CT in forensic practice with an illustrated overview of the technology, and the areas of practice in which micro-CT can potentially be applied to enhance forensic investigations.

1. Introduction

Since the first description of the use of cross sectional imaging in medico-legal practice by Wullenweber in 1977 [1], forensic practitioners have realised and embraced the potential applications of computed tomography for forensic practice. This has been dependent upon the speed of development of the technology itself as well as the translation of clinical into forensic practice. Today so-called 'necroradiology' [2] has become a routine part of autopsy practice across the world with a realisation that the invasive autopsy may no longer be required in certain types of death investigation [3,4]. An expanding literature exists on the potential role of computed tomography (CT) and its application to forensic science and autopsy practice (post-mortem computed tomography, PMCT).

The use of micro-CT within forensic practice remains an emerging technology, principally due to its current limited availability to forensic practitioners. This review provides those with little or no previous experience of the potential roles of micro-CT in forensic practice with an illustrated overview of the technology, and the areas of practice in which micro-CT can potentially be applied to enhance forensic investigations.

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2. Micro-CT; the principles

The fundamental principles of micro-CT are analogous to clinical computed tomography, functioning by X-ray emission [5]. However, micro-CT provides much greater spatial resolution and therefore overcomes limitations with regards to image quality and detail. The tomographic information is reconstructed from a series of radiographic images, typically between several hundred to a few thousand, taken as the sample is revolved between emitter and detector. The X-rays are attenuated as they pass through the sample such that each element of the radiographic image is determined by the line integral of the path through the intervening material. However, as the sample is imaged from multiple angles covering a range of 0–180°, or more commonly 0–360°, the contributed attenuation of each point in the sample can be uniquely calculated by filtered back projection, a process based on the Radon function [6]. This generates a data set known as a voxel map, where a voxel is a volumetric element with a position in space and an associated unit of attenuation. It is typical for voxel maps to have Cartesian coordinates and isotropic voxel spacing. This differs from clinical CT and other medical imaging techniques, such as magnetic resonance imaging (MRI), which collect slices of information that have good spatial resolution in plane but poorer slice spacing, and are therefore inherently anisotropic. The isotropy of voxel spacing in micro-CT removes the need for interpolation between slices when rendering samples in 3D, eliminating a source of image artefacts, and allowing for greater versatility during virtual inspection. Since the contrast of the image is given directly by the attenuation values of neighbouring volume elements or sub-volumes, and not by line integrals representing a path through the complete object, neighbouring or superimposed structures have very little or no influence, producing a sharper, clearer image than is available with other imaging modalities (traditional radiography) [7]. Additionally, micro-CT is a non-invasive, non-destructive technique, leading to its extensive utility in studies measuring alterations in bone stereology, volume and micro-architecture [8].

Recent technical developments in the areas of computer memory and processor speed, and the increased availability of mega pixel charge-coupled device detectors, have subsequently made micro-CT a practical approach to obtain quantitative information from small specimens.

3. Micro-CT imaging

The East Midlands Forensic Pathology Unit, Leicester, takes advantage of access to a micro-CT system within the Department of Engineering, University of Leicester, for forensic investigations. The instrument in question is a Nikon Metrology XTH 225 micro-CT scanner, with a Paxscan detector. Data is reconstructed using Nikon Metrology's proprietary software and all rendering and subsequent analysis is performed in VGStudioMax 2.1. A typical examination for forensic bone samples has the X-ray emitter conditions set between 95 kV and 115 kV with a current range of 115–142 μA and a filter of 0.5 mm thick copper. The bone images acquired for this review were produced under these conditions.

For applications where it is necessary to quantify material density from reconstructed data, care should be taken to ensure that objects of known density are included alongside the sample during imaging. Where this is not possible, samples of known density should be imaged separately at fixed emitter conditions (i.e. kV, μA and filter) and these conditions used for all sample imaging. Calibration should be repeated with a period determined by the thermal drift of the detector panel, or whenever a change of X-ray source filament is required. Similar steps should be taken where it is challenging to resolve the components of an image by their X-ray attenuation, which is common where multiple materials with similar density are present (such as in wet tissues).

Resolution is an important physical parameter, primarily dependent upon the size of the pixel (picture element) matrix employed and the subsequent spacing of volume elements (voxels) [7]. Spatial resolution is also influenced by several other factors, including; the inherent resolution of the X-ray detector, focal spot size, geometric magnification, stability of the rotation mechanism and the filtering algorithm utilised for CT reconstruction [8]. The largest factor in determining the resolution achievable in practice for both micro-CT and clinical CT is the geometric magnification. For the vast majority of systems, both clinical and micro-CT, the emitter and detector are held at fixed distance from one another, see Fig. 1. In clinical CT the sample distance is also fixed, having been chosen at manufacture so that the projected image of the part the body in question can be captured by the detector fan. For micro-CT systems the distance between emitter and object can be altered, so that smaller objects can be imaged at closer proximity to the emitter. The closer the object is to the emitter, the larger the projected image captured by the detector. It is this magnification that is the primary factor in determining micro-CT's improved resolution. The spatial resolution achievable in reconstruction is also limited by the greatest distance that any part of the sample moves between radiographic images. The greatest movement is always at the widest part of the sample, as this is furthest from the centre of rotation. Performing smaller rotations between frames improves the reconstructed resolution. It is also common practice to average a number of frames in order to improve the signal to noise ratio (SNR) of each radiographic image. As the rate at which radiographic images can be detected is typically limited by the frame rate of the detector panel, the time required to generate a full scan is proportional to the desired resolution and signal quality. To obtain very high quality images long scans times of approximately 6 h may be required. It is possible to achieve scans suitable for micro-CT reconstruction in less than an hour where either the required resolution is low, or density contrast is extremely good, eliminating the need for SNR refinement.

4. Applications of micro-CT in forensic practice

The following section reviews a series of examples where micro-CT has been employed in forensic practice. It is provided as a resource for those wishing to explore the application of micro-CT in their area of interest, providing a good overview of the areas in which micro-CT imaging been successful and those where many challenges remain.

4.1. Gunshot wounds

Gunshot residue (GSR) examination has a significant role in the evaluation of firing range in gunshot fatalities. There are a variety of methods reported within the literature which may be employed to examine the distribution of GSR in relation to entrance wounds.

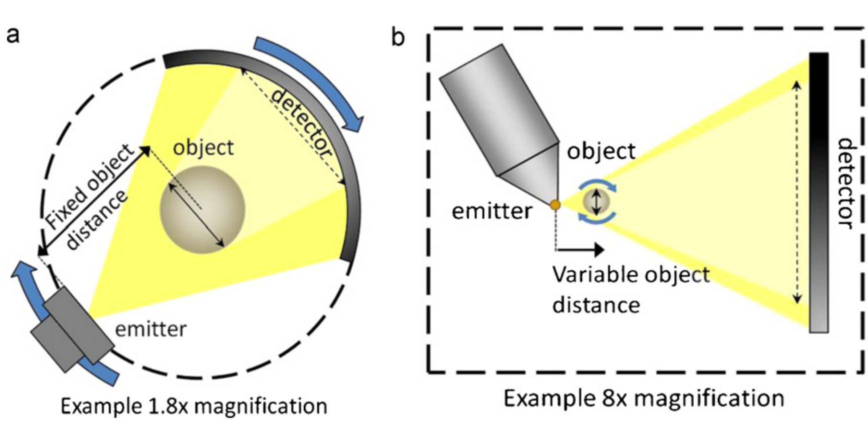

Fig. 1. (a) Schematic of a typical clinical computed tomography system. (b) Schematic of a typical micro-CT system, illustrating the improved image magnification possible with variable distance from emitter to object. This is only achievable because the object can be rotated rather than the emitter and detector.