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# Quantitative characterisation of ballistic cartridge cases from micro-CT

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## ARTICLE INFO

## ABSTRACT

Evaluation of cartridge cases is essential within forensic ballistic analysis and is used in an attempt to establish a connection to the weapon used to fire it. This study consists of two experiments. The aims of Experiment 1 were to establish whether micro-CT is appropriate and repeatable for ballistic cartridge case analysis and if measurements can be extracted repeatably and reliably. Experiment 2 aimed to compare cartridge cases from two weapons to establish the magnitude of variation within and between weapons. A total of 48 cartridge cases fired by two distinct weapons were collected and micro-CT scanned to a high resolution. One randomly selected cartridge was scanned ten times under the same conditions to ensure repeatability of the scanning conditions in Experiment 1. Three novel measurements to quantitatively assess the firing pin impressions were proposed in Experiment 1 and comparatively analysed from two weapons in Experiment 2. Experiment 1 showed that micro-CT is an effective and highly repeatable and reliable method for 3-dimensional imaging and measurement of ballistic cartridge cases. Furthermore, high agreement for inter-rater reliability was found between five raters. Quantitative micro-CT analysis of the firing pin impression measurements in Experiment 2 showed a significant difference between the two studied weapons using Welch's $t$-test ($p < 0.01$). This study shows the advantage and reliability of utilising micro-CT for firing pin impression analysis. Quantitation of the firing pin impression allows distinction between the weapons studied. With expansion to further weapons, application of this methodology could complement current analysis techniques through classification models.

## 1. Introduction

In forensic casework, ballistic identification is an essential tool in the investigative process. Cartridge cases are one of the most important pieces of ballistic evidence due to the likelihood of retrieving these from a crime scene [1]. Typically, analysis techniques are based on the specific impressions left by a weapon on cartridge cases on loading, discharge, and ejection [2]. Analysis of ballistic cartridge cases is a well-established forensic practice and predominantly focuses on the comparison between suspect and test-fired cartridge cases [3,4]. Focus remains on breech face striations and firing pin morphology, and typically relies on network systems such as the National Ballistics Intelligence Service (NABIS) in the UK, the National Integrated Ballistic Information Network (NIBIN) in the USA, the INTERPOL Ballistic Information Network (IBIN), and other national scale organizations [2]. These systems rely on Integrated Ballistic Identification System IBIS® [2,5]. IBIS correlates and compares images with a suspect cartridge case image to provide possible matches from previous crimes and/or test-fired firearms [5,6].

When a cartridge case is struck by a firearm's firing pin, the primer is ignited which initiates the firing of the projectile, and an impression is left on the primer cup – this impression is representative of the weapon fired [1,7]. Firing pin impressions are indicative of the firearm model used and individualistic deviations to the firing pin of a weapon could enable more unique identification in analysis. Firing pin depth has been shown to be altered based on direction of the weapon when fired [8]. While both IBIS and academic research has evaluated firing pin impressions, these have focussed on microscopy techniques which are both limited to capturing surface detail and are dependent on the illumination strategy [8,9]. Previously proposed techniques evaluated impressions in relation to the breech face surface and cannot consider internal features. Consequently, analysis methods based on data from 2D or 3D imaging have only been able to consider surface topography [10,11]. Micro-CT however allows for both 3-dimensional surface analysis and examination of the internal cartridge case's features as well.

Micro-CT has been employed in many forensic fields for over a decade and has been utilised in sharp force trauma analysis [12,13],

dismemberment investigation [14–17], forensic anthropology [18–20], strangulations [21–23], bloodstains [24,25], and others [26]. Furthermore, other areas of forensic ballistics have used micro-CT to visualise and characterise bullet jacket thickness [27,28], gunshot residue (GSR) [29,30] and gunshot wounds (GSW) [31,32]. A recent study [33] suggested there is still limited literature on this topic and further validation studies are necessary. However, micro-CT for cartridge case comparison has yet to be studied. By taking thousands of radiographs through 360 degrees rotation of the object, micro-CT produces 3-dimensional digital volumes representing the cartridge case including its internal structures. Precise quantitative measurements of external and internal cartridge case structures can then be taken from micro-CT scans. For forensic ballistic analysis, this suggests that micro-CT could reveal and allow measurement of additional features not possible through traditional techniques, ultimately allowing for more precise identification of the firing weapon.

The focus of this research was to analyse ballistic cartridge cases using micro-CT imaging to repeatably produce 3-dimensional digital models and to define measurements that quantitatively assess firing pin impressions. The first experiment aimed to establish whether micro-CT is an appropriate imaging technique for ballistic cartridge case analysis and whether cartridge cases can be repeatably and reliably measured quantitatively from micro-CT data. The second experiment sought to determine whether measurements of firing pin impressions, taken from micro-CT, statistically differ between the two weapons used in this study.

## 2. Materials and methods

### 2.1. Materials

Two weapons were chosen as an initial study into repeatability and firing pin quantification using micro-CT. To represent casework more realistically, 9 mm Luger cartridges were utilised in this study fired horizontally two handguns [34].

#### 2.1.1. Experiment 1 – method validation

Experiment 1 involved the micro-CT scanning of one randomly selected cartridge case (R1) fired from a single weapon, Steyr M9.

#### 2.1.2. Experiment 2 – variability assessment

Experiment 2 utilised 24 consecutively fired cartridge cases from two distinct weapons, Steyr M9 and Beretta 92FS. Cartridge cases were collected following firing and micro-CT scanned as below.

### 2.2. Methods

#### 2.2.1. Micro-CT scanning

Cartridge cases were scanned at a 5 μm voxel resolution on a Zeiss Xradia 520 Versa (Fig. 1) with the optimum scanning settings (140 kV, 10 W, 20 s exposure, 1601 projections and HE5 filter). The resolution achieved was the best possible based on the diameter of the samples and the size of the x-ray detector. To improve efficiency of the scanning procedure, a 3D printed custom apparatus was created to hold five cartridge cases to allow batch scanning (Fig. 1). A calibrated work-piece was included before and after each batch scan to allow voxel rescaling which improves measurement accuracy [35,36]. The work-piece was calibrated using a coordinate measuring machine (CMM) with a resolution of 0.01 μm. Scans were reconstructed using Zeiss' proprietary software and then exported to VGStudio MAX 2.2 (VolumeGraphics, Heidelberg, Germany) for analysis. Surface determination, i.e. isolating the metal casing from surrounding air, was established through the automatic ISO 50 thresholding in VGStudio MAX.

### 2.3. Measurements

#### 2.3.1. Experiment 1 – method validation

Firstly, to assess the accuracy and precision of measurements using the micro-CT procedure, the calibrated work-piece (included in each batch scan) was scanned 8 times, measured, and compared against the known measurement distance from the CMM. The accuracy is represented by the % error of measurements when compared to the established measurement from the CMM, and the precision is represented by the RSD of the measurements across the 8 micro-CT scans.

Secondly, five different measurements were taken from each repeated scan of the single cartridge casing; these are defined in Table 1 and Fig. 2. These measurements were chosen as they are common to all cartridge cases and relate to the mechanics of the firing pin impacting the cartridge. Note that the nadir point was defined as the deepest point of the firing pin impression and relates to two measurement taken. Firstly, all measures were taken by a single operator on each of the ten scans to establish repeatability of the whole cartridge case micro-CT scanning procedure. After this, to assess inter-rater reliability of the micro-CT measurements defined above, five raters, each with a range of experience using 3D software, measured four features on the ten scans.

#### 2.3.2. Experiment 2 – variability assessment

To metrologically assess the uniqueness of the firing pin impressions of the cartridge, the 'Firing Pin Sphere Radius', 'Nadir Height', and 'Nadir Offset' measurements validated in Experiment 1 (see Table 1 and Fig. 2) were collected from a total of 48 ballistic cartridge cases fired consecutively by the two distinct weapons; a Steyr M9 and Beretta 92FS. Cartridge cases were collected following firing and micro-CT scanned using the same method described in Experiment 1. Comparison between the fired cartridges from the two weapons was performed using Welch's *t*-test using MATLAB (MathWorks, Inc., MA, USA).

## 3. Results and discussion

### 3.1. Experiment 1 – method validation

The accuracy and precision of micro-CT measurements in this procedure were found to be <0.4% and 0.01% respectively, as shown in Table 2.

Micro-CT was found to be a suitable 3D imaging technique for the examination of cartridge cases enabling visualisation of internal structures with a resolution of 5 μm (examples shown in Fig. 3).

The inter-rater reliability of the measurements defined in this study was quantified using Intraclass Correlation Coefficient (ICC) which revealed high levels of agreement between the five raters (ICC > 0.99) as evident in Table 3 [37–39]. Finally, the micro-CT scanning, processing and measurement process was found to be repeatable with measurements across the ten repeated scans showing a low relative standard deviations (RSD) of less than 2% (Table 4).

Overall, this suggests that utilising quantitative data from micro-CT scans of ballistic cartridge cases is a repeatable and reliable method. Scanning of one cartridge case on ten separate occasions ensured the scanning procedure enables repeatability. An accuracy of <0.4% and precision of 0.01% show high reliability of the micro-CT methodology. High agreement between raters with a range of experience also shows the reliability and low subjectivity of the methodology. Micro-CT allows for internal visualisation and quantitation, impossible just using surface topography. Nevertheless, the long scan times and data processing would be a limitation for analysis within forensic casework. However, this potential limitation
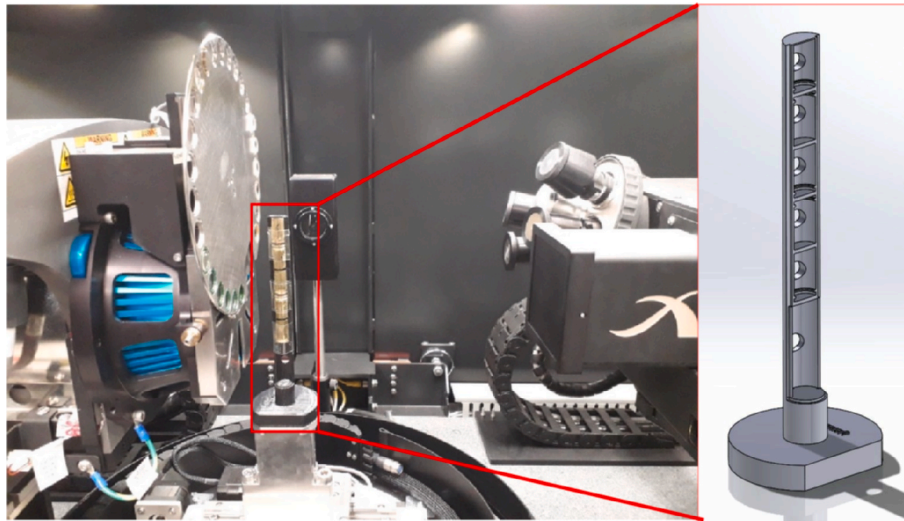
**Fig. 1.** Internal set up of the Zeiss Xradia 520 Versa Micro-CT showing the x-ray source [left], cartridge cases mounted into the 3D printed apparatus for batch scanning [middle] and x-ray detector [right].

**Table 1**
Description of each measurement utilised to establish repeatability of the micro-CT scanning procedure.

| Measurement Name | Description |
| --- | --- |
| Rim Cylinder | Radius of a best fit cylinder applied to the external surface of the cartridge rim |
| Under the Rim Cylinder | Radius of a best fit cylinder applied to the external surface of the area under the cartridge rim |
| Firing Pin Sphere Radius | Radius of a best fit sphere applied to the firing pin impression |
| Nadir Height | Single axis distance between the lower surface of the cartridge rim and the Nadir point[a] |
| Nadir Offset | Single plane distance between the central axis of the cartridge and the Nadir point[a] |

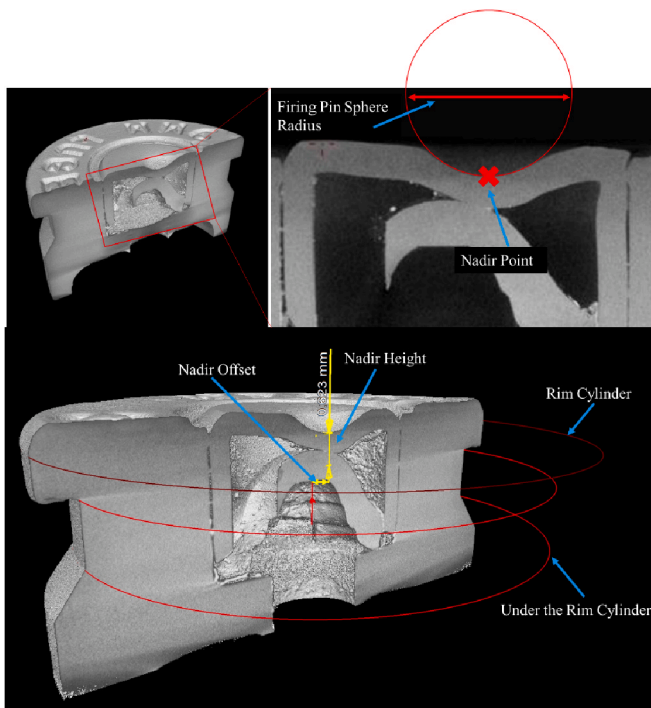[a] Nadir point is defined as the deepest point of the firing pin impression.



**Fig. 2.** Diagram showing the firing pin sphere radius, Nadir point, Nadir height, Nadir offset, rim cylinder, and under the rim cylinder measurements used in Experiment 1 and Experiment 2.

will naturally be reduced as micro-CT technology continues to evolve and scan times are optimised.

### 3.2. Experiment 2 – variability assessment

In Experiment 1 a highly repeatable method was validated for quantifying cartridge case fire pin impressions from micro-CT data. The repeatability of the measurements across ten repeated scans was high (RSD < 2%) as well as the inter-rater repeatability (ICC > 0.99) Although these variances were low, the magnitude of these relative to variances across different cartridge cases (from the same weapon) and different weapons were not yet known. To address this, this experiment compared the within and between variance of 48 cartridge cases fired by two different weapons. This was to provide an insight into the level of variability both between cartridges from the same weapon and between different weapons.

The defined firing pin measurement results are given in Table 5 and also represented in Fig. 4. As the data approximated a normal distribution and had heteroscedasticity, three Welch's unequal variance $t$-tests were used to assess the difference between the two weapons for each of the three measurements. Significant differences between each weapon were found for: Firing Pin Sphere Radius, $t$ (23) = 21.5, $p < 0.001$; Nadir Height, $t$ (23) = 14.4, $p < 0.001$; and Nadir Offset, $t$ (23) = 24.7, $p < 0.001$. The within weapon variation of the firing pin measurements is indicated by the 3 SD spread in Table 5 and Fig. 4.

Overall, the variability between firing pin measurements fired by different weapons could enable differentiation between fired weapons. The discriminatory power of these measurements for

**Table 2**

Measurement data of the calibrated work-piece: the exact measurement from CMM, the micro-CT measurements ± 3 SD, the % error, and RSD.

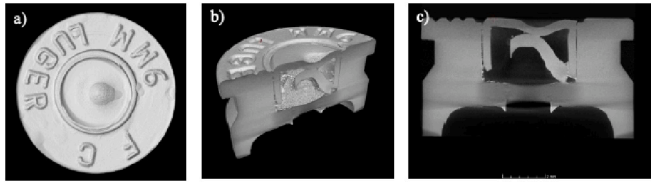|  | Exact Measurement (mm) | Micro-CT Measurement (mm) | % Error | RSD |
|---|---|---|---|---|
| Work-piece | 3.9836 | 3.998 ± 0.0013 | 0.37% | 0.01% |



**Fig. 3.** 3D images of the achievable high resolution micro-CT scans of a ballistic cartridge case; a) top-down view of the visualised digital model, b) 3-dimensional clipped view, and c) 2-dimensional cross-section through the centre of a cartridge case.

**Table 3**

Measurement data from the inter-rater study showing mean ± 3 SD across the 10 repeated scans in Experiment 1.

| Rater | Firing Pin Sphere Radius (mm) | Under the Rim Cylinder (mm) | Nadir Height (mm) | Nadir Offset (mm) |
|---|---|---|---|---|
| 1 | 1.03 ± 0.05 | 4.31 ± 0.00 | 0.58 ± 0.03 | 0.46 ± 0.06 |
| 2 | 1.01 ± 0.03 | 4.31 ± 0.00 | 0.57 ± 0.03 | 0.46 ± 0.05 |
| 3 | 1.03 ± 0.01 | 4.31 ± 0.01 | 0.57 ± 0.04 | 0.46 ± 0.04 |
| 4 | 1.02 ± 0.03 | 4.31 ± 0.00 | 0.58 ± 0.05 | 0.48 ± 0.04 |
| 5 | 1.03 ± 0.02 | 4.31 ± 0.00 | 0.59 ± 0.02 | 0.46 ± 0.04 |

**Table 4**

Repeatability measurements indicating mean, standard deviation (SD) and relative standard deviation (RSD) of each.

| Measurement | Mean (mm) | SD (mm) | RSD |
|---|---|---|---|
| Firing Pin Sphere Radius | 1.03 | 0.00 | <0.5% |
| Rim Cylinder | 4.93 | 0.00 | <0.1% |
| Under the Rim Cylinder | 4.31 | 0.00 | <0.1% |
| Nadir Height | 0.57 | 0.01 | <1% |
| Nadir Offset | 0.48 | 0.01 | <2% |

**Table 5**

Firing pin impression measurement results showing the mean ± 3 SD and t-test results for each measurement.

| Weapon Model | Firing Pin Sphere Radius (mm) | Nadir Height (mm) | Nadir Offset (mm) |
|---|---|---|---|
| Steyr M9 | 1.04 ± 0.09 | 0.59 ± 0.19 | 0.44 ± 0.17 |
| Beretta 92FS | 0.75 ± 0.17 | 0.94 ± 0.29 | 0.09 ± 0.11 |

weapon prediction is likely to be increased with multivariate statistical methods on a larger database of weapons; Fig. 5 shows the discrimination of the three measurements combined in a 3D scatter plot and suggests the between weapon variation of the combined measurements may enable weapon prediction with a larger experimental database.

## 4. General discussion

In any forensic analysis, the ultimate goal lies in determining crime information from forensic evidence. Despite public perception to the contrary, so-called forensic 'matches' are not commonplace. With forensic disciples under scrutiny to ensure any subjectivity is kept to a minimum [40–43], employing robust, repeatable analysis procedures is essential. Validating novel methods is a necessary step towards advancing forensic analysis techniques [16].

The field of forensic ballistics is an integral area of analysis within casework. Firing- pin impressions on ballistic cartridges are formed when a weapon's firing pin strikes the primer leaving a representative indent in the metal casing. These impressions are frequently evaluated in relevant cases using both 2-dimensional and 3-dimensional methods [6,8,9]. Despite micro-CT application to many areas of forensic science [14,18,21–24,26,30–32], as a technique for ballistic cartridge analysis this has yet to be employed.

Micro-CT has previously been shown to be a useful tool in the analysis of bullet jacket dimensions for a non-destructive measurement technique [27]. The method demonstrated in the current study shows a further application of micro-CT for forensic ballistic analysis using quantitative firing pin assessment. The ability to view internal structures and fully visualise the 3-dimensional structure of ballistic cartridges using micro-CT, without lighting issues often encountered with traditional microscopy [8], is currently unparalleled. Due to this internal visualisation of ballistic cartridges afforded by micro-CT, metrological assessment is also possible. Scans of ballistic cartridge cases in this study highlights the applicability of micro-CT as a complementary technique within forensic ballistic analysis. An achievable resolution of 5 µm (depending on detector size and cartridge calibre) indicates a high-resolution technique capable of accurately visualising impression details of cartridges.

Firing pin impression analysis has long been implemented in forensic ballistic analysis, as it is known these features are representative of the weapon fired [1,44]. This study proposes Firing
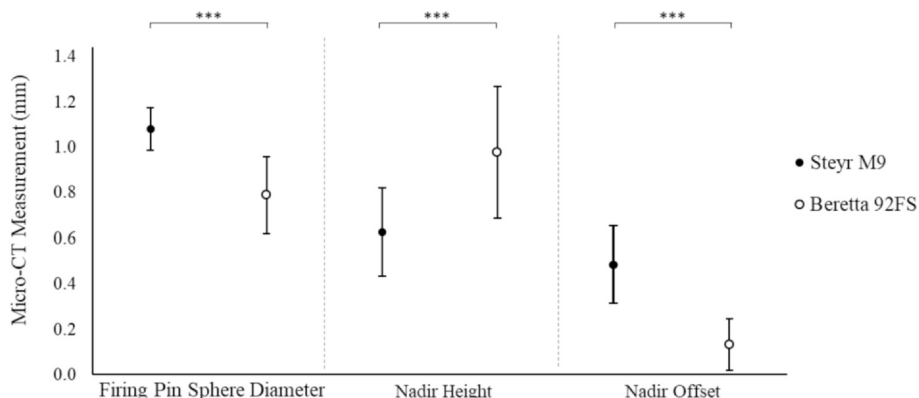


**Fig. 4.** Mean ± 3SDs (mm) Firing Pin Sphere Radius, Nadir Height and Nadir Offset, for both Steyr M9 & Berretta 92FS.
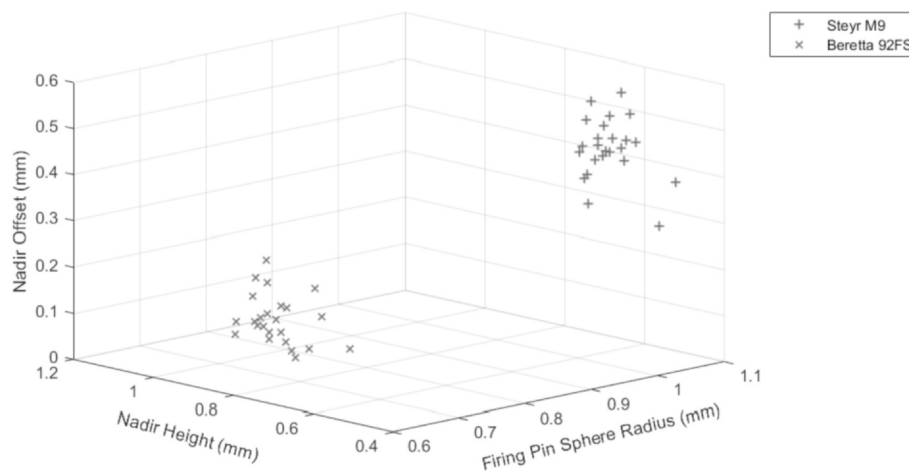
**Fig. 5.** 3-dimensional scatter plot of the three functional firing pin impression measurements.

Pin Sphere Radius, Nadir Height, and Nadir Offset as three possible quantitative analysis measures to assess the weapon used to fire a ballistic cartridge case. These three new measurements of ballistic cartridge cases are accessible due to the enhanced analysis elucidated through micro-CT scanning allowing 3-dimensional representation of the casing.

Each model of weapon is manufactured in a different way and to different specifications. Hence, firing pins between brands and/or models will differ. The extent of variance will establish how applicable the proposed technique will be to ballistic investigations. Each measurement proposed quantifies a different aspect of the firing pin: Firing Pin Sphere Radius quantifies the relative size of the firing pin used, Nadir Height establishes the depth the firing pin extends into the primer, and Nadir Offset quantifies the distance from centre that the firing pin strikes. In this preliminary study, the significant variance between weapons of these measurements suggests the possibility of a level of weapon identification from firing pin quantification. As well as the firing pin impression, in ballistic casework there are two additional areas of interest; the breech face impression, and the ejector mark [45]. Breech face striations were not considered in this study as they were beyond the resolution achievable with micro-CT and are well studied through traditional methods. Ejector marks were identified on some of the cartridge cases studied, due to the large within weapon variation between shape and location of ejector marks, particularly when located on the indented manufacturers lettering, these were not studied in the current work. Further work into quantifying ejector marks may elucidate more information on the weapon used.

While encouraging, the method developed in this study was derived and validated from two weapons. This work established that the firing pin impression quantitation significantly differs between the two weapons however more work is needed with a larger dataset of cartridge cases from many weapons. With such expansion on this work, class and individual classification may be possible along with test-fired and suspect comparison. Assuming a representative database of quantitative firing pin data, the classification of weapon used may be possible using statistical models such as random forests [17].

Previous studies have shown that multiple factors affect aspects of the firing pin impression [8,44]. Manzalini and colleagues recently proposed the depth of firing pin impression was dependent on the orientation of the weapon when fired [8]. In the proposed micro-CT study, all weapons were fired in a horizontal orientation to best match the majority of casework examples. If applied to casework, the orientation would be a variable to be experimentally quantified prior to considering weapon identification. Altering the orientation of firing would likely increase variability of the functional

measurements studied, and hence requires further study to establish weapon specifics.

This study proposes the use of linear measurements from micro-CT data for analysis of firing pin impressions. Combining distinct independent measurements improves analysis methodology. Utilisation of 3-dimensional measurements in combination with the linear measurements described could increase the diagnostic capability of ballistic analysis from micro-CT. For example, the volume or surface area of the firing pin impression could be included however further exploration on how to measure such additional parameters is required.

Micro-CT has been shown to be an effective imaging tool for the 3D visualisation and measurements of ballistic cartridge cases with three new firing pin impression measurements defined (termed Firing Pin Sphere Radius, Nadir Height and Nadir Offset). The repeatability and reliability of the imaging process and the measurements defined was established in Experiment 1. In Experiment 2, these quantitative assessments were found to significantly differ between cartridge cases fired by two weapons. Expansion of the proposed micro-CT methodology to establish model specific and weapon specific quantitative data could allow for a greater level of information to be determined from ballistic cartridge evidence and complement current comparison techniques.

**CRediT authorship contribution statement**

**K. Alsop:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **D. Norman:** Investigation, Validation, Writing – review & editing. **G. Remy:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – review & editing. **P. Wilson:** Formal analysis, Writing – review & editing. **M.A. Williams:** Conceptualization, Writing – review & editing, Supervision.

**Conflicts of interest**

The authors declare no conflicts of interest.

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