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The effect of human decomposition on bullet examination

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ABSTRACT

Most firearm related homicides involve the deceased being forensically examined within a day or two, however, there are times when bodies have been examined and the fired components removed several days or weeks after death, when the body is in an active or advanced state of decomposition. In these cases, ballistic investigation has been found to be complicated due to the damage to the bullets, however the extent of this is not yet known. To date, there have been no studies investigating the effect of human decomposition and the subsequent analysis of bullets lodged in the body in an Australian context. Herein, seven fired copper jacketed bullets were manually inserted into three specific tissue types; lungs, abdomen and leg muscle (twenty-one bullets in total), of human donors in both cool and warm conditions at the Australian Facility for Taphonomic Experimental Research (AFTER). Bullets were removed every three days for a period of twenty-one days, and each bullet underwent manual microscopic examinations by firearms examiners across Australia. Results have indicated that the bullets corrode quickly in warm conditions, compared to bullets exposed to decomposition in cooler conditions. The results of this study will inform investigators and pathologists of the need to remove and examine fired bullets from decomposed bodies as soon as possible, especially in warm conditions to provide firearms examiners with the best opportunity to link fired bullets to a common source.

1. Introduction

Firearms related incidents are common worldwide, in Australia there were 196 reported homicides between 1 July 2017 and 30 June 2018 [5]. Approximately 15 % of these involve firearms. When a firearm is fired, the bullet is expelled from the cartridge case and travels along the barrel, where the bullet is impressed with land and groove marks from the rifling which are unique to the firearm used [24]. These markings are examined under a microscope by qualified experts to determine if a bullet can be traced back to any suspect firearms. The quality of the bullet's surface features and the amount of surface available on fragmented bullets will greatly impact this examination. In cases where an individual is shot, the bullets are often retained within the body [12,13]. If these bullets are not recovered within a relatively short timeframe, extending to no more than a few days in warm and humid conditions, they will be exposed to chemicals species, such as acids resulting from the breakdown of the body [19,29]. The limited research that has been conducted in the Northern Hemisphere has provided some indications of the possible effects decomposition has on fired bullet striae [28]. However, in an Australian context, it is currently unknown how decomposition will affect the bullets and their subsequent microscopic analysis.

Forensic Taphonomic reconstruction provides a scientific determination of time since death and to determine the presence and extent of post-mortem human alteration of the remains at the scene [14]. A notable case in Australia, where there was a cross-over between Taphonomy and Forensic Firearms Examination, was during the 'Backpacker Murders' investigation from New South Wales in the early 1990s [12] where the decomposition resulted in issues when identifying exibit fired bullets to a single firearm. One of the first victims recovered was shot ten times; seven fired .22 Long Rifle calibre lead bullets were recovered from the skull of the deceased and three fired .22 Long Rifle calibre lead bullets recovered from the soil beneath the victim [12,13]. These bullets had been within or adjacent to the victim for approximately 5-months, and each of the ten bullets was able to be identified to each other, indicating the same firearm was used in the homicide [13]. It was reported by Dutton, that this body had been in the Belanglo State Forest during the Australian winter period and had been in a shallow grave, under a large rock overhang. Conversely, one of the last victims recovered in this case, had been shot six times and the recovered bullets

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examined were unsuitable for any comparison work, due to the corrosion and scaling on the fired .22 Long Rifle calibre lead bullets. These bullets had been contained within the decomposing victim for approximately 22 months; this time was taken as being from the last confirmed sighting (26th December 1991) to the discovery day (4th November 1993) [13]. This case demonstrates the importance of understanding the effect of the decomposition on bullet examination.

Shortly after death, the body begins to decompose primarily via two processes: autolysis and putrefaction. Autolysis is the destruction of the cells by enzymatic digestion, resulting in their eventual rupture and the release of fluids from the body [29]. Autolysis commences within minutes of death due to the lack of oxygen inhibiting aerobic metabolism [7]. Putrefaction involves microorganisms destroying soft tissue and is initially indicated by a green discolouration of the cadaver, due to the formation of sulfhemoglobin in the blood [29]. Autolysis and putrefaction lead to a host of chemicals being present in the cadaver resulting from the cellular and microbial breakdown of the tissue [19,29]. The lack of oxygen precipitates autolysis, where carbon dioxide in the blood increases, lowering the pH [29]. Putrefaction causes the formation of gases that include hydrogen sulphide, methane, ammonia, and sulphur dioxide and is also associated with butyric and propionic acids [29]. Different areas of the body can produce differing chemical environments, such as the high acidic concentrations within the stomach or the production of several acids and sulphur containing compounds reported in leg muscle [10] that degrade into aldehydes and ketones due to the higher protein content in muscles [10]. These differences may result in any embedded bullets undergoing different levels of damage due to the 'localised' conditions experienced. This can make some fired bullets recovered from different tissue unsuitable for comparison work.

There has been limited research into the effect of decomposition processes on fired bullet striae, all of which has been confined to the Northern Hemisphere [8,22,25,27,28]. It is known that climate, along with moisture, soil pH, age and body trauma play a major part in the rate of decomposition [7,9,10,29], and therefore the extent of breakdown of macromolecules and subsequent release of decomposition products needs to be examined in an Australian environment to determine variability of any in the damage to bullet striae.

The aim of this project was to investigate the impact of decomposition on the degradation of fired copper bullet striations, and ergo, if there was a time after insertion when the fired bullets may no longer be identifiable, after targeting specific tissue types and regions within decomposing human donors. This was done through microscopic examinations utilising expert firearms examiners qualified by the Australian and New Zealand Police Advisory Agency National Institute of Forensic Science (ANZPAA NIFS) and the development of observation scales to determine the length of exposure experienced by a fired copper bullet to a decomposing body.

2. Materials and methods

2.1. Bullet selection

In order to select the most relevant bullet types, the Integrated Ballistics Identification System (IBIS) was interrogated (Version 3.0, ULTRA Forensic Technology Inc.). Data indicated that .22 Long Rifle calibre fired bullets had the highest number of matches followed by 9mm Parabellum ammunition with the second highest calibre matches on IBIS [3] .22 Long Rifle bullets were not selected for this study, despite their prevalence, primarily due to their relatively small diameter and potential for loss within the decomposing bodies. Instead, 9mm Parabellum calibre 124grain Full Metal Jacket (FMJ) copper bullets were selected as they are commonly encountered in casework and account for approximately 29.9 % of the exhibit and test fired bullets captured on IBIS [3].

2.2. Bullet preparation

A total of twenty-one 9mm calibre FMJ copper jacketed fired bullets were used. The selected bullets were fired into a bullet recovery water tank using a 9mm Parabellum calibre self-loading pistol. Following collection from the water recovery tank, the fired bullets were dried, and each bullet had a small hole drilled into the base and tapped with a metallic eyelet (Everhang®) to which a length of picture framing wire (Everhang®) was attached. The other end of the wire had a coloured plastic keyring (J. Burrows®) secured for identification to avoid marking the bullets themselves.

2.3. Field trials

This work was conducted at the Australian Facility for Taphonomic Experimental Research (AFTER), a research facility owned and operated by the University of Technology Sydney. The facility is in an open wooded region with low scrub [4,11], typically described as Cumberland Dry Sclerophyll Forest with sandy clay loam or gravelly sandy clay located inside a high security facility [20].

Two trials were conducted, one representing cool environments (Australian Winter) and one representing warm environments (Australian Summer/Autumn) (Table 1). Each study consisted of one human donor, which were placed inside AFTER. The human cadavers used in this study were acquired through the UTS Body Donation Program and were placed at AFTER within three days of death. During transport and holding cadavers were stored under refrigerated conditions. No other preservation methods were performed on the cadavers. Consent was provided by all donors to use their remains for the purposes of research at AFTER, in accordance with the NSW Anatomy Act (1977). The research project was approved under the UTS Human Research Ethics Committee Program (UTS HREC REF NO. ETH18–2999).

The unclothed human donors (Table 1) were placed in the supine position at AFTER. The bullets were manually inserted into predetermined organs (Fig. 1) and left to decompose for a total of 21 days. The organs chosen were the lungs, abdomen and leg muscle, as these regions have different tissue types, such as elastin and collagen in the lungs or skeletal muscle in the legs, or different chemical environments such as the acid nature of the stomach [18]. The decision to target these areas was also based upon the experience of one of the authors. Additional bullets were fired and kept as controls, devoid of contact with decomposing remains, and were stored in metal filing cabinets within the examination laboratory storeroom in clear, resealable plastic bags to simulate casework procedures. Wire cages were placed over each donor to deter predation from larger scavengers, whilst allowing insect activity and exposure to the environment. The state of decomposition, based on the descriptors by [15] were recorded each sampling day. The environmental data including minimum, maximum, and average daily temperatures, relative humidity and mean rainfall was sourced from the Bureau of Meteorology (BoM) site recordings at the Royal Australian Air Force Base near Richmond, New South Wales [26].

Three bullets per location were removed on days 3, 6, 9, 12, 15, 18 and 21 after insertion, cleaned in the field using a bleach solution (CleeraWinc®, Sydney) and rinsed with water to ensure they did not pose any biological hazard and that no further degrading of the striae

Table 1
Human donor details and exposure environment.

Species	Age	Manner of Death	Placement date	Exposure environment (Month/s)
Human 1	70	Cancer	23 July 2019	Cool (July/August)
Human 2	56	Cardiovascular disease	8 February 2022	Warm (February/March)

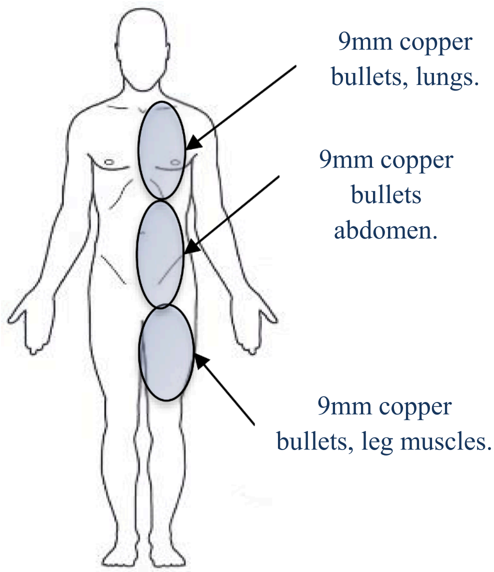

Fig. 1. Location of copper bullet insertion sites.

occurred. The bullets were then placed into individual specimen tubes and returned to the laboratory, where the bullets were again cleaned using a 5 % bleach solution (CleeraWinc®, Sydney), placed in an ultrasonic cleaner (EMAG®) for approximately five minutes, before being rinsed in cold tap water, dried, and labelled.

2.4. Bullet analysis

The cleaned and recovered bullets were examined using Leica Microsystems Leica FSC [21], and Projectina Vision-X comparison microscopes. The analysis of the bullets was carried out by the first author and five volunteer participants (approved by the UTS Human Research Ethics Committee, HREC ETH20–5678). The participants and first author were all microscopy trained Forensic Firearms Examiners and Australasian Forensic Science Assessment Body (AFSAB) experts from the Australian Federal Police (AFP), Tasmania Police Force (TASPOL), and New South Wales Police Force (NSWPF). The participants from the AFP and NSWPF were provided with instructions on the requirements of the microscopic examinations and reporting procedures in person. Participants from TASPOL were mailed the fired bullets with written instructions.

Each examiner was provided with the recovered fired bullet samples (3x lung, 3x abdomen, and 3x leg muscle per sampling day) and one control (a fired bullet not exposed to decomposition). The sampling location and recovery day were not provided to the assessors to limit bias during the analysis. The trained participants reported their findings using the Association of Firearms and Toolmark Examiners (AFTE) Range of Conclusions and the Theory of Identification [1,2]. This is the accepted method employed in the Forensic Firearms Examination field for reporting conclusions of microscopic analysis.

2.5. Scoring systems

Two scoring systems were used to enable the evaluation of the bullet damage due to exposure to decomposition. The first scoring method was based on the reported AFTE Range of Conclusions [2] where the external expert analysts were asked to rate the bullets using the following scale:

- Positive identification (P) = 2 points,
- Inconclusive Result (I) = 1 points,
- Unsuitable for comparison (U) = 0 points

An overall score was obtained by applying the point scoring system to each participant's result by recovery area, taking the median of these points. The answers from the participants were recorded and graphed.

The second scoring systems evaluated the level of corrosion exhibited by the bullets (Table 2) and was developed for this work. The corrosion scores were subjective and graded on a scale of one (1) to five (5), with a score of one (1) representing the greatest damage from corrosion observed, whilst a score of five (5) represents the least observed corrosion damage observed. This scale was developed with forensic examiners working at crime scenes and forensic laboratories in mind, where the corrosion scale may be used to inform investigators of possible post-mortem intervals, particularly when microscopic examinations were not possible due to damage to the bullet.

3. Results and discussions

3.1. Environmental data

The Hawkesbury region generally has cool winters and warm summers [6]. The minimum and maximum temperatures were 4.2 and 17.6 °C, respectively for the cool trial and 17.3 and 27.7 °C for the warm trial (Table 3).

3.2. Visual decomposition

The visual decomposition of Human 2 (warm) indicated a faster rate of decomposition compared to the human (Human 1) donor in winter (Fig. 2). Human 2 progressed from the fresh stage to early decomposition on day 3 and then to advanced decomposition by day 18. Human 1

Table 2
Copper Jacketed Bullet Corrosion Scale.

Grade	Detail Visualised	Representative Images
5	• Evidence of Class Characteristics. • Individual Characteristics present. • <25 % black scale formed that does not hinder examination, with limited/no discolouration of copper surface. Majority has untarnished copper surfaces	
4	• Evidence of all Class Characteristics. • Agreement of Individual Characteristics present. • 25–50 % scaling, corrosion and discolouration of copper surface that does not hinder identification **OR** • Any amount of scaling, corrosion or discolouration that <u>does not</u> hinder identification.	
3	• Evidence of Class Characteristics • Some agreement of Individual Characteristics, however insufficient to form identification. • 50–75 % scaling or corrosion products present with discolouration of copper surface, hindering identification. • Some regions of untarnished copper jacket	
2	• Evidence of Class Characteristics (discernible). • Little evidence of Individual Characteristics (some striae apparent). • 75–100 % coverage of corrosion, scale formed with discolouration of surface.	
1	• Some evidence of Class Characteristics. • No evidence of Individual Characteristics (no striae apparent). • ~100 % heavy corrosion, scale formed with discolouration of copper surface.	

Table 3
Meteorological data across the two trials. Royal Australian Air Force (RAAF) Base Richmond, New South Wales (BoM, 2023).

Study	Months	Mean minimum temp (°C)	Mean maximum temp (°C)	Mean relative humidity (%) (0900 hr)	Mean relative humidity (%) (1500 hr)	Mean rainfall (mm)
Human Donor 1	July/August (Winter)	4.2	17.6	90.9	62.1	12.8
Human Donor 2	February/ March (Autumn)	17.3	27.7	87	62	358

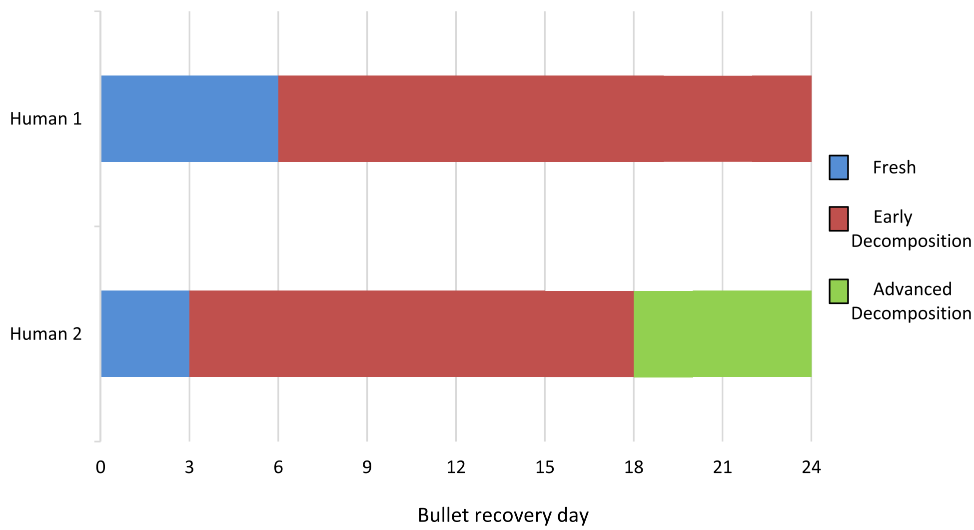

Fig. 2. Visual decomposition of Human 1 (cool conditions) and Human 2 (warm conditions).

on the other hand did not enter early decomposition until day 6 and did not progress further during the length of the current study. This difference in decomposition rate is likely due to the differences in their respective starting dates, as temperature plays an important role in the rate of decomposition [16,17,19,23]. This was further demonstrated by the greater tissue loss in the human donor in summer (Human 2), compared to the human donor (Human 1) in winter. The different rates may also be attributed to the biological differences between the human donors, such as the distribution of body weight and degree of insect activity [20]. A differing level in insect activity was also observed whereby the donor (Human 2) in the warm climate had a lot more insect activity than Human 1 in the cold environment.

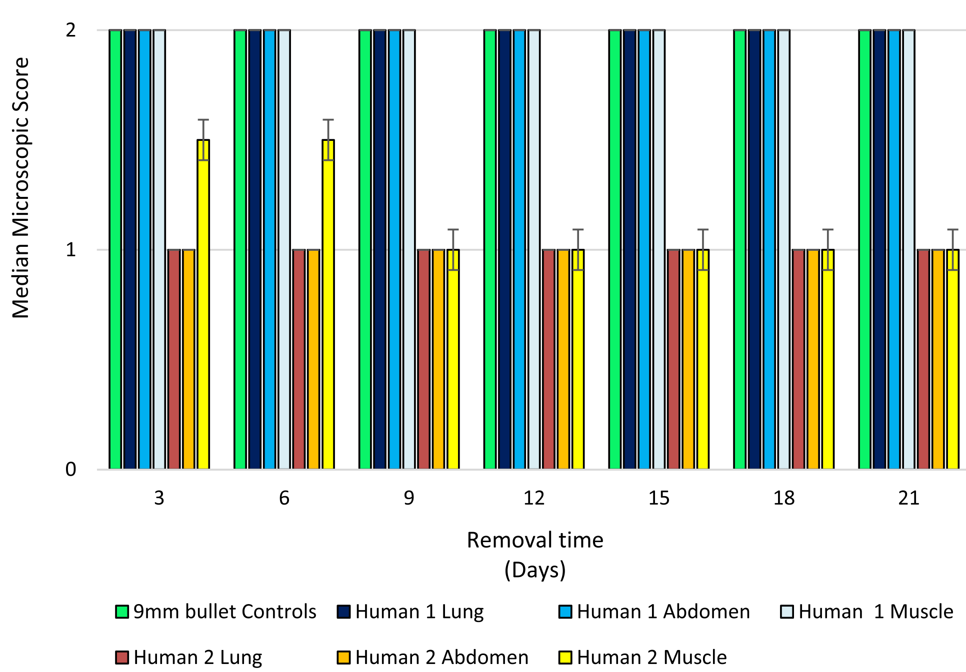

Fig. 3. 9mm Parabellum calibre copper FMJ microscopic results for Human 1 and Human 2 donors. Error bar represents n = 4 examiners.

The slower decomposition rates in cooler conditions could mean that the generation of organic acids and gases are hindered. It is speculated, that the initial decomposition stages of the human in these cooler conditions would not have affected the bullet surface via corrosion due to the relatively slow formation of the organic acids (e.g., lactic acid) and gases (e.g., hydrogen sulfide) in the anaerobic environment [7].

This warm period (experienced by Human 2) was characterised by persistent, heavy rain over most of this time (mean rainfall was 358 mm, Table 3), where the mean rainfall for this region during February and March, (1994–2023) was 111.5 mm [26].

3.3. Microscopy results

The bullet samples recovered from the human donors were analysed by external experts that had no prior knowledge of the location or recovery day of each bullet they were asked to examine.

All examiners were able to identify the bullets from Human 1 (cool environment) from all sampling days and locations (Fig. 3). This indicated that the 9mm Parabellum calibre copper FMJ bullets were not affected by the decomposition process over the entire study period (Figs. 4 and 5), likely due to the slower decomposition rate in cold climates.

The copper jacketed 9mm Parabellum calibre fired bullet samples from Human 2 proved difficult to examine microscopically and gave inconclusive results (Fig. 3), because of severe corrosion and loss of striae (Figs. 6 and 7). The only exceptions to the inconclusive results occurred during the examinations on the bullets from muscle recovered on days 3 and 6, where some identifications were made by the examiners, resulting in a median score of 1.5 for days 3 and 6. The inconclusive results were due to the rapid decomposition rates of Human 2 and the increased microbial and chemical activity compared to the cool conditions [16,17,19,23]. This affected the bullets from all three regions examined. Overall, the microscopic examination of 9 mm Parabellum copper jacketed FMJ bullets recovered in cool allowed the bullets to be identified back to a known source, even after a period of exposure to the decomposition environment for 21 days. However, no agreement on identifications were recorded by all examiners for any bullets retrieved from Human 2 in warm conditions.

3.4. Corrosion results

Corrosion was recorded for bullets retrieved in cool and warm conditions (Figs. 8 and 9). Despite the lack of a change in microscopic score

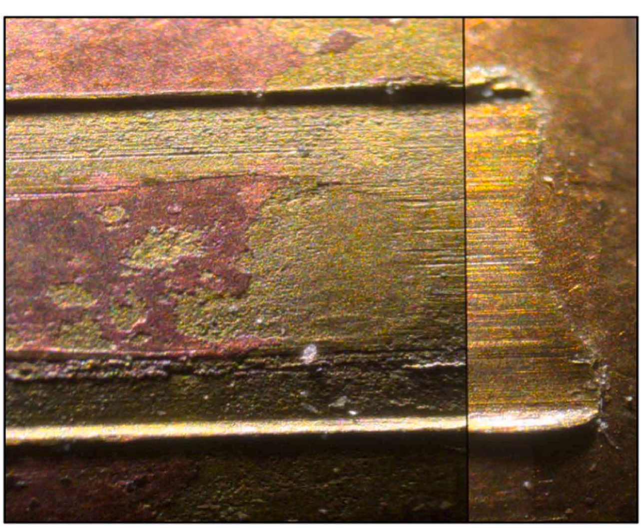

Fig. 4. Microscopic comparison of the bullet retrieved from Human 1 Lungs (left) at 18 day and the control bullet (right).

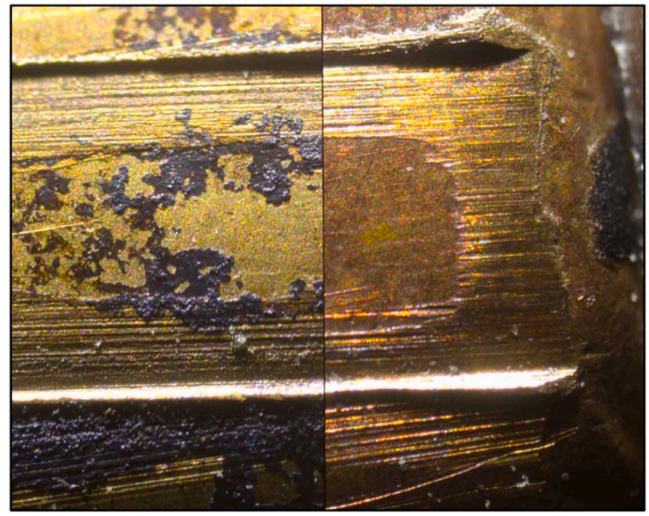

Fig. 5. Microscopic comparison of the bullet retrieved from Human 1 Abdomens (left) at 18 day and the control bullet (right).

Fig. 6. Microscopic comparison of the bullet retrieved from Human 2 Lungs (left) at 18 day and the control bullet (right).

above, the *Lung* and *Abdomen* bullets from Human 1 (cool conditions) experienced a steady decrease in corrosion scores as exposure time increased, meaning that the bullets from Human 1 *Lung* and *Abdomen*, although microscopically identifiable, did undergo surface corrosion due to the decomposition processes, whilst the bullets recovered from the *Muscle* did not undergo any appreciable corrosion (Fig. 10). Bullets from the muscle region on the final two sampling days could not be located and were therefore not included. There may therefore have been some corrosion in the later sampling dates, however this could not be investigated. Overall, the corrosion scores decreased in values from day 9 onwards (Fig. 10) for the Human 2 donor. An increase in corrosion scores (and therefore indicating less corrosion) was observed in the *Abdomen* from day 15–21 for Human 2, and *Muscle* samples from day 15 to day 18 in the bullets collected from Human 2 despite the slower visual decomposition rate noted with this human donor in the cool conditions (Fig. 2). This slight improvement in corrosion scores for the recovered bullets in Human 2, especially with the *Abdomen* and varying scores in the Human 2 *Muscle* from days 15–21 may be due to the heavy rainfall prevalent at this time altering the chemical environment, within the *Abdomen* and leg *Muscles*. No results were recorded for Human 2 *Muscle*

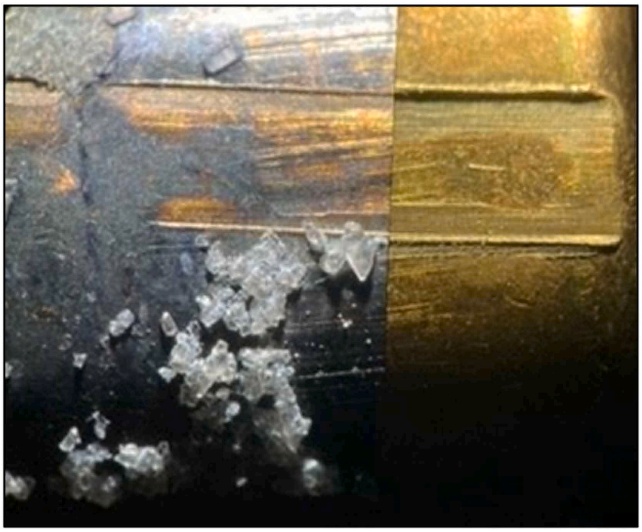

Fig. 7. Microscopic comparison of the bullet retrieved from Human 2 Abdomen (left) at 18 day and the control bullet (right).

Fig. 8. Surface corrosion of bullet retrieved from Human 1 lung in removal order, left to right (control bullet is at the far right).

Fig. 9. Surface corrosion of bullet retrieved from Human 2 lung in removal order, left to right (control bullet is at the far left).

on days 18 and 21, due to the bullets being lost within the cadaver.

The results for the cool conditions (Human 1) showed that the bullets recovered from the *Abdomen* appeared to increase in corrosion on day 9 (represented by a lower score), whilst the bullets recovered from the *Lungs* did not corrode until day 15. The corrosion results for the copper bullets recovered from Human 2 in warm conditions were found to be corroded on the first sampling event, 3 days after placement, which was characterised by surface discolouration and scale formation on the bullet's surface. The *Abdomen* results for the Human 2 sample were steady for days 3 and 6, before decreasing with time. There was substantial rainfall during this period, and the abdomen of Human 2 had collapsed by the last sampling day and the skeletal elements were exposed. This may mean that some of the bullets exposed to the Human 2 *Abdomen* and *Muscle* may not have been exposed to the decomposing tissue in these areas, and instead only exposed to the ambient weather conditions.

Overall, the corrosion scales gave some indication of damage in both climates and demonstrated that a difference in the physical appearance of the bullets were evidenced over time. These differences in physical appearance were a result of surface discolouration, including a dulling of the surface colour and the formation of scale on the surface. Even in the case of the warm climate donor (Human 2) where no microscopic results could be attained, some information regarding the damage over time could still be determined. The use of the corrosion scale developed for this project to conduct an examination of copper jacketed bullets would however need to be approached with caution, as the variations observed, especially for the *Lungs* and *Abdomen,* would mean that no significant information pertaining to time of death estimate could be relied upon using the bullet damage alone. This subjective corrosion scale did not provide any definitive results to allow for time-of-death estimates, although as with the microscopy results, in general corrosion occurred rapidly in warm conditions compared to the corrosion observed in cooler conditions. Any copper jacketed bullets recovered from a deceased person with discolouration, black scale and/or a dull gold coating would strongly indicate exposure to the decomposition environment.

This research also indicated that the *Muscles* in human donors produced relatively steady results in terms of microscopic identifications and increased corrosion results for copper jacketed bullets. The results for *Lungs* and *Abdomen* produced more variations, which is suspected to be due to the complex chemical and microbial environments in these tissue areas [10].

As with all subjective assessments, the human factor cannot be overlooked. Some examiners may naturally be cautious in their approach to microscopy and will likely give an inconclusive result compared to other examiners. This subjective assessment is largely based upon the examiner's training and experience. In addition, bias cannot be discounted, as the examiners may have assumed that the fired bullets were from the same firearm and after a period of time examining the bullets, they may therefore have subconsciously made positive identifications as they became more familiar with the bullets.

4. Conclusions

In this study, the effect of human decomposition processes on 9 mm calibre copper jacketed fired bullets embedded in different tissue types of human donors were examined in cold and warm climates. The visual decomposition rate for the human cadaver was reduced during the cooler conditions, compared to the accelerated decomposition of Human 2 in warm conditions.

The microscopic analysis of the 9mm calibre copper jacketed FMJ bullets from both Human 1 and Human 2 were undertaken following bullet recovery in cool and warm conditions respectively. During the cool conditions all recovered copper jacketed bullets could be identified to a common source. This indicated that the decomposition of Human 1 did not affect the fired bullet striae even after being exposed to the decomposition environment for up to twenty-one days. Conversely, the higher decomposition rates in warmer conditions resulted in greater affects to the copper jacketed bullets, hindering microscopic identifications as early as three days after insertion.

The development of a subjective corrosion scale was undertaken to assess the effects of decomposition from the test regions being the *Lungs, Abdomen Muscles*, and to attempt to determine the length of exposure to a decomposing body. The copper jacketed 9mm Parabellum calibre fired bullets underwent varying degrees of corrosion on their surfaces, including the formation of surface scale and discolouration.

When the results of the microscopic examinations were assessed in conjunction with the corrosion scale, the 9 mm copper jacketed FMJ bullets exposed to the decomposition environment in cool conditions did not produce corrosion results that affected the microscopic examinations of the fired bullets from Human 1, due to the slower decomposition during the cool conditions. However, the bullets exposed to the

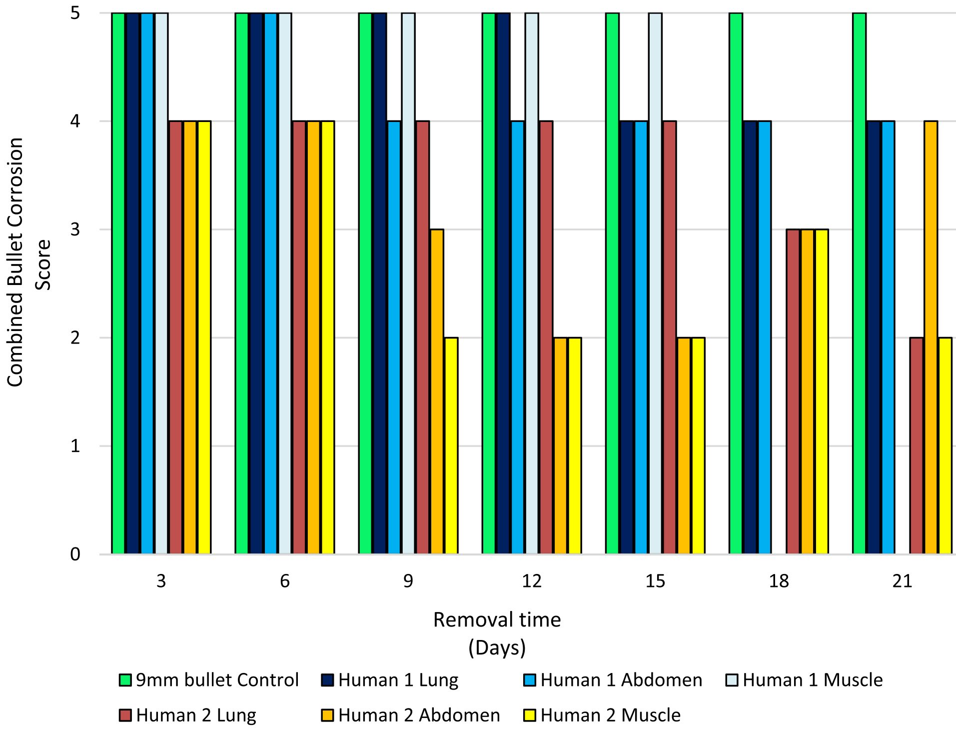

Fig. 10. 9mm Parabellum calibre combined bullet corrosion scores for Human 1 and Human 2 donors.

decomposition environment in warm conditions produced corrosion that greatly hindered subsequent microscopic examinations.

Future work should be conducted to analyse the changes that occur to the copper surfaces and specifically identify the by-products observed on each bullet type over time and to confirm the chemical makeup of the black scaling and discolouration on copper. The rate of formation of these chemical species may assist in time-of-death estimates. One major limitation of this study was the number of available cadavers, this is unfortunately common during human taphonomic studies due to the low availability of donors. Replication studies using additional donors would be required to validate and strengthen the results. The pH levels of the soil were not recorded during the field stage. However, as the bullets were not in direct contact with the soil in the presented work, this was not deemed as a requirement for the interpretation of the results. Overall, this work will inform practices around bullet recoveries from decomposing remains at crime scenes and highlight the need to remove these as soon as possible, particularly during warm climates to provide firearms examiners with the best opportunity to link fired bullets to a common source.

CRediT authorship contribution statement

Maiken Ueland: Writing – review & editing, Visualization, Supervision, Resources, Methodology, Conceptualization. **Matthew Bolton:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Scott Chadwick:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Conceptualization.

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.

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References

[1] Association of Firearm and Toolmark Examiners (AFTE) 2020, AFTE Theory of Identification as it Relates to Toolmarks, viewed 15 June 2020. ⟨www.afte.org/about-us/what-is-afte/afte-theory-of-identification⟩.
[2] Association of Firearm and Toolmark Examiners (AFTE) 2020, AFTE Range of Conclusions, viewed 15 June 2020. ⟨www.afte.org/about-us/what-is-afte/afte-range-of-conclusions⟩.
[3] Australian Criminal Intelligence Commission (ACIC), 2021, Australian Ballistics Information Network (ABIN), Statistics Summary, retrieved 28 April 2021.
[4] S. Blau, J. Sterenberg, P. Weeden, F. Urzedo, R. Wright, C. Watson, Exploring non-invasive approaches to assist in the detection of clandestine human burials: developing a way forward, Published online 7 February 2019 Feb 7. Forensic Sci. Res. 3 (4) (2018) 304–326, https://doi.org/10.1080/20961790.2018.1493809.
[5] Bricknell, S. 2020, Homicide in Australia 2017-2018. Statistical Report 23, Australian Institute of Criminology, viewed 3 July 2020. ⟨www.aic.gov.au/sites/default/files/2020-05/sr23_homicide_in_australia_2017-18.pdf⟩.
[6] Bureau of Meteorology 2020, Climate Statistics for Australian Locations, viewed 8 August 2020, ⟨http://www.bom.gov.au/climate/averages/tables/cw_067021_All.shtml⟩.
[7] D.O. Carter, D. Yellowlees, M. Tibbett, Cadaver decomposition in terrestrial ecosystems, Nat. volume 94 (2007) 12–24, https://doi.org/10.1007/s00114-006-0159-1.
[8] Chow, S.-M. Striupaitis, P. Haskell, N. and Gaensslen, R.E. Time-Dependent Effects of Putrefaction in Bodies on Individualising Striation Marks on Bullets – A Pig Model. Association of Firearm and Toolmark Examiners Journal, volume 35, number 4, Fall, 2003.
[9] Cross, P. and Simmons, T. 2010. The Influence of Penetrative Trauma on the Rate of Decomposition. Journal of Forensic Science, March 2010, volume 55. Number 2.
[10] B.B. Dent, S.L. Forbes, B.H. Stuart, Review of human decomposition processes in soil, Environ. Geol. 45 (2004), 576–58.
[11] A. Deo, S.L. Forbes, B.H. Stuart, M. Ueland, Profiling the seasonal variability of decomposition odour from human remains in a temperate Australian environment, Aust. J. Forensic Sci. 52 (6) (2020) 654–664. DOI: 10.1080/00450618.2019.1637938.
[12] Dutton, G. 1993, Expert Certificate (s.177), Forensic Ballistics Unit, Physical Evidence Section, reference: J1992/557, J1993/763 and J1994/340, 13 September 1994.

[13] Dutton, G. 1997. A Case Study of Forensic Firearms Evidence in the Belanglo Forest 'Backpacker' Murders. Association of Firearms and Toolmark Examiners Journal, volume 29, number 2, Fall, 1997.

[14] Fulp, K. 2021, A Study of Decomposition in the Arizona Sonoran Desert Using Pigs Graduate Faculty of Texas Tech University. ⟨https://ttu-ir.tdl.org/⟩. Viewed 6 June 2024.

[15] A. Galloway, The Process of Decomposition: A Model from the Arizona-Sonoran Desert, in: W.D. Haglund, M.H. Sorg (Eds.), Forensic Taphonomy. The Post-mortem Fate of Human Remains, CRC Press, 1997.

[16] Gill-King, H. 1996, *Chemical and Ultrastructural Aspects of Decomposition*. Boca Raton (FL): CRC Press.

[17] Goff, M.L. 2010, *Current Concepts in Forensic Entomology*. Chapter One, Chaminade University, Hawaii, Forensic Science Program, Springer Science.

[18] Guyton, A.C. and Hall, J.E., 2006. Textbook of Medical Physiology. 11th edition, Elsevier Saunders publishing.

[19] Iqbal, M.A. Ueland, M. and Forbes, S.L. 2018 *Recent advances in the estimation of post-mortem interval in forensic taphonomy.* Australian Journal of Forensic Sciences. Taylor & Francis Group. ⟨https://doi.org/10.1080/00450618.2018.1459840⟩.

[20] Z. Knobel, M. Ueland, K.D. Nizio, D. Patel, S.L. Forbes, A comparison of human and pig decomposition rates and odour profiles in an Australian environment, Aust. J. Forensic Sci. 2018 (2018).

[21] Leica Microsystems, 2020, Motorized Forensic Comparison Macroscope Leica FS C, viewed 15 June 2020, ⟨www.leica-microsystems.com/products/light-microscopes/p/leica-fs-c⟩.

[22] Love, E. Association of Firearm and Toolmark Examiners Journal, volume 12, number 1, January 1980.

[23] R.W. Mann, W.M. Bass, L. Meadows, Time since death and decomposition of the human body: variables and observations in case and experimental field studies, J. Forensic Sci. Vol 35 (No. 1) (1990) 103–111.

[24] Nichols, R. 2018, Firearm and Toolmark Identification. The Scientific Reliability of the Forensic Science Discipline. Academic Press. Elsevier.

[25] Rao, D. Singh, H. and Mowatt, J. Effects of human decomposition on test fired bullet – Experimental Research. Egyptian Journal of Forensic Science, 2015, ⟨http//dx.doi.org/10.1016/j.ejfs.2015.01.003⟩.

[26] Richmond, New South Wales, Daily Weather Observations, Bureau of Meteorology, 2023, Australian Commonwealth Government, ⟨http://www.bom.gov.au/climate/dwo/202007/html/IDCJDW2119.202007.shtml⟩.

[27] O.C. Smith, L. Jantz, H.E. Berryman, S.A. Symes, Effects of human decomposition on bullet striations, J. Forensic Sci. JFSCA volume 38 (number 3) (1993) 593–598 (May, pp).

[28] S. Szymoniak, R.E. Simi, J.C. Harris, Fired bullets and the implications for comparison during different stages of human decomposition: a pilot study, Assoc. Firearm-.-. Toolmark Exam. J. volume 55 (number 2) (2023) 2023.

[29] A.A. Vass, S.A. Barshick, G. Sega, J. Caton, J.T. Skeen, J.C. Love, J.J.A. Synstelin, Decomposition chemistry of human remains: a new methodology for determining the post-mortem interval, J. Forensic Sci. volume 47 (3) (2002) 542–553.