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Short Communication

Examination of misconceptions surrounding fatal fire victims

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A R T I C L E I N F O

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A B S T R A C T

Fire deaths are not unusual in forensic investigative practice but due to the destructive nature of fire they are often very difficult to investigate. With the need to identify the deceased and the events surrounding the manner and cause of death, knowledge of thermally induced alteration to the human body is important. Within the fire investigation community, a number of misconceptions have been present for years regarding the protrusion of the tongue as an indicator of life during the fire, and fractured skulls as the result of brains boiling and skulls exploding. This work presents qualitative analysis on the experimental burning of 42 unembalmed human donated cadavers by the San Luis Obispo Strike Team (SLOFIST) on their annual Forensic Fire Death Investigation Course (FFDIC) between 2017 and 2019. Prior to burning, the position of the tongue within the dental arch was confirmed and sharp, blunt, surgical and gunshot trauma to the cranium documented. Temperature was recorded from ignition through to suppression with thermocouples present both within the scene and the body. Post burn analysis on the position of the tongue, observation of cranial fractures and presence of brain tissue were recorded and analysed in conjunction with thermocouple data, fire scene dynamics and body demographics. The results provide a more comprehensive understanding of the thermal environmental factors involved in producing the phenomena that facilitate these misconceptions, identifying that a more thorough understanding of individual fire scenes and their development is essential when interpreting alteration and injury to the body of the fatal fire victim.

1. Introduction

Fire has been used as a medium to alter or destroy the human body since prehistory, with cremation being a funerary practice that continues to be widespread today. In forensic investigative practice, burnt human remains are discovered in a variety of scenarios. In addition to house fires (accidental or deliberate) these contexts include burnt vehicles [1–3], the result of suicide/self-immolation [4–6] burning to conceal crimes [7–9] and mass fatality incidents [10,11]. It is also used as a method to disguise criminal activity and homicide [12] with the common misconception that bones turn to piles of dust or ash [13] leaving little visible evidence of burnt remains for recovery and identification [14,15].

Following the identification of the decedent the question most often raised is whether or not the individual was alive during the fire, the answer to which can only be provided through post mortem examination of the human remains by a forensic pathologist. Following autopsy, it is recommended that findings be compared to the fire scene conditions recorded by the fire investigator [16]. Fire investigators document evidence of fuel loading and fire development and in fatal fires, investigators will also record the body within the scene including body position such as pugilism, clothing, and any observable trauma [17,18]. As fire investigation becomes more standardised with the creation of both Codes of Practice for and the Competency Framework [19] in the United Kingdom, evaluation of the thermal alteration to human remains is becoming more evidence based with the need to investigate these phenomena in a more scientific setting.

Various phenomena have been subject to unempirical fire death myths within the fire investigation community such as pugilism (a boxing pugilistic position with arms raised) considered evidence of the victim's activity at death [20]. Experimentation has established that this unique post fire positioning is the result of thermal penetration into the body causing contraction of muscles and tendons [14,21] which is now widely recognised by fire investigation personnel [17,22,23]. This paper examines the phenomena of tongue protrusion as an indicator of life during the fire, and skull fracturing as the result of increased pressure produced by brains boiling.

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2. Tongue protrusion

Tongue protrusion of the fatal fire victim was proposed as a sign of vitality by Bernitz *et al.* (2014) in a retrospective study of 107 post-mortem reports of fire fatalities [24]. It is argued that the retrospective analysis presented is not sound [25], prompting reviews of further historical autopsy reports to investigate this phenomenon further [26].

A pathophysiological explanation for tongue protrusion is for many cases an indication of strangulation, hanging, or death by asphyxia [27]. In burnt remains protrusion of the tongue is proposed to be simply a physical reaction related to mucosal tract damage and the human body's response to the inhalation of hot gases [28]. This is evidenced through burns to the tongue and heat induced rigor of the genioglossus muscle [29–31]. It is additionally suggested that this phenomenon is the result of the early heating process although no exposure temperatures or fire duration are proposed [32], and conversely it is also discussed as a consequence of heating bodily fluids to boiling point with subsequent evaporation resulting in the swelling of the lips and tongue protrusion [33].

Whilst post mortem reports provide detailed professional observations of the decedent, analysis does not refer to the specific fire environments victims were recovered from. Fire location is an important factor affecting the body with victims recovered from an outdoor setting not exposed to the same developmental factors as those in an enclosed space with overhead radiated heat, smoke density and chemical concentration [30]. Tongue protrusion has been witnessed in a wide variety of accidental, homicide, and suicide fatal fire victims in both indoor and outdoor scenes and it is identified that this phenomenon requires more scientifically based investigation [16,34].

2.1. Burnt remains and 'exploded skull'

It is proposed in the literature that cranial damage in the fatal fire victim is the consequence of the brain boiling, with increased internal pressure resulting in the cranial vault exploding and fracturing [35–38]. The challenge for investigators is in establishing whether fracturing exhibited on the skull is caused by trauma prior to the fire, or as a consequence of the thermal environment or any other factor (e.g. falling debris). In forensic pathology and forensic anthropology this challenging assessment can be supported by X-rays and Computed Tomography (CT) to assist in the interpretation of cranial trauma [7,28,39–43].

In order to understand the effect fire has on the human body, studies have been undertaken with burning of a porcine proxy [44–46] and observation of human cadaver burning through a professional crematoria retort window or door [3,14]. Professional cremation is performed by exposing the body to flame and high temperatures between 850 °C and 1100 ℃, with exposure times between 1.5 and 3 h in duration depending on the individual's size [47]. Whilst the temperatures reached correlate with those of real fires, the duration times are not comparable [48] and do not replicate a real fire scene with its variable fuel loads and dynamics [22,49,50].

A study by Pope and Smith (2004) investigated the mechanism behind cranial trauma in real time fire environments [51]. Their controlled observations of 40 unembalmed human heads inflicted with various types of trauma (sharp, blunt and gunshot) and exposed to real fire environments resulted in identifying that pre existing trauma can be both recognized and reconstructed in burnt cranial bone. Using a control of 10 heads without pre existing trauma, they additionally reported that none of the skulls exploded.

The results of Pope and Smith's study have both challenged and changed the way in which fractured skulls are assessed in forensic examination facilitating in depth analysis in quantifying fracture in burnt cranial bone, with the presence of brain matter only referred to briefly.

This paper aims to investigate the above two phenomena through fire scene experimentation. Observational recording of tongue position pre and post burn was analysed against individual biological data such as sex and Body Mass Index (BMI), and scene specific data such as exposure temperatures, fire dynamics and duration.

Where cranial trauma was identified post burn, analysis was performed to identify if its presence was the result of pre existing trauma or as a result of thermal damage. This research also examines if the presence of observable brain matter both within and external to the cranial vault is indicative of pre fire trauma, or whether it is the result of the fire scene environment.

3. Materials and methods

Experimentation was undertaken over a three year period from 2017 to 2019 through the organisation San Louis Obispo Fire Investigation Strike Team (SLOFIST) whose Executive Board is compiled of members from Fire Investigation, Law Enforcement, Coroners, Bureau of Tobacco and Firearms and Explosives, and Forensic Science. Annually in late June, the organisation provides a unique one week Forensic Fire Death Investigation Course (FFDIC) for the education of medical, legal, fire, law and forensic personnel involved in the investigation of fatal fires.

The course consisted of burning 10 different scenes recreated from accidental and intentional fatal fire scene casework of the instructing staff. The scenes contained either one or two human cadavers placed either within a vehicle or a compartment room. Donated vehicles were cars of various makes, models and age, with a single deviation recorded with the burning of a recreational vehicle (RV). Individuals are placed on either of the front seats, the rear seat, within the trunk/boot, or sat outside and leaning against the vehicle.

Compartment scenes were individually constructed of timber, chipboard and studs, and finished internally with gypsum wallboard covering the walls and ceiling. Whilst their sizes varied, all compartments were constructed with a functioning window and a standard residential door installed. Type K thermocouples were inserted within each compartment at ceiling, middle and floor levels to record fire thermal development. Each compartment was furnished with donated and local thrift store furniture to reflect the fatal fire scenario such as a bedsit (bedroom with kitchen facilities), standard bedroom, living room or bathroom (see Table 1).

Following the classroom teaching element of the FFDIC, student teams were assigned a scenario and were expected to document, investigate and recover remains from their fatal fire scene [20]. Two additional burns were conducted each year to facilitate first hand observation of heat and flame on human remains. Radiant heat was created by ignition of an external pyre with a chair positioned 2.5–4 m away (radiant demo), and a compartment demonstration consisting of three walls, a floor and ceiling containing two beds with bodies positioned face down (Demo prone) and face up (Demo supine). The absence of the fourth wall allowed real time observations to be undertaken whilst the individuals were enveloped in flame, the remains of which have been included in the dataset for analysis. Secondary to education, this course provides a unique opportunity for experimental investigation to be undertaken on the burning of human remains in a real time environment [20,21,51–53] (see Table 2).

Burning was undertaken in the morning with ignition through a variety of sources to accurately replicate both accidental and intentional fires [20]. The time frame of each burn was variable and dependent on instructor staff assessment ranging from three and a half minutes to over an hour with all fires developing through to flashover.

Flashover is a phenomenon whereby gases held within the ceiling smoke layer radiate onto the surfaces below until ignition point is reached, igniting the ceiling layer. This increase in radiant heat onto the surfaces below instigates ignition of all available surfaces within the scene [54,55], and is a compartment based phenomenon [56,57].

Fire suppression was performed through gas cooling/fogging which is the application of water in a fine mist format into the fire environment. Utilising small water droplets increases the surface area in contact with the thermal environment, facilitating a faster reduction of

Table 1
Three year experimental dataset of 42 cadavers.

Scene code	Scene venue	Burning time in minutes	Sex	Age	BMI	Weight Lb
2017/1	Car	13	Female	69	36	211
2017/2	Car	11.5	Male	81	16	164
2017/3	Bedsit	9	Female	83	22	180
2017/4	RV seat area	15	Male	76	23	152
2017/5a	Car outside	53	Male	84	26	101
2017/5b	Car trunk	53	Male	81	27	190
2017/6	Bedroom	7.5	Male	84	24	138
2017/7	Bathroom	9	Male	72	12	83
2017/8	Sitting room	6.5	Male	76	21	149
2017/9	Bedroom	7	Female	76	22	136
2017/10	Car	22.5	Male	53	26	209
2017/ DEM. R	Demo outside chair1	8	Male	69	21	136
2017/ DEM. P	Demo bedroom2	4.5	Male	87	27	222
2017/ DEM. S	Demo bedroom3	4.5	Male	84	29	223
2018/1	Car	12.5	Male	65	21	144
2018/2	Car	19.5	Male	92	26	170
2018/3	Bedsit	27.5	Female	67	24	128
2018/4	Car	22	Male	74	20	139
2018/5a	Car	11	Male	82	30	190
2018/5b	Car trunk	11	Female	101	16	101
2018/6	Bedroom	10.5	Female	62	25	145
2018/7	Bathroom	23	Male	60	16	96
2018/8	Sitting room	14	Female	54	21	111
2018/9	Bedroom	6.5	Female	82	23	125
2018/10	Car	41.5	Male	81	26	173
2018/ DEM. R	Demo outside chair1	13	Male	82	27	198
2018/ DEM. P	Demo bedroom[2]	5.5	Female	71	31	189
2018/ DEM. S	Demo bedroom3	6.5	Male	74	24	172
2019/1	Car	10.5	Female	52	25	145
2019/2	Car	12	Male	59	39	266
2019/3	Bedsit	5.5	Male	60	23	143
2019/4	Car	14	Female	90	25	125
2019/5a	Car	14	Male	81	20	125
2019/5b	Car trunk	14	Female	75	18	88
2019/6	Bedroom	6.5	Female	64	31	193
2019/7	Bathroom	4	Male	64	29	178
2019/8	Sitting room	3.5	Male	88	18	106
2019/9	Bedroom	6	Female	87	16	90
2019/10	Car	9	Male	70	21	148
2019/ DEM. R	Outside chair1	16	Male	95	21	136
2019/ DEM. P	Open bedroom[2]	5	Female	52	36	200
2019/ DEM. S	Open bedroom3	5	Female	69	34	214

[1]Outside radiant heat demonstration [2]Bedroom demonstration body prone (face down) [3]Bedroom demonstration body supine (on back) Shading identifies tongue protrusion dataset.

temperature through the absorption of heat energy [58–60], and suppression of the naked flame. This form of fire suppression is preferred over high pressure straight stream water application which has the potential of disturbing material within the scene prior to investigation.

Donated human remains were acquired through the Genesis program and Medical Education and Research Institute (MERI) by the San Luis Obispo County Sheriff Coroner Office in accordance with medical ethics. In addition, this work went through Cranfield University Research Ethics System. Following death, donated remains were frozen and stored at the MERI. All individuals identified for SLOFIST were deceased within 1 year prior to the course and were transported overland in a refrigerated lorry the week before. The initial temperature within the lorry was set to 6.7 °C (40 °F), slowly rising to 12.8 °C (55 °F) over the two days travelling to allow thawing during transit. The effect of freezing and thawing of human remains has been investigated, identifying that tissue cells become diluted and hypotonic due to the melting crystals resulting in a 'softening' of muscle, with tissue cells that are dead before freezing not reaching their prior volume [61].

For each body, MERI provided the following information: unique identifying number, sex, age, height, weight, previous medical procedures, blood screening results for hepatitis B and C, HIV and syphilis, cause of death, date of death. The age range of donated individuals was 52–101 years. This dataset is applicable to fatal fire casework [62]. In the United Kingdom individuals aged 50+ years accounted for 73.6% ± 4.9% of fire fatalities in years 2013–2020 [63]. It is suggested people over 60 years are at highest risk of dying in fires due to co-existing medical, social and biological factors [64,65], with the risk doubling for over 65 years, and quadrupling for those over 75 years of age [66].

In total 42 bodies were burned over a three year period, all unembalmed to ensure as natural as possible reaction to elevated heat. On the day of burning the defrosted bodies were fully dressed in single layer clothing, predominantly cotton t-shirts and trousers, thicker jogger cotton trousers or a dress of a cotton/nylon mixture. Tongues of all cadavers were observed and recorded to be present within the dental arch. Mouths were then closed and a stocking placed over the head to provide anonymity to the individual. Results for tongue protrusion were collected for 31 bodies post burn which are identified shaded in Table 1 above.

In accordance with research undertaken by Pope and Smith (2004) in their study of traumatic injury into burned cranial bone [51], gunshot trauma to the skull was inflicted by the County Sheriff's Office using a handgun with 10 mm ammunition in the controlled environment of the firing range. Blunt force trauma to the head was inflicted with a tyre iron, or iron bar by instructors to replicate casework trauma pertinent to the individual scenario. Cranial medical intervention reported in MERI paperwork recorded positive for pre burn cranial trauma. Undertaking experimentation and data acquisition is accomplished with the caveat that it does not impact the provision of teaching of the FFDIC. X-Rays and CT scans were not undertaken due to both the time impact and disruption this would have on the course, and the complexity of both acquisition and transport of mobile equipment to the remote burning site.

Thermocouples were placed within the thoracic cavity of each cadaver by MERI personnel via intubation in the airway before placement within the scenes. It is unknown if the presence of the thermocouple in the esophagus had any influencing effect on the presence or absence of tongue protrusion. It was also recognized that temperatures recorded would not be recorded directly from the genioglossus muscle beneath the tongue with the thermocouple placement in the thoracic cavity mitigating the potential of thermocouple displacement from the mouth. The defrosted cadavers were placed within the scene between 6.30am and 7.30am to enable body temperatures to acclimatise to the environment temperature before ignition mid to late morning. Ambient temperature was recorded by thermocouples at point of ignition. Time recording initiated at ignition and stopped at suppression.

Still photography was undertaken using an Olympus SP800UZ camera both pre and post burn, with video recording undertaken externally from ignition through to suppression. Each scene was fitted with type K thermocouples at ceiling, middle and floor levels within compartments, and in the seating area within vehicles.

Following the burns, visual examination was undertaken on each body both within the scene and during the recovery process where possible. Tongue protrusion was assessed and recorded as present or absent beyond the dental arch as originally defined by Berntiz and

Table 2
Scene dynamics where positive tongue protrusion observed.

Scene	Venue	Body position	Burn time mins	Scene max temp °C	Time in minutes scene max Temp °C	Max Body Temp °C	Time in minutes Body max Temp °C
2017/4	RV	Sitting	15	886	15	993	15
2017/5a	Outside car	Sitting	53	962	20.5	645	25.5
2017/9	Room	Supine	7	760	7	67	7
2017/10	Car	Sitting	22.5	873	17.5	11	18.5
2017/DemS*	Open bedroom	Supine	4.5	1111	3.5	634	3
2018/3	Room	Supine	27.5	875	27.5	838	27.5
2018/9	Room	Supine	6.5	914	5	623	5
2019/7	Room	Sitting	3.5	1271	3.5	103	2.5
2019/9	Room	Supine	6	939	6	920	6
2019/DemS*	Open bedroom	Supine	5	>393*	–	881	3.5

*Thermocouple failure at 393°C with scene developing to flashover.

colleagues [24]. Cranial damage was identified where fractures of any kind (radiating, concentric, mosaic and linear) were evident. In accordance with the method of observing trauma with the naked eye by Pope and Smith [51], cranial damage was photographed and recorded. Where brain tissue was identified, it was recorded as visible when observed both within the cranium and externally. Following recovery, all human remains were retrieved and returned to their original body bag ready for transportation back to MERI for final cremation.

Statistical analysis was undertaken on the dataset results using IBM SPSS 28 package. Analysis was undertaken between variables using a one-way ANOVA in order to avoid Type I errors of inter variable T Test analysis.

4. Results

Data for tongue protrusion was collected on 31 bodies (Table 1) with 11 bodies excluded due to their post burn position obscuring observation, or as a result of all flesh consumption. Maximum thermocouple temperatures were recorded for both scene and cadavers where present (Fig. 1).

Burn 2019/DemS experienced thermocouple failure at 1.5 min, registering a temperature of 393 °C. Whilst the fire underwent the phenomenon of flashover which is initiated at *c*600 °C [23,67] analysis is undertaken on the maximum scene temperature recorded as >393 °C.

Positive tongue protrusion was identified and recorded as present in all three burn venue categories of compartments, vehicles and demonstration burns containing cadavers that exhibited this phenomenon.

Analysis identified that internal temperatures of cadavers within the compartments reached their maximum within 1.5 min of the scene maximum temperature, with four scenes reaching maximum temperatures simultaneously.

Vehicle scene thermocouple results reveal that in the RV scene 2017/4, maximum body and scene temperatures were reached simultaneously. The cadaver inside the car of scene 2017/10 experienced a 1 min delay with the maximum scene temperature. In scene 2017/5a the body was sat external to the vehicle leaning against the front left wing of the car resulting in a 5 min delay between maximum temperatures.

Analysis of maximum scene temperature and maximum body temperature identified that whilst both scene and body temperature increase as fire develops, positive tongue protrusion is observed in

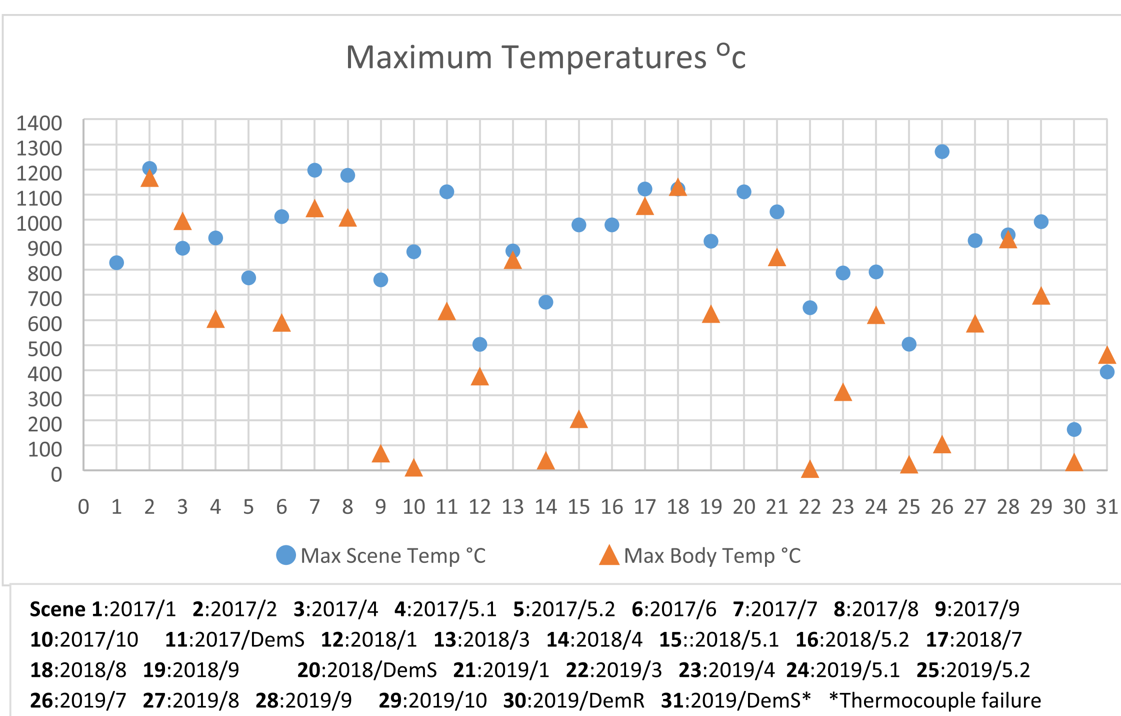

Fig. 1. Maximum temperature reached in scene with corresponding body temperature for tongue protrusion dataset.

cadavers exposed to scene temperatures in excess of 600℃ in addition to 2019/DemS at > 393 °C (Fig. 2).

Examination of exposure duration within the scenes indicated that tongue protrusion can be present early within the scene as the fire is developing (Fig. 3).

An outlier observed within the data (Scene 2018/5) is the extended duration of 53 min evidencing both presence and absence of tongue protrusion on cadavers within the same scene with one body placed within the passenger seat, and a second body placed within the boot/trunk.

A one-way ANOVA was performed to compare the presence of tongue protrusion with scene and body temperatures, the duration of the burn and biological factors such as sex and BMI (Table 3).

A Lavenes test for homogeneity of variance was undertaken, identifying that data sets of positive and negative tongue protrusion have homogenous variance with no significance (Table 3).

4.1. Burnt remains and 'exploded skull'

Examination and data collection for skull damage was undertaken on all 42 bodies (Table 1). Pre existing trauma to the head was recorded prior to burning, present through gunshot and blunt force trauma undertaken pre burn by SLOFIST staff, and antemortem medical intervention for brain tumour treatment (Fig. 4).

Following the burn, brain tissue was recorded as positive when observed both within the cranium and externally. Twelve individuals presented with observable brain tissue of which nine had prior recorded trauma. The remaining three individuals presented a positive result where structural elements of the scene were in direct contact with the cranium (Table 4).

Brain tissue was observed in ten scenes, predominantly within compartment rooms with bodies principally lying on a bed or floor, with one exception (scene 2019/9) where the individual was in a sitting position upon a sofa.

Burn duration was variable with a single compartment left to burn to the ground (2018/7). Two individuals within vehicles that evidenced exposed brain tissue were both positioned within the boot/trunk of the vehicle (2017/5 and 2018/5) with the fire developing within the main cab.

Examination of temperature and duration (Fig. 5) identified compartment scenes as the predominant venue with brain matter still present following transition of the fire through flashover.

A one-way ANOVA was performed between scene and body temperatures, the duration of the burn and BMI of the cadaver with results revealing no significant relationship was present. Levenes test for homogeneity between the positive and negative observational brain matter groups identified homogenous variance with no significance (Table 5).

Ten bodies exhibited cranial fractures post burn with no brain tissue visible (Table 6). A single skull had neither pre existing trauma or associated debris but presented fractures at the location of an extra-sutural bone within its structural composition that potentially provided a weak point within the cranium. This latter statement can only be supported, however, by further examination.

In total twenty two of the human cadavers, 52% of overall dataset exhibited skull fracture of varying degrees. Fourteen (64%) had cranial trauma prior to the burn, with a further seven bodies (32%) sustaining trauma through interaction of debris collapse, and one single body (4%) evidencing fracture through extrasutural cranial bone.

5. Discussion

The advantage of undertaking experimentation using human remains in real fire scenes as opposed to a proxy analogue or a cremation retort is that it allows direct applicability to the investigation of fatal fires. Observing bodies within the fire environment has led to a far deeper and more comprehensive understanding of the effect the thermal environment and flame has on human remains [20,21,32,52,53].

Work previously undertaken assessing burned cranial trauma employed X-Ray to record trauma prior to the burning of 30 separate heads [51]. The 10 heads used as the experimental control were still attached to bodies and were not subject to X-Rays, with no pre existing trauma recorded. The post burn analysis focused on prior trauma, with traumatic changes recorded with the naked eye [51]. The position of the isolated heads within the scenes was not recorded, and did not form part of the fatal fire scene for recovery. The research presented here focused on cadavers or human remains as they would be found and subsequently recovered from the fatal fire scene, and how the dynamics of the fire in different scenes affected the outcome of body alteration.

Fire development was recorded for each scene by thermocouples at ceiling, middle and floor heights, with scenes progressing through flashover with the exception of 2017/4 due to the prevailing wind. Studies have identified flashover temperatures at the point of flashover to be 600 °C [56,68,69], with the post flashover environment producing temperatures as high as 1100 °C [70] which can remain high for several minutes making the environment untenable for survival [22,54].

The development of fire and its transfer of heat to objects, structures and human bodies present within the scene is governed by scene dynamics such as fuel loading, dimensions, and ventilation [23,67].

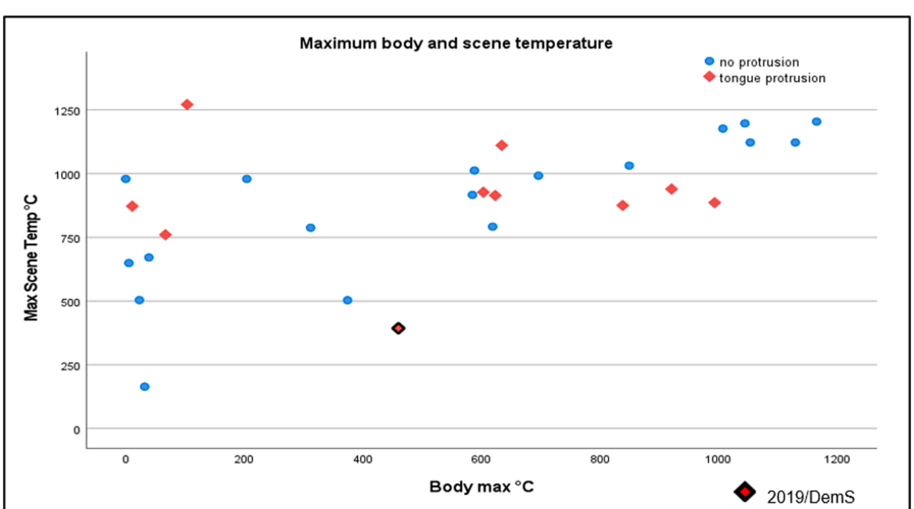

Fig. 2. Scene and body temperatures with tongue position observation.

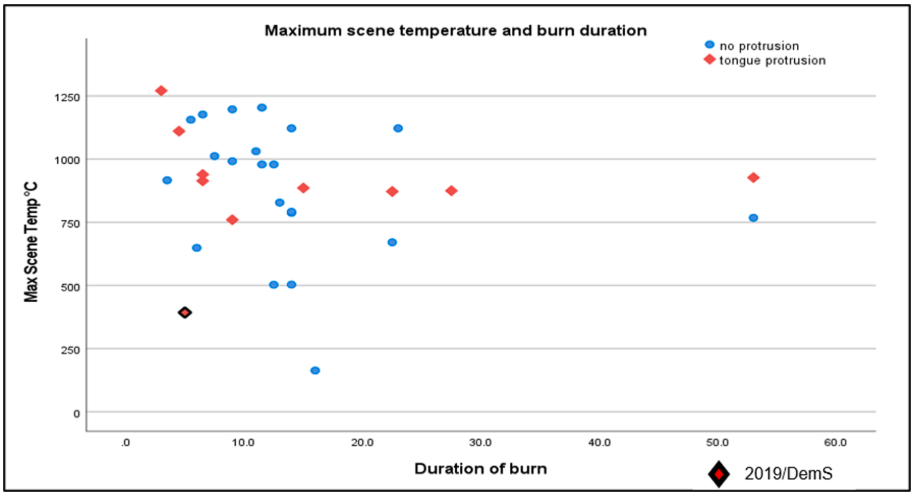

Fig. 3. Burn Duration and Maximum Temperature for tongue position observation.

Table 3
Statistical analysis for significance of tongue protrusion.

Positive Tongue Protrusion	N	Mean	Std	CI 95% Lower	CI 95% Upper	One-Way ANOVA	Lavenes test For homogeneity
Scene Max Temp °C	10	894.8	266.75	732.59	1057	F (1,29) =.0.013, p =.910	1.648, p = 209
Body max Temp °C	10	525.26	358.51	268.80	781.73	F (1,26) = 0.005, p-.927	1.039, p =.317
Burn Duration Minutes	10	15.60	15.43	4.55	26.65	F (1,29) = 0.152, P =.699	2.720, p =.110
Sex	10	1.5	0.527	1.12	1.88	F (1,29) = 2.136, p =.155	3.537, p =.070
BMI	10	24.26	4.56	21.00	27.53	F (1,29) = 2.318, p =.139	0.182, p =.673

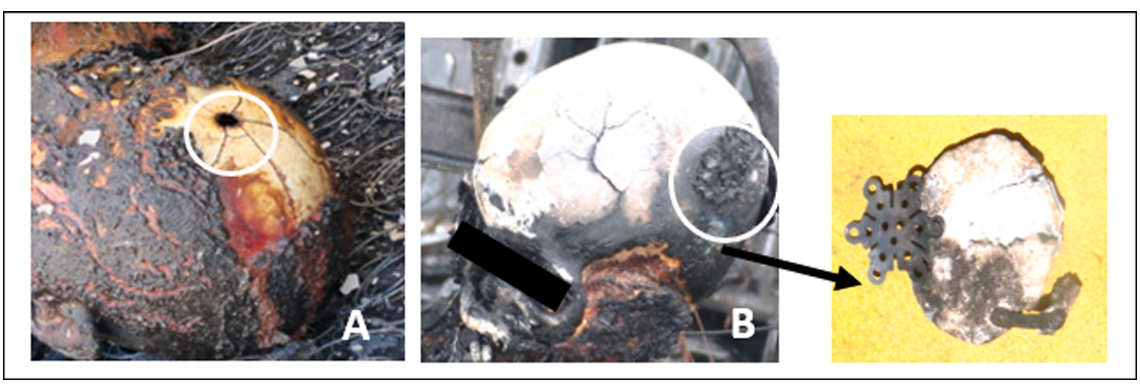

Fig. 4. Pre-existing cranial trauma identified by white circle A: Gunshot wound. B: Craniotomy surgery with implant to secure bone in place post-surgery.

Table 4
Cadavers with fractured cranial elements and brain tissue visible.

Scene	Venue	Max Scene Temp °C	Brain Tissue Visible	Pre Existing Trauma	Associated Debris
2017/5b*	Car trunk	962	Y	Y	N
2017/7	Bathroom	1197	Y	N	Y
2017/Demo.P	Open bedroom	1111	Y	Y	N
2018/3	Bedsit	875	Y	Y	N
2018/5b*	Car trunk	979	Y	Y	N
2018/7	Bathroom	1122	Y	N	Y
2018/8	Sitting room	1127	Y	Y	Y
2018/Demo.P	Open bedroom	1156	Y	Y	N
2018/Demo.S	Open bedroom	1156	Y	Y	Y
2019/8	Sitting room	916	Y	Y	N
2019/9	Bedroom	939	Y	Y	N
2019/DEM.P	Open bedroom	>393*	Y	Y	N

5b* remains within the trunk/boot of vehicle *Thermocouple failure.

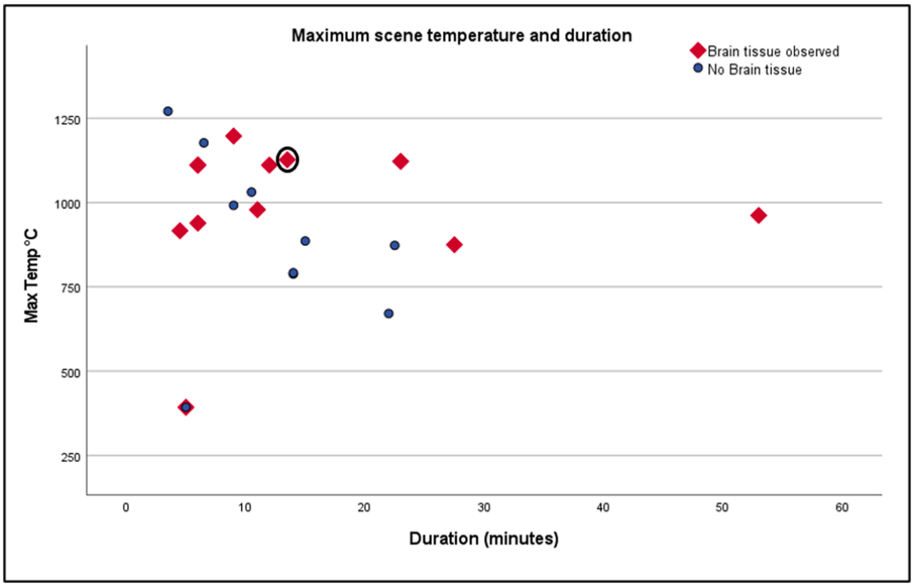

Fig. 5. Burn Duration and Maximum Temperature for brain matter observation Scene 2018/DemP and 2018/DemS contained 2 bodies in the same scene both with observable brain tissue and are both represented by a single marker highlighted by the circle.

Table 5
Statistical analysis for the presence of brain tissue post burn.

Observable Brain Tissue	n	Mean	Std	CI 95% Lower	CI 95% Upper	One-Way Anova	Levenes Test for homogeneity
Scene Max Temp °C	12	986.96	213.57	851.26	1122.65	F (1,21) = 1.007, p =.328	0.382, p =.544
Body max Temp °C	11	744.43	395.11	479	1009.87	F (1,19) = 0.1.639,p =.217	0.342, p =.566
Burn Duration (Mins)	12	14.71	14.69	5.76	23.65	F (1,21) = 0.267, p =.611	22.070, p =.129
BMI	12	22.21	7.054	17.73	26.76	F (1,21) = 0.677, p =.420	2.511, p =.129

Table 6
Cadavers with fractured cranial elements but no brain visible.

Scene	Venue	Max Scene Temp°C	Fractured Cranium	Pre-existing Trauma	Associated Debris
2017/4	RV	886	Y	N	Y
2017/7	Room	1197	Y	Y	N
2017/8	Room	1177	Y	Y	N
2017/10	Car	873	Y	Y	N
2018/4	Car	671	Y	N	Y
2019/1	Car	1031	Y	N	Y
2019/4	Car	788	Y	N	Y
2019/5	Car	792	Y	N	N
2019/10	Car	992	Y	N	Y
2019/DemS	Room	>393	Y	Y	N

Following ignition, as the fire develops heat is transferred via buoyancy induced convection, transferring heat as the air travels over the cooler surfaces in the early stages of the fire at <c150–200 °C [23,71,72]. Following the transfer of heat, the cooler air falls becoming entrained at the fire base, providing the fire with a steady flow of oxygen and promoting continuous fire growth.

This process of heat exchange is highly complex and dependant on the flow effect created by the scene dynamics such as room dimensions, and the presence of open apertures such as doors or windows which can affect fire development through external factors such as wind direction. This transfer of heat results in the release of toxic gases which rise from the surface of objects and are held within the ceiling smoke layer. As fire continues to develop the cyclic process of convection creates turbulence within the gases which continue to rise in temperature resulting in the transition from convection to radiation as the primary mode of heat release. Once gases reach their ignition point they spontaneously ignite within the ceiling layer, which is subsequently followed by ignition of all surfaces below. This phenomenon of flashover is compartment based, with the transmission of heat release in vehicles primarily by convection and also dependant on the interior fuel materials present, the position (open/closed) and presence of doors and windows, and external variables such as wind and rain [1].

Temperatures recorded within the scenes fluctuate in accordance with fire development as discussed above. Where maximum scene temperature is recorded, temperatures are not sustained for an extended period of time but represent the highest temperature the human remains were exposed to in the turbulent thermal fluctuating atmosphere, thus providing an indication of the heat release and thermal transfer within the environment.

Within this study tongue protrusion was evidenced in a variety of fire scenes, with two case scenarios replicated three times, all resulting in tongue protrusion. The first (scene 9 for each year) remained the same for all three years of experimentation with the scene scenario being ‘the use of flammable liquid poured onto a mattress and ignited in an attempt to disguise a homicide’ (see Fig. 6).

Ignition was undertaken by direct contact of a flare to accelerant that had been poured onto the mattress in immediate proximity to the bodies. This resulted in heat introduced directly and immediately to the bodies rather than the gradual heat increase through convection as the fire developed. Duration of the fires was recorded at 7 min, 6.5 min and

Fig. 6. Scene 2017/9 Bed ignited with flammable liquid.

6 min with the maximum differential between burns being 60 s.

Secondly the supine bodies in the open bedroom demonstration, all exhibited tongue protrusion (Fig. 7). The absence of the fourth wall (removed for observational purposes) provided the fires with constant entrainment of oxygen promoting fire growth, resulting in the rapid engulfing of the body in flames.

Tongue protrusion was recorded in scene 2018/3 where an individual was lying supine on the floor with furniture placed over the body to chest height, resulting in close proximity of burning wood to the head. The fire slowly developed with an extended time frame of 27.5 min in accordance with facilitating the burn to a post flashover environment from which students on the FFDIC would be required to investigate and subsequently recover the body.

Thermocouple data recorded the slow progression of the fire (Fig. 8), with floor temperature and internal body temperature remaining low until flashover which resulted in temperature rise. The post flashover environment facilitated an increase of temperature both at floor level and within the body to >800 °C, with the temperature at floor level producing the maximum temperature within the scene of 875 °C recorded just before suppression.

Finally, scene 2019/7 contained an individual sat within a bath filled with water. The burn time was short at 3.5 min with development assisted by an open door and the prevailing wind. It is unclear if the presence of water and potential evaporation is related to tongue protrusion, or the heightened development and quick suppression. The duration of the two other bath scenes in the data set were significantly longer with 2017/7 burning for 9 min and 2018/7 left to naturally suppress with thermocouple recording stopped at 23 min. The soft tissue surrounding the head including the ears, nose and eyes were consumed in both scenes, and therefore no comparative analysis was undertaken. This has identified an area of further scientific study on the effect of the presence of water within the fire scene on the human body, with research already evidencing that victims will shelter from fire in the bathroom, often within a bath of water if evacuation is no longer an option [73–75].

Fig. 7. 2018 open bedroom demo with body supine.

Examining the results of tongue protrusion in compartments, analysis reveals that the duration of the fire event is not an influencing factor in compartment scenes for tongue protrusion. Omitting the temperature for 2019/DemS which was subject to thermocouple failure, maximum scene temperatures for positive tongue protrusion (Fig. 3) predominantly ranged from 750 °C to 1000 °C ($n = 7$), with two scenes recording highest temperatures (>1000 °C) with a shorter duration. Analysis of temperature and duration of the scene dataset revealed no significance in the relationship between the variables and positive tongue protrusion, with results identifying the temperature range of 211–1197 °C in scenes with no tongue protrusion and duration ranging from 3.5 to 53 min.

Examination of tongue protrusion within vehicle fires had varied results. Vehicle scene 2017/5a contained two cadavers, one in the trunk/boot of the car, and one sat positioned externally against the front left wheel arch. Ignition was at the rear of the vehicle with the fire slowly developing and moving forward to the front, with the boot/trunk not directly enveloped by fire and the contained body did not evidence tongue protrusion.

Heat radiated out from the vehicle to the body as the fire developed, resulting eventually in direct flame interaction with the head and resulting in tongue protrusion (Figs. 9 and 10). The results produced by this burn recorded both positive and negative for the same duration.

All three vehicle fires where tongue protrusion was present were ignited at the rear of the vehicle, with fires slowly advancing forward. Scene 2018/4 was the burning of the RV with the fire remaining predominantly in the rear of the vehicle due to the prevailing wind. Internally the fire dynamics were more in keeping with a compartment scene due to the high ceiling and interior area volume. The remains seated in the front of 2017/10 were exposure to developing flame in the front seats for 2 min before suppression with the internal body thermocouple recording no rise in temperature indicating thermocouple failure had occurred. This deficit in the recording of internal body temperature is also replicated in scene 2017/9 where the temperature does not rise above 60 °C even though the room transitioned through flashover.

Thermocouple failure within the two bodies discussed above, and the low temperature of the body in the bath hindered comprehensive investigation of a relationship between the presence of tongue protrusion with scene and body temperatures. It is recognised that the malfunction has resulted in a limitation to this study, and the subsequent analysis of data on the reduced dataset identified no statistically significant relationship present. Maximum scene temperature where tongue protrusion was observed ranged from 760 °C to 1271 °C, with internal body temperature on the limited data of 7 individuals ranging from 623 °C to 993 °C. Individuals with no tongue protrusion were recorded with internal temperatures ranging from 23 °C (recorded in a demonstration burn of radiant heat with the body sat in a chair external to burning compartment) through to 1165 °C.

Cadaver specific biological parameters were analysed to investigate the relationship between positive tongue protrusion and sex. This did not identify any significant association with an equal distribution between the sexes with tongue protrusion proportionate to their overall sex data set; the ratio revealed Male $n = 5$ (23% of male dataset) and Female $n = 5$ (50% of female dataset). The BMI of individuals with tongue protrusion ranged between 16 and 33 which are outliers, with the remaining eight cadaver BMI range in from 22 to 28. Individuals recorded as negative for tongue protrusion ranged in BMI from 12 to 39 with 41% of the negative dataset within the range of 22–28 BMI.

Studies undertaking retrospective analysis of pathological data have enabled investigation of tongue protrusion against additional indicators of victim vitality, such as carboxyhaemoglobin (CHOb) levels in blood,

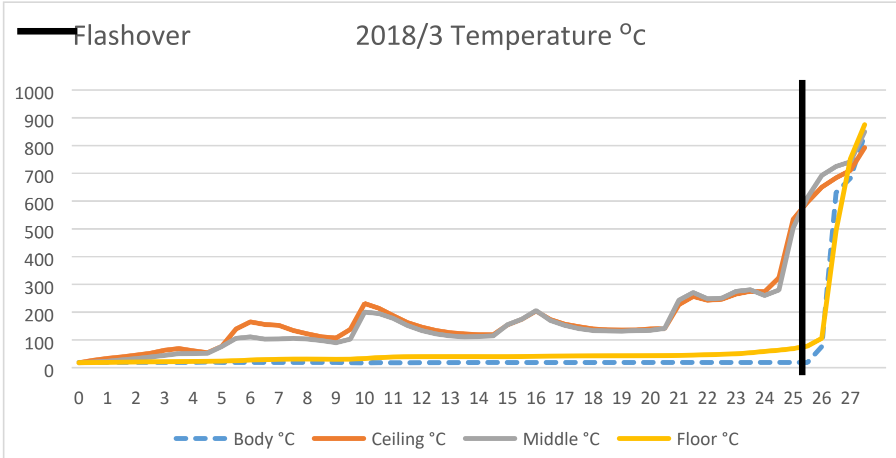

Fig. 8. Thermocouple temperature data for 2018/3.

Fig. 9. White circle highlighting open.

Fig. 10. White circle highlighting tongue protrusion mouth with no tongue visible.

Fig. 11. Partial calcination of skull.

and soot in the larynx [24,25,29]. In these studies, the data sample sex is provided within the materials and methods but no further differential analysis was undertaken to investigate the presence of tongue protrusion and individual biological sex.

It has been evidenced in this research, that in fully developed fires, structural debris can result in the fracturing and damage of burnt bone. This is particularly pertinent to cranial trauma as fractured and damaged skulls have previously been considered an indicator of exploded cranial vaults [76,77].

It is reported in the literature that the top of the skull or cranial vault is more thermally susceptible due to the thin upper layer of covering skin (Fig. 11) as opposed to the lower part or base of the head which is protected by thicker muscles [32], and that darker colour around peri-mortem fractures are the result of shielding from ‘oozing tissue and fluids’ [78]. This is especially evident in vehicle fires where flames are held within the low roof engulfing the head of the victim (Fig. 12).

As fire continues to develop within the vehicle cab, soft tissues of the face including the eyes, ears, lips and tongue also become consumed.

Fig. 12. Head in roof flame (indicated by arrow).

This is in line with the present analysis where cranial fractures have been identified but no observed brain tissue on cadavers seated within vehicles. Cranial fractures with no observable brain tissue was identified on six bodies with no previously recorded trauma. All six bodies were present within vehicles and exposed to burn length ranging from 9 to 22 min, with five directly associated in contact with debris and a further single body at a site where there was an extrasutural cranial bone. In contrast, bodies in the boot/trunk exposed to high temperatures but not enveloped in flame presented brain matter that was still visible.

As bones become devoid of flesh through exposure to intensive heat and flame they become fragile and calcined in nature due to the structural reordering of the bone as it transitions through different temperatures. Organic elements pyrolyse at approximately 600 ℃ and mineral elements become altered or pyrolysed between 800 and 1100℃ leaving bone white and calcined in appearance and more fragile and susceptible to breakage [79–82]. These temperatures are analogous to flashover and the post flashover environment, identifying that accidental cranial trauma from structural debris is more predisposed after the fire has developed through this transition. Observation of fire development at a scene such as fuel loading and fire dynamics can assist forensic pathologists and anthropologists in identifying if injury and destruction of the body is consistent with the thermal conditions [83,84].

The presence of brain tissue was identified predominantly within compartment scenes (83% of dataset) with all compartments undergoing flashover and cadavers exposed to the post flashover environment before suppression. Two bodies exhibited observable brain tissue without pre existing trauma to the cranium were present in bath scenes with the body in water at ignition point. Both scenes had a lengthy duration with scene 2017/7 suppressed at 9 min, and 2018/7 with thermocouple recording stopped at 23 min and left to naturally supress. It is unclear if the presence of the body in water is a contributing factor to the continued presence of observable brain matter whilst the soft facial tissue of ears, nose, lips and eyes were consumed by the fire. This result has identified an additional factor that would benefit from further investigation into fatal fire victims and their presence in water as discussed above.

Analysis of duration (Fig. 5) identified a predominance of shorter time frame in the observance of brain tissue. The fire dynamics of the lengthier burns of 2018/5 at 53 min with a body in the trunk, and 2018/3 at 27.5 min with a slow developing fire (Fig. 8), and 2018/7 in a bathroom with thermocouple recording stopped at 23 min have been discussed above. Nine cadavers (75%) recorded as positive for observable brain matter exposed to the fire environment for under 11 min, with outliers in this reduced dataset 2018/5 body in trunk of car (11 mins), and 2017/7 body in bath water (9 min). Reducing the data set further to compartments, seven cadavers (58%) recorded as positive were exposed to the fire environment for a shorter time period of 3.5–6 min.

Statistical analysis of the positive dataset did not identify any relationship significance between observable brain matter with duration time of burn. It is recognised that the limitation of the small dataset in this experimentation does not facilitate a more comprehensive analysis of the relationship between duration and temperature from which decisive conclusions can be drawn.

6. Conclusion

This paper presents a qualitative examination of a unique dataset investigating the effect of a variety of fire environments on human remains. Recording the burning of multiple scenes enabled investigation of the effect high temperature and flame have on the human body in relation to two phenomena that have facilitated misconception surrounding fatal fire victims.

The results have demonstrated that tongue protrusion following a fire is not a sign of vitality at the start of the fire. Rather than identify a criterion through biological demographics of sex or BMI that distinguish an individual to predisposition to tongue protrusion, the results of this experimentation have identified that fire demographics and the fatal fire scene venue are influencing factors in the production of this phenomenon. The authors suggest that the occurrence of tongue protrusion is potentially far higher in fatal fire victims than previously considered, but due to the continued development of the fire, organic elements including the tongue are consumed leaving no evidence of this previously exhibited phenomenon.

The presence of brain tissue was observed predominantly within compartment scenes with a short post flashover exposure and in vehicle fires where the cadaver had no direct flame interaction. Cadavers within the seating area of the cars exhibited cranial fracture but no brain tissue, the result of fire retained within the roof consuming the soft tissue of the head. Where cranial fractures were identified it was associated with pre existing cranial trauma or post burn debris contact with a single anomaly of an extrasutural cranial bone in its structural composition potentially providing a weak point within the cranium.

This study has sought to investigate the thermal mechanisms and environments within which tongue protrusion, cranial damage and brain tissue are evidenced. The limitation of an original small dataset becoming further reduced due to thermocouple failure, and the inability to rerun experimentation has hindered the collection and subsequent analysis of data.

The results do however highlight that a more thorough understanding of individual fire scenes and their development is essential when interpreting alteration and injury to the body of the fatal fire victim. The results presented in this paper are indicative but not conclusive, and the authors would welcome further data collection and analysis by other researchers.

The authors confirm that the data supporting the findings of this study are within the article. Raw data that supports the findings of this study are available from the corresponding author, upon reasonable request.

CRediT authorship contribution statement

Mary-Jane Harding: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Nicholas Márquez-Grant:** Software, Validation, Writing – review & editing, Visualization, Supervision. **Mike Williams:** Software, Validation, Formal analysis, Writing – review & editing, Visualization, 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.

References

[1] D. DeHaan, P.E. Fisher, Fatal fire in a parked motor vehicle, Fire Arson Investig. (2003) 42–47.
[2] I. Galtés, S. Scheirs, Differentiation between perimortem trauma and heat-induced damage: the use of perimortem traits on burnt long bones, Forensic Sci. Med. Pathol. 15 (3) (2019) 453–457, https://doi.org/10.1007/s12024-019-00118-1.
[3] M. Bohnert, T. Rost, M. Faller-Marquardt, D. Ropohl, S. Pollak, Fractures of the base of the skull in charred bodies-post-mortem heat injuries or signs of mechanical traumatisation? Forensic Sci. Int. 87 (1) (1997) 55–62.
[4] V. Laloë, Patterns of deliberate self-burning in various parts of the world: a review, Burns 30 (3) (May 2004) 207–215, https://doi.org/10.1016/j.burns.2003.10.018.
[5] G. Ziólkowski, A. Cruel, Theatre of Self-Immolations. Contemporary Suicide Protests by Fire and Their Resonances in Culture, Routledge, OXFORD, 2020.
[6] J.R. Ashton, S. Donnan, Suicide by burning as an epidemic phenomenon: an analysis of 82 deaths and inquests in England and Wales in 1978–9, Psychol. Med. 11 (4) (1981) 735–739.
[7] H. Iwase, Y. Yamada, S. Ootani, Y. Sasaki, M. Nagao, K. Iwadate, T. Takatori, Evidence for an antemortem injury of a burned head dissected from a burned body, Forensic Sci. Int. 94 (1-2) (1998) 9–14.
[8] A. Baker Bontranger, S. Nawrocki, Taphanomic analysis of human cremains from fox hollow serial homicide site, in: C. W. Schmidt and S. A. Symes (Eds.), The Analysis of Burned Human Remains, first ed. Elsevier Ltd, London, 2008, pp. 211–266.
[9] P. Edirisinghe, I. Kitulwatte, S. Gangahawatta, Multidisciplinary forensic investigation into a partially burnt dismembered body found by a road side, MLJSL 2 (2) (2016) 45–49.
[10] A. Mundorff, Anthropologist triage: three distinct mass fatality events involving fragmentation and commingling of human remains, in: B. Adams (Ed.), Commingled Human Remains. Method in Recovery, Analysis and Identification, first ed., Elsevier Inc, Oxford, 2014, pp. 365–389.
[11] A.Z. Mundorff, E.J. Bartelink, E. Mar-Cash, DNA preservation in skeletal elements from the world trade center disaster: recommendations for Mass Fatality Management, J. Forensic Sci. 54 (4) (2009) 739–745, https://doi.org/10.1111/j.1556-4029.2009.01045.x.
[12] Z.I. Bledar Xhemali, A.S. Gentian Vyshka, The fire will do the rest': concealing homicide through posthumous burning of corpses, Anthropology 03(01) (2015). doi: 10.4172/2332-0915.1000146.
[13] W. Spitz, R. Clark, Medicolegal Investigation of Death: Guidelines for the Application of Pathology to Crime Investigations, fourth ed., Charles C Thomas, Springfield, 2006.
[14] S.A. Symes, D.C. Dirkmaat, S. Ousley, E. Chapman, L. Cabo, Recovery and interpretation of burned human remains, Bibliogov.project (2012).
[15] D.C. Dirkmaat, L.L. Cabo, S.D. Ousley, S.A. Symes, New perspectives in forensic anthropology, Am. J. Phys. Anthropol. 137 (S47) (2008) 33–52, https://doi.org/10.1002/ajpa.20948.
[16] J. Konefal, E. Nordskog, Fire Death Investigation. A guide for Homicide, Coroner and Arson Investigations. ISBN 13: 978-0-578-46676-7. 2019.
[17] Nfpa, 921 Guide for Fire and Explosion Investigation, fourth ed., National Fire Protection Association, 2016.
[18] D. Dirkmaat, Recovery and investigation of fatal fire victims - forensic taphonomy, in: W. Haglund, M. Sorg (Eds.), Advances in Forensic Taphonomy, First.CRC Press, 2002.
[19] C. Blacksell, Competency Framework for Fire Investigation, National Fire Chief Council, 2021.
[20] J.D. Dehaan, Post-mortem repositioning of human bodies in fires, Int. J. Crimi. Forens. Sci. 2 (2018) 62–78.
[21] E. Pope, The Effects of Fire on Human Remains: Characteristics of Taphonomy and Trauma, University of Arkansas, 2007.
[22] J. DeHaan, Fire and bodies, in: C. Schmidt, S. Symes (Eds.), The Analysis of Burned Human Remains, Elsevier, First. London, 2008, pp. 1–14.
[23] J. DeHaan, D. Icove, Kirks Fire Investigation, Seventh Edition. Pearson, 2012. Accessed: Jun. 16, 2022. Available: ISBN: 0-13-283001-9.
[24] H. Bernitz, P.J. van Staden, C.M. Cronjé, R. Sutherland, Tongue protrusion as an indicator of vital burning, Int. J. Leg. Med. 128 (2) (2014) 309–312, https://doi.org/10.1007/s00414-013-0861-4.
[25] M. Bohnert, Protrusion of the tongue in burned bodies as a vital sign?, Int. J. Legal Med. 128(2) (2014). doi: 10.1007/s00414-013-0929-1.
[26] M. Bohnert, P. Hejna, Tongue protrusion in burned bodies, Int. J. Leg. Med. 130 (5) (Sep. 2016) 1253–1255, https://doi.org/10.1007/s00414-016-1357-9.
[27] P. Saukko, B. Knight, KNIGHT'S Forensic Pathology, Hodder Arnold, London, 2004.
[28] J.-B. Coty, C. Nedelcu, S. Yahya, V. Dupont, C. Rougé-Maillart, M. Verschoore, C. Ridereau Zins, C. Aubé, Burned bodies: post-mortem computed tomography, an essential tool for modern forensic medicine, Insights Imag. 9 (5) (2018) 731–743.
[29] I. Bianchi, M. Focardi, V. Bugelli, B. Gualco, F. Pradella, V. Pinchi, Tongue protrusion in post mortem fire, J. Forensic Odont-Stomatol. 37 (1) (2019) 26–31.
[30] V. Živković, S. Nikolić, Regarding the editorial 'The autopsy evaluation of "straightforward" fire deaths', Forensic Sci. Med. Pathol. 14 (3) (Sep. 2018) 419–420, https://doi.org/10.1007/s12024-018-9966-x.
[31] S. Nikolić, V. Živković, Protrusion of the tongue in bodies burned after death: two cases of arson to cover homicide, Med. Sci. Law 55 (4) (2015) 300–303, https://doi.org/10.1177/0025802414542260.
[32] E.J. Pope, O. Smith, Identification of traumatic injury in burned cranial bone: an experimental approach *, J. Forensic Sci. 49 (3) (2004). www.astm.org.
[33] B. Madea, E. Doberentz, Protrusion of the tongue in burned bodies as a vital sign? Letter to the editor concerning the paper "Tongue protrusion as an indicator of vital burning" by Bernitz et al. Int. J. Leg. Med. 129 (2) (2015) 313–314.
[34] H. Bernitz, Reply to letter received from Prof Michael Bohnert regarding article on "Tongue protrusion as an indicator of vital burning", Int. J. Leg. Med. 128 (2) (2014) 319–320.
[35] W.G. Eckert, S. James, S. Katchis, Investigation of cremations and severely burned bodies, Am. J. Forensic Med. Pathol. 9 (3) (1988) 188–200.
[36] Q.C. Kahil Karim, Speeches Given at the Council of the British Academy of Forensic Sciences Friends' Dinner-9 March 2005, 2005.
[37] Z. I. Bledar Xhemali, A.S. Gentian Vyshka, 'The fire will do the rest': concealing homicide through posthumous burning of corpses, Anthropology 03(01) (2015), doi: 10.4172/2332-0915.1000146.
[38] C. Durão, M.P. Machado, E. Daruge Júnior, Death in the 'microwave oven': a form of execution by carbonization, Forensic Sci. Int. 253 (2015) e1–e3, https://doi.org/10.1016/j.forsciint.2015.05.012.
[39] M. Tsokos, Heat-induced post-mortem defect of the skull simulating an exit gunshot wound of the calvarium, Forensic Sci. Med. Pathol. 7 (2) (Jun. 2011) 227–228, https://doi.org/10.1007/s12024-010-9215-4.
[40] R. Hausmann, P. Betz, Thermally induced entrance wound-like defect of the skull.
[41] V. Pinchi, et al., Multiple deaths caused by a fire in a factory: identification and investigative issues, J. Forensic Odonto-Stomatol. 34 (2) (2016) 47–59.
[42] M.J. Thali, K. Yen, T. Plattner, W. Schweitzer, P. Vock, C. Ozdoba, R. Dirnhofer, Charred body: virtual autopsy with multi-slice computed tomography and magnetic resonance imaging, J. Forensic Sci. 47 (6) (2002) 15569J.
[43] C.P. Campobasso, A.S. Dell'Erba, M. Belviso, G. di Vella, Craniofacial identification by comparison of antemortem and postmortem radiographs: Two case reports dealing with burnt bodies, Am. J. Forensic Med. Pathol. 28 (2) (Jun. 2007) 182–186, https://doi.org/10.1097/PAF.0b013e31806195cb.
[44] J.D. DeHaan, S.J. Campbell, S. Nurbakhsh, Combustion of animal fat and its implications for the consumption of human bodies in fires, Sci. Justice 39 (1) (1999) 27–38, https://doi.org/10.1016/S1355-0306(99)72011-3.
[45] H. Collord-Stalder, Digital Microscopic Methods for Sharp Force Trauma in Burned Human and Nonhuman Remains, 2020.
[46] J.D. DeHaan, S. Nurbakhush, Sustained combustion of an animal carcus and its implications for the consumption of human bodies in fire, J. Forensic Sci. 46 (5) (2001) pp.
[47] J. Schultz, M. Warren, J. Krigbaum, Analysis of human cremains: gross and chemical methods, in: C. Schmidt, S. Symes (Eds.), The Analysis of Burned Huan Remains, Elsevier, First.BURLINGTON, 2008.
[48] C.L. Fojas, L.L. Cabo, N.V. Passalacqua, C.W. Rainwater, K.S. Puentes, S.A. Symes, in: Skeletal Trauma Analysis: Case Studies in Context, John Wiley & Sons, Ltd, Chichester, UK, 2015, pp. 204–221.
[49] P. Mayne Correia, O. Beattie, A critical look at methods for recovering, evaluating, and interpreting cremated human remains, in: Advances in Forensic Taphonomy, 2002.
[50] T.J.U. Thompson, Recent advances in the study of burned bone and their implications for forensic anthropology, Forensic Sci. Int. 146 (2004) S203–S205.
[51] E. Pope, O. Smith, Identification of traumatic injury in burned cranial bone: an experimental approach, J. Forensic Sci. 49 (3) (2004) 1–10, https://doi.org/10.1520/jfs2003286.
[52] J.D. Dehaan, Sustained combustion of bodies: some observations, J. Forensic Sci. 57 (6) (2012) 1578–1584, https://doi.org/10.1111/j.1556-4029.2012.02190.x.
[53] E. Pope, C. Juarez, A. Galloway, Refined classification system for thermally damaged human remains by body segment, Forens. Anthropol. 5(1) (2022), doi: 10.5744/fa.2021.0008.
[54] V. Babrauskas, Estimating room flashover potential, Fire Technol. 16 (2) (1980) 94–103.
[55] S.W. Carman, Improving the understanding of post-flashover fire behaviour, CarmenFireInvestigations.com (2008).
[56] NIST, National Institute of Standards and Technology, 2022.
[57] NFPA, Fire Investigator. Principles and Practice to NFPA 921 and 1033Fifth, Jones and Bartlett Learning, 2019.
[58] S. Svensson, M. van de Veire, Experimental study of gas cooling during firefighting operations, Fire Technol. 55 (1) (2019) 285–305, https://doi.org/10.1007/s10694-018-0790-3.
[59] A. Jones, P.F. Nolan, Discussions on the use of fine water sprays or mists for fire suppression, J. Loss Prevent. Process Ind. 8 (1) (1995) 17–22.
[60] J. Mawhinney, B. Dlugogorski, A. Kim, A closer look at the fire extinguishing properties of water mist, Fire Saf. Sci. 4 (1994) 47–60.
[61] A. Miras, H. Yapo-Ette, C. Vianey-Saban, D. Malicier, L. Fanton, Method for determining if a corpse has been frozen: measuring the activity of short-chain 3-hydroxyacyl-CoA dehydrogenase (SCHAD), Forensic Sci. Int. 124 (1) (2001) 22–24.
[62] M. Taylor, D. Appleton, J. Fielding, G. Oakford, Fire injury analysis, Fire Mater. 46 (6) (2022) 888–895.
[63] Nomis, Office for national statistics, www.nomisweb.co.uk (2020).
[64] I. Miller, P. Beever, Victim behaviours, intentionality, and differential risks in residential fire deaths, Safety Secur. Eng. 82 (2005) 845–854. www.witpress.com.
[65] P.G. Holborn, P.F. Nolan, J. Golt, An analysis of fatal unintentional dwelling fires investigated by London Fire Brigade between 1996 and 2000, Fire Saf. J. 38 (1) (2003) 1–42.
[66] A. Hussain, K. Dunn, Burn related mortality in greater Manchester: 11-year review of regional coronial department data, Burns 41 (2) (2015) 225–234, https://doi.org/10.1016/j.burns.2014.10.008.
[67] D. Icove, J. DeHaan, G. Haynes, Forensic Fire Scene Reconstruction, third ed., Pearson, NJ, 2012. Available: ISBN: 0-13-295620-9.

[68] Spearpoint Michael, K. McGrattan, F. Mowrer, Simulation of a compartment flashover fire using hand calculations, zone models and a field model, in: 3rd International Conference on Fire Research and Engineering, 1999, pp. 3–14.
[69] R.D. Peacock, P.A. Reneke, R.W. Bukowski, V. Babrauskas, Defining flashover for fire hazard calculations, Fire Saf. J. 32 (4) (1999) 331–345.
[70] D. Drysdale, An Introduction to Fire Dynamics, second, John Wiley & Sons, Chichester, 2002.
[71] J. Lentini, Scientific Protocols for Fire Investigation, second ed., CRC Press, Boca Raton, 2012.
[72] P.S. Veloo, J.G. Quintiere, Convective heath transfer coefficient in compartment fires, J. Fire Sci. (2013) 1–14.
[73] J. Handmer, S. O'Neill, Examining bushfire policy in action: Preparedness and behaviour in the 2009 Black Saturday fires, Environ. Sci. Policy 63 (2016) 55–62.
[74] R. Blanchi, J. Leonard, K. Haynes, K. Opie, M. James, F.D. de Oliveira, Environmental circumstances surrounding bushfire fatalities in Australia 1901–2011, Environ. Sci. Policy 37 (2014) 192–203, https://doi.org/10.1016/j.envsci.2013.09.013.
[75] J. Whittaker, K. Haynes, J. Leonard, K. Opie, Experiences of sheltering during the Black Saturday bushfires: implications for policy and research for policy and research [Online]. Available: Wollongong (2017) https://ro.uow.edu.au/smhpapers/4771.
[76] N. Geddes, Vanishing hands and other myths, New Sci. 1956 (2009) 33–35.
[77] L. Capasso, Herculaneum victims of the volcanic eruptions of Vesuvius in 79 AD, Lancet 356 (9238) (2000) 1344–1346.
[78] S.A. Symes, C.W. Rainwater, E.N. Chapman, D.R. Gipson, A.L. Piper, Patterned thermal destruction of human remains in a forensic setting, in: The Analysis of Burned Human Remains, Elsevier, 2008, pp. 15–vi.
[79] P. Shipman, G. Foster, M. Schoeninger, Burnt bones and teeth: an experimental study of color, morphology, crystal structure and shrinkage, J. Archaeol. Sci. 11 (4) (1984) 307–325.
[80] P. Mayne Correia, Fire Modification of Human Remains: A Review of the Literature. Forensic Taphonomy: The Postmortem fate of Human Remains, CRC Press, FLORIDA, 1997.
[81] T.J.U. Thompson, M. Islam, K. Piduru, A. Marcel, An investigation into the internal and external variables acting on crystallinity index using Fourier Transform Infrared Spectroscopy on unaltered and burned bone, Palaeogeogr. Palaeoclimatol. Palaeoecol. 299 (1–2) (Jan. 2011) 168–174, https://doi.org/10.1016/j.palaeo.2010.10.044.
[82] P. Walker, K. Miller, R. Richman, Time, temperature, and oxygen availability: an experimental study of the effects of environmental conditions on the color and organic content of cremated bone, in: Analysis of Burned Human Remains, First., 2008, pp. 129–136.
[83] R. Costagliola, J.-P. Campana, M. Costagliola, Burns and fire disasters, Burns and Fire Disasters XXIX (2016) 289–294.
[84] J.L. McAllister, D.J. Carpenter, R.J. Roby, D. Purser, The importance of autopsy and injury data in the investigation of fires, Fire Technol. 50 (6) (2014) 1357–1377, https://doi.org/10.1007/s10694-013-0341-x.