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Research Paper

A retrospective comparative study to evaluate the reliability of post-mortem interval sources in UK and US medico-legal death investigations

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ABSTRACT

Post-mortem interval (PMI) information sources may be subject to varying degrees of reliability that could impact the level of confidence associated with PMI estimations in forensic taphonomy research and in the practice of medico-legal death investigation. This study aimed to assess the reliability of PMI information sources in a retrospective comparative analysis of 1813 cases of decomposition from the Allegheny County Office of the Medical Examiner in Pittsburgh, US (n = 1714), and the Crime Scene Investigation department at Southwest Forensics in the UK (n = 99). PMI information sources were subjected to a two-stage evaluation using an adapted version of the 3x5 aspects of the UK police National Intelligence Model (NIM) to determine the confidence level associated with each source. Normal distribution plots were created to show the distribution frequency of the dependent variables (decomposition stage and source evaluation) by the independent variable of PMI. The manner, location, and season of death were recorded to ascertain if these variables influenced the reliability of the PMI. A confidence matrix was then created to assess the overall reliability and provenance of each PMI information source. Reliable PMI sources (including forensic specialists, missing persons reports, and digital evidence) were used across extensive PMI ranges (1 to 2920 days in the US, and 1 to 240 days in the UK) but conferred a low incidence of use with forensic specialists providing a PMI estimation in only 35% of all homicide cases. Medium confidence PMI sources (e.g., last known social contact) accounted for the majority of UK (54%, n = 54) and US (82%, n = 1413) cases and were associated with shorter PMIs and natural causes of death. Low confidence PMI sources represented the lowest frequencies of UK and US cases and exclusively comprised PMI information from scene evidence. In 96% of all cases, only one PMI source was reported, meaning PMI source corroboration was overall very low (4%). This research has important application for studies using police reports of PMI information to validate PMI estimation models, and in the practice of medico-legal death investigation where it is recommended that i) the identified reliable PMI sources are sought ii) untested or unreliable PMI sources are substantiated with corroborating PMI information, iii) all PMI sources are reported with an associated degree of confidence that encapsulates the uncertainty of the originating source.

1. Introduction

Estimating the post-mortem interval (PMI), the time between death and discovery, has many applications for the practice of medico-legal death investigation at scenes of decomposition [1–3]. For most non-suspicious and natural causes of death, which constitute the vast majority of deaths [4], the PMI is often sought by family members of the deceased for emotive reasons. In missing persons cases, an accurate PMI can assist the police in identifying the deceased. Arguably, the most critical application of the PMI is in homicide investigations, where the PMI can be used to identify potential suspects, corroborate witness statements, and produce leads for CCTV and technology-related enquiries [2].

Obtaining an accurate PMI estimation presents a major challenge

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due to the vast array of extrinsic and intrinsic variables that influence the decomposition process [4–6]. Despite the wealth of forensic taphonomy research into these variables, their interrelationships on the rate and pattern of decomposition remain largely uncertain [4]. In medico-legal death investigations, where only a 'snapshot' of decomposition is encountered upon body discovery, the onset of variables, along with their associated effects, at best may be uncertain, or at worst, unknown [5]. Inherently, this presents further difficulties when estimating a PMI from the level of observed decay. Furthermore, the predictability of the PMI decreases as the time frame since death increases. Therefore, the estimated PMI is currently associated with low confidence in the practice of medico-legal death investigation [6].

In medico-legal death investigations, it is routine practice for investigators to obtain a reported PMI from various available circumstantial sources of information. This could include witness statements from family members or friends detailing the last time the deceased was known to be alive, dates from newspapers, TV guides, or unopened mail, days crossed off on a calendar, the last written entry of a personal diary, suicide notes, and technology-related advances such as their last access to social media accounts, mobile phone, and CCTV records [4,7–10]. Unlike the complex interrelationships of extrinsic and intrinsic decomposition variables, the sources of the reported PMI information are consistently known and are often relied on to conclude a PMI estimation. Arguably, these sources confer different levels of reliability, which no study has yet attempted to quantify.

In non-suspicious deaths, these circumstantial sources are sufficient to conclude a PMI estimation, which is nearly always given as a range (rather than a specific time or date) to reflect associated uncertainty. In homicide cases, when more accurate PMI estimations are required, this circumstantial evidence is often deemed too imprecise [4]. This prompts the engagement of forensic specialists (forensic pathologists, forensic anthropologists, and forensic entomologists) to provide expert opinions on PMI estimations which serve to corroborate the circumstantial evidence obtained by police. Using the level of observed decomposition to estimate the PMI is generally considered unreliable as it is complicated by the differential decomposition that results from taphonomic variables [2]. Consequently, forensic specialists estimate the PMI using a combination of their education and experience [11]. Even in forensic entomology, which arguably produces more accurate PMI estimations, the PMI is still reported as a range in what is termed the 'minimum PMI' based on estimates of larval age [5]. This provides further evidence that the confidence in PMI estimations is overall relatively low in the practice of medico-legal death investigations.

Despite the wealth of forensic taphonomy research that has attempted to devise reliable models of PMI estimation over the past 40 years, there is currently no single, accurate method of PMI estimation used routinely in medico-legal death investigations [3]. This is likely due to a shortfall in reliably quantifying the effect of complex taphonomic variables on the decomposition state [12]. Accumulated degree-days (ADD) is the most researched variable and accounts for the effects of both temperature and time on decomposition accumulation and subsequent PMI estimations [7]. While ADD-based PMI prediction models provide a theoretical solution to model decomposition variability across different geographical regions, there is no consistent agreement on the quantification of the ADD effect, with results ranging from 25 to 94% [3,13–15]. This inhibits the transferability of results to produce a practical solution for medico-legal PMI estimations.

Retrospective case study analysis offers large sample sizes of forensic decomposition cases in an attempt to validate PMI estimation models [4,7–10]. In these studies, the reported PMI is usually taken from law enforcement or police reports that detail the aforementioned sources of the PMI information, such as electronic communication, witness statements, and other circumstantial evidence. These sources of PMI information are likely to confer varying degrees of reliability. Explanations for model failings are often attributed to errors within the model itself [14], or the uncontrollable effects of taphonomic variables [4], while only a handful acknowledge that the reported PMI could present a source of bias [8,11,16]. Furthermore, several studies assume the same relative error of the 'known' PMI throughout the datasets, regardless of the information source from which it is derived [8,11]. Arguably, if unreliable PMIs are used as the source of PMI model validation, it impedes the ability to measure the model's effectiveness and questions the overall validity of the results.

The minimum criteria for sample inclusion in retrospective taphonomic studies is a known PMI. Witness statements and suspect confessions are considered reliable PMI sources, given that they originate from police and law enforcement reports [4]. Megyesi et al. [7] study of developing a sequential decomposition scoring system to estimate the PMI was based on 68 cases of 'known' PMI from circumstantial evidence of suicide notes and confessions in police reports and entomological evidence. However, there was no differentiation between the reliability of their PMI information sources, and it was later recognised that the entomologically derived PMI estimations were deemed unreliable in the absence of reporting the associated error rate [16]. This suggests that researchers are questioning what constitutes a reliable reported PMI in these retrospective studies; however, no study has yet quantified the reliability of the varying sources of PMI information.

This study aims to quantify the reliability of the reported PMI sources in medico-legal death investigation reports of decomposition cases. This is essential to forensic taphonomy research (if this information serves a primary purpose in PMI validation studies) and in the practice of medico-legal death investigation where actual PMI estimations could be reported with an associated degree of confidence that encapsulates and quantifies the uncertainty of the reported PMI source. The latter concept is by no means unfamiliar to the police. The National Intelligence (3x5x2) model (NIM) is currently used by UK police forces to quantifiably grade the reliability of all intelligence information [17]. The NIM harbors the benefits of standardising reported information so that it can be communicated in a consistent and effective manner between police forces. In addition, the NIM enables analysts to communicate a level of confidence associated with the reported information, using agreed predictive language that also measures the strength of the source reliability [18]. This study seeks to apply an adapted version of the NIM (3x5x2) model to sources of reported PMI information so that its reliability can be graded, and any uncertainty can consequently be expressed with a quantifiable level of confidence. Importantly, this could lead to more reliable PMI estimations in forensic taphonomy research and in the practice of medico-legal death investigations.

2. Method

This comparative study was conducted using retrospective data of decomposition cases from the United States (US) and the United Kingdom (UK).

2.1. Allegheny County Office of the Medical Examiner

In the US, research was undertaken at the Allegheny County Office of the Medical Examiner (ACOME) in Pittsburgh, Pennsylvania. The ACOME provides medico-legal death investigation for sudden, unnatural, and violent deaths across Allegheny County in Pittsburgh, which has 1.2 million people [19]. It has a unique infrastructure in housing a morgue operation service (including a forensic investigation, autopsy suite, and histology departments) and a plethora of forensic laboratory services in the same building.

After being notified of a death by the Emergency Medical Service (EMS) or police; the forensic investigators (FI) gather detailed information on the circumstances surrounding the death, such as medical history, body condition, and demographic data to triage cases that fall under the jurisdiction of the Medical Examiner [19]. The forensic investigators (FI) then attend the scene to conduct a further investigation with law enforcement, including photographic documentation of the scene and evidence, establishing the deceased's identity, and evaluating post-mortem changes and traumatic injuries of the body in-situ. The deceased is then transported back to ACOME and stored in a morgue cooler until the commencement of an autopsy examination, if required.

Case information was extracted from death investigation case reports stored in the ACOME Medical Examiner's Information Management System (MEIMS). The death investigation reports are completed by the forensic investigators and contain four sections. First, a 'general death information' form of demographic data, medical history, and the official time of death, recorded upon initial notification of the death by the Emergency Medical Services (EMS) or police. Second, a 'report of the scene investigation' including the location of death, body position, ambient temperature, and details of rigor mortis following the FI scene attendance. Third, a 'body intake information' such as the weight and height of the deceased. Fourth, a free-text 'story' or narrative of contemporaneous scene observations including circumstantial and contextual information leading to the death, the identification of the deceased, and an analysis of the body in-situ (evaluation of post-mortem changes and traumatic injuries). Importantly, this section details the reported PMI (calculated as the number of whole days between death and discovery) and the origin or source of this information.

2.2. Southwest Forensics

In the UK, decomposition cases were collected retrospectively from the Crime Scene Investigation (CSI) department in Southwest Forensics (SWF), which is a collaboration of 4 police forces across the southwest region: Wiltshire, Dorset, Devon and Cornwall, and Avon and Somerset which has a combined population of 4.6 million people. CSI will be notified of an unexplained or sudden death via the central control room or by the first attending officer (FAO). The CSI will then attend the scene, usually accompanied by a police officer from the Criminal Investigation Department (CID). The CSI will be responsible for scene and evidence documentation through photography and scene notes and will assist CID in ruling out any suspicious or third-party involvement. If the death is deemed non-suspicious, then a routine hospital post-mortem will ensue. If the death appears suspicious, a Crime Scene Manager (CSM) will then be requested to the scene, and after further examination, a Home Office post-mortem will be conducted to determine the cause and manner of death the cause and manner of death [20]

The CSI department utilises a forensic case management system, termed Socrates, which was centralised across SWF in 2015 to facilitate crime scene data sharing between the four geographical regions. Socrates enables the recording of demographic case details and contains a free-text section for CSI scene notes. The origin or source of PMI information was detailed in this free-text section.

2.3. Case selection

A total of 2163 cases involving adult individuals in a state of decomposition were available for analysis from both the US and UK datasets (Fig. 1). In the US, decomposition cases were extracted retrospectively from ACOME's MEIMS over 10 years between 2007 and 2016 (n = 2011). Each decomposition case had a one-word descriptor of the decay level that was pre-assigned by autopsy technicians in consultation with forensic pathologists. The codes were as follows: 'early decomposition', 'moderate decomposition' (interchangeable with 'bloat' phase [7]), 'advanced decomposition', 'mummification', and 'skeletonization'. Adipocere, an alternative decomposition process characterised by the formation of a whitish-waxy substance produced during the saponification of fat tissue, was encompassed under the 'advanced decomposition' code due to its association with late-stage decomposition [21]. Cases exhibiting adipocere were determined when the investigator's report referenced adipocere. All adipocere cases were exclusively associated with the 'advanced decomposition' code.

The remaining cases were collected retrospectively from SWF CSI over 5 years between 2015 and 2019 (n = 152). The stage of decomposition was extracted from the CSI scene notes and confirmed by viewing the scene/and or post-mortem photographs. For consistency across the datasets, the same aforementioned decomposition codes were used. For example, if scene notes stated, 'skin slippage', this was assigned 'early decomposition' as per the canonised stages of decomposition in the forensic taphonomy literature [7,22]. If adipocere was recorded in the CSI scene notes, this was assigned 'advanced decomposition' as it was in the ACOME dataset.

This study aimed to assess the reliability of the reported PMI information in decomposition case reports between the US and UK datasets. The sample inclusion criterion required an available reported PMI and details of the origin of the PMI information source. Cases were excluded from both datasets if the PMI was unknown (ACOME n = 297, SWF n = 53) (Fig. 1). Therefore, the final sample size for ACOME was 1714 cases, compared to 99 cases in SWF. The final overall sample comprised 1183 decomposition cases with a reported PMI that contained an identified origin of the information source. While the population of the SWF area (4.6 million) is greater than the ACOME jurisdiction (1.2 million), the number of decomposition deaths per total of the respective populations was greater in ACOME (0.14%) vs. SWF (0.002%).

2.4. Recorded variables

A number of variables were recorded from each case to identify any patterns or trends that may influence the reliability of the reported PMI. These were categorised according to intrinsic variables (including demographic data and the cause and manner of death) and extrinsic variables (location of death and meteorological seasons).

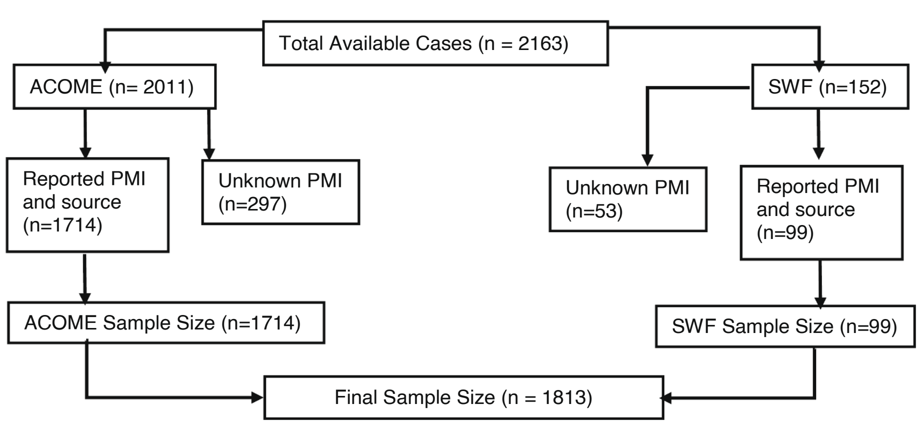

Fig. 1. ACOME and SWF Decomposition Case Selection.

2.5. Assessment of the PMI

In both ACOME and SWF datasets, the last known alive date and source of this information were extracted from the FI or CSIs scene notes, respectively, in 1813 cases. The PMI (in whole days) was then calculated from the documented last known alive date to the date of discovery.

The PMI information was categorised according to the source from which the information was obtained (Table 1). Each source was then assigned a code consisting of a number and sequential letter (e.g., 1A = CCTV). Sources of a similar origin were grouped by the same number (e.g., all source codes starting with the number 1 related to digital PMI information) (Table 1). Assigning codes to the source of the PMI information was necessary to make the large dataset receptive to quantitative handling and to ensure consistent and accurate recording of PMI sources. There was a total of 32 PMI information source codes.

2.6. Reliability assessment of PMI information

UK police and law enforcement agencies use the 3x5x2 grid derived from the National Intelligence Model (NIM) to grade the reliability of intelligence information. In the 3x5x2 grid, the '3′ represents source evaluation, '5′ denotes intelligence evaluation and, '2′ refers to the handling and dissemination conditions of the intelligence information. For intelligence to be shared, there must be a legitimate policing purpose, such as protecting life and preventing the commission of offences [17]. Since the event of death has already occurred and the PMI information does not serve a purpose to prevent crime, the '2′ intelligence handling conditions were removed. In this study, the coded PMI information was therefore, subject to a 2-stage evaluation using only the 3x5 aspects of the model and graded by the primary author who has received police intelligence training and is experienced in using the 3x5x2 NIM model in police casework.

The first stage, 'source evaluation', evaluates the source reliability and establishes the credibility of the information [17]. There are three defined options for source evaluation: i) reliable (e.g., CCTV and technical products), ii) untested (where the information may or may not be reliable, but it has not been substantiated, e.g., information from members of the public) and, iii) unreliable (where there are reasonable grounds to doubt the reliability of the source, e.g., information received to the source by unknown third-party information) [17].

The second stage, 'intelligence assessment', evaluates the reliability of the information and its origin. There are 5 possible options denoted alphabetically by grades (A-E) [17]. Grade A is 'known directly to the source', where information has been witnessed first-hand, e.g., a confirmed eye-witness account of the death. Grade B is 'known indirectly to the source but corroborated'. The source may not have witnessed the information, but the reliability can be verified by the corroboration of independent sources that confer the latter 'A' grade. For example, if the PMI information is obtained from scene evidence such as a receipt, this information is indirectly known by investigators as they were not present when the person purchased the item. However, if the date on the receipt can be corroborated by information graded 'A' (e.g., last known sighting of the deceased by a family member), this would result in a Grade B intelligence assessment. Grade C refers to information 'known indirectly to the source' and can be defined by Grade B's description, but without a corroborating source. Grade D is 'not known', where there is no means of assessing the information. Finally, Grade E refers to information that is 'suspected to be false', regardless of the origin of the source [17].

The resulting source evaluation and intelligence assessment grades were then inputted into a confidence matrix which, in police terms, indicates the confidence level for intelligence dissemination [17]. In this study, the confidence matrix was used to interpret the confidence level in the overall reliability of the reported PMI and the originating source of this information.

Table 1
Sources of PMI Information.

Code	PMI Source	Source Description
Digital		
1A	CCTV	Dated and timed video surveillance showing the person alive or at the moment of death. In some homicide cases, this could include footage of the deceased being transported by offender(s).
1B	Mobile phone records	Mobile phone records including dates and times of last dialled calls, last sent messages, drafted notes, etc.
1C	Internet access	Laptop or computer browser history showing dates and times of most recent website access.
1D	Email	Time and date of last sent emails from laptops, computers, mobile phones, or other electronic devices.
1E	ANPR	Automatic Number Plate Recognition reads vehicle registration plates to detect and track vehicle locations.
1F	Swipe card access	Key card entry to buildings (e.g., place of work or hotel), including the date and/or time of entry and exit of location.
1G	Bank transaction	Bank transaction history, including time and date of last credit/debit card purchases or outgoing money transfer.
People		
2A	Witnessed death	A third party has witnessed the death.
2B	Suspect confession	In homicide cases, a suspect has provided a full confession to police detailing the time and date of death.
2C	Social contact	Last known social contact with deceased obtained from family, friends, neighbours, etc. Including the last seen alive time and date.
Organisations		
3A	Police incident	Last known sighting following a police incident involving the person (deceased).
3B	GP appointment	Last known sighting by GP appointment.
3C	Hospital discharge	Last known sighting by discharge from hospital or hospital appointment.
3D	Colleagues	Last known sighting by colleagues in the workplace.
3E	Community services	Last known sighting by community health services includes home carers, home nursing visits, meals, medication delivery, etc.
3F	Building manager/ landlord	Last known sighting by a building manager or landlord.
3G	Hotel staff	Last known sighting by hotel staff in hotel accommodation, confirmed by check-in/check-out times.
3H	Other professional service	Last known sighting by any other professional service or organisation.
Scene Evidence		
4A	Newspapers	Most recent newspaper date.
4B	Mail	Date of last opened mail or date of first unopened mail.
4C	Receipts	Time and date of most recent purchase as displayed on the receipt.
4D	Food & drink	Expiration date of food and/or drink products.
4E	Diary	Dated diary with last written entry.
4F	Calendar	Dated calendar with last crossed off day.
4G	Dated suicide note	Dated suicide note believed to be written by deceased at the time of death.
4H	Dated cheque	Last dated cheque in the handwriting of deceased.
4I	Marked medication packet	Last pill/tablet taken on medication packets marked with the day of the week.
4J	Television guide	Date of the page on an opened television guide or date range of television guide.
Forensic Specialists		
5A	Forensic Pathologist	Expert opinion from external and internal post-mortem indicators of time since death (PMI).
5B	Forensic Entomologist	Estimating PMI from developing larval stages.
5C	Forensic Anthropologist	Expert opinion on the level of decomposition to estimate a PMI.
Missing Persons		
6A	Missing persons report	Police confirmed missing persons report that detailed the last known alive time and date.

2.7. Statistical analysis

All statistical analysis was conducted using XLSTAT software (version 2020.5.1) in EXCEL. Frequency distribution tables were first constructed to show the frequency of cases distributed over the PMI by i) the stage of decomposition, ii) PMI source evaluation (reliable, untested, and unreliable), and iii) the PMI confidence matrix (high, medium, and low). The PMI (in days) is a measure of time and was, treated as an independent, continuous variable. However, when presenting the mean PMI day for each information source category, the PMI was treated as a dependent variable for ease of graphical representation. The stage of decomposition, PMI source evaluation, and PMI confidence matrix, although defined as categorical variables, were transformed to continuous data by their frequency counts and were treated as dependent variables.

Normal distribution is a continuous probability function commonly employed to find the distribution of the data and depends upon calculating the mean and standard deviation of the dataset. Normal distribution plots were created to show the distribution frequency of the dependent variables (decomposition stage and source evaluation) by the independent variable of PMI. The specified mean and standard deviation of the PMI were calculated according to each dependent variable dataset. For example, the normal distribution plot for the decomposition stage was calculated by the specific mean PMI and associated standard deviations for early, moderate, and advanced decomposition cases.

Excess kurtosis was calculated as a statistical measure of curve skewness and to describe the distribution tails, which indicate the density of outliers relative to the mean of the distribution [23]. Excess kurtosis values can range from −3 (a platykurtic distribution with fewer and 'less extreme' outliers) to infinitely positive (a leptokurtic distribution, characterised by more and 'greater extreme' outliers) compared to the normal distribution, which has a kurtosis of 0.

A two-sample Kolmogorov-Smirnov test (KS) was used to determine significant differences between the UK and US in the distribution curves of dependent variables (decomposition stage and source evaluation) by the independent variable of PMI. The K-S test is a non-parametric test suitable for assessing if two independent samples of data (in this case, the UK and the US) follow the same distribution, irrespective of sample size. The K–S test generates a D statistic, the maximum deviation between the two samples tested which measures the effect size denoted as: $D = Z\sqrt{n1n2/n1 + n2}$ (where Z is the test statistic and n is the number of observations) [24]. The higher the D value, the greater the variance between two samples, with statistical significance considered at $p \leq 0.05$.

Frequency graphs were also created to show the PMI source evaluation and PMI confidence distribution according to the intrinsic (manner of death) and extrinsic variables (location and season of death). This determined whether certain variables influenced the overall reliability and assessment of the reported PMI information. For example, assessing which manners of death were associated with higher frequencies of 'reliable' or 'high confidence' PMI information.

3. Results

3.1. Overall descriptions

There was a greater predominance of males in both the US (73%, n = 1250) and UK (78%, n = 77) datasets compared to females (27% US v 22% UK). The age range of the US sample was 18 to 97 years, with a mean age at death of 58 years (SD ± 15.1). The UK comparative was 21 to 89 years with a mean age at death of 54 years (SD ± 15.5). The most common manner of death in both datasets was 'natural', accounting for 65% of the US deaths (n = 1112) and 63% of the UK deaths (n = 62). This was followed by 'accidental': (20% US v 14% UK), 'suicide' (10% US v 12% UK) and 'undetermined' (3% US v 8% UK). Homicides accounted for the lowest proportion of all manners of deaths in both the US (2%, n = 31) and UK 3%, n = 3) datasets.

There was a total of 21 different causes of death assigned across the dataset, with the most common being a 'natural process or disease' in the US (65%, n = 1109) and the UK (59%, n = 58), with atherosclerotic cardiovascular disease accounting for 10% of both US (n = 183) and UK (n = 10) manners of death. 'Drugs and/or poisoning' presented the subsequent highest frequency in both datasets (20% US v 14% UK). Deaths resulting from trauma were comparably similar (7% US v 8% UK); however, the US had a greater number of 'firearms-related deaths (4%, n = 113) compared to the UK (1%, n = 1). The cause of death was undetermined due to advanced decomposition in 2% of the US sample and 4% of the UK sample.

The samples predominantly consisted of indoor deaths: 97% in the US (n = 1669) and 75% in the UK (n = 74). In the UK, all indoor deaths occurred inside a private residence, and most US indoor deaths occurred inside a private residence (99%, n = 1644). In the remaining 1% of US indoor cases, the deaths occurred inside a public building (n = 15) or vehicle (n = 10). Outdoor deaths made up the remaining death location in the US (3%, n = 45) and the UK (25%, n = 25). Of the outdoor deaths, woodland was the most common outdoor death location in the US (40%, n = 18) followed by the road (27%, n = 12), field or rear garden (16%, n = 7), water (e.g., sea, lake, river) (13%, n = 6), and buried (4%, n = 2). Conversely, a field or rear garden was the most common outdoor death location in the UK sample (32%, n = 8), followed by woodland (24%, n = 6) and water (24%, n = 6), then the road (n = 20%, n = 5). There were no burials present in the UK dataset.

Meteorological seasons were evenly distributed throughout both datasets. In the US, the highest number of deaths occurred in summer (28%, n = 486), followed by spring (25%, n = 431), winter (24%, n = 417) and autumn (23%, n = 380). In the UK, autumn was the most frequent season of death (32%, n = 32), followed by summer (25%, n = 25) and then spring and winter (each accounting for 21%, n = 21).

The reported PMI was calculated in whole days and ranged from 1 to 2920 days, with a mean PMI of 11 days (SD ± 92.2) for US cases. UK cases had a shorter PMI range: 1 to 575 days but a higher mean PMI of 46 days (SD ± 82.5). The percentage frequency distribution of PMI days showed a predominance of shorter PMIs in the US dataset, where approximately 76% of all US cases fell between 1 and 7 PMI days (n = 1309) with a modal PMI of 2 days (n = 270) (Fig. 2). The comparative UK data showed PMI days were more evenly distributed, with 49% of cases falling between 1 and 14 PMI days (n = 48) and the remaining 51% of cases falling between 15 to > 300 days (n = 51). The UK had a consistently higher percentage of cases at longer PMIs between 14 and 300 days (representing 58% of all UK cases (n = 57)) when compared to the US (13%, n = 221) over the same PMI range.

All stages of decomposition were represented in the dataset. In the US, early decomposition was assigned most frequently in 54% of cases (n = 933). This was followed by moderate decomposition (also referred to as 'bloat' [7]) (27%, n = 462), advanced decomposition (16%, n = 278), mummification (2%, n = 28) and skeletonization (1%, n = 13). Therefore, as the decomposition stage progressively increased, the frequency of cases decreased. Conversely, in the UK, moderate decomposition was most prevalent (36%, n = 36), followed by advanced decomposition (30%, n = 30), early decomposition (18%, n = 18), mummification (8%, n = 8) and skeletonization (7%, n = 7).

The frequency distribution of the PMI for early, moderate, and advanced cases of decomposition presented asymmetrical and positively skewed curves for both the UK and US (Fig. 3). Since the PMI value cannot be less than zero days, this imposed a boundary on the left-hand side of Fig. 3, where data values clustered, typical of positively skewed distributions. This was unsurprising for early decomposition, given that it is the first stage of decomposition that correlates with early PMIs.

Both UK and US early decomposition cases presented a leptokurtic skewness as indicated by an excess kurtosis of +12.2 (UK) and +5.2 (US), respectively. The higher, narrower central peak characterised the leptokurtic skewness with a greater density of cases clustering around

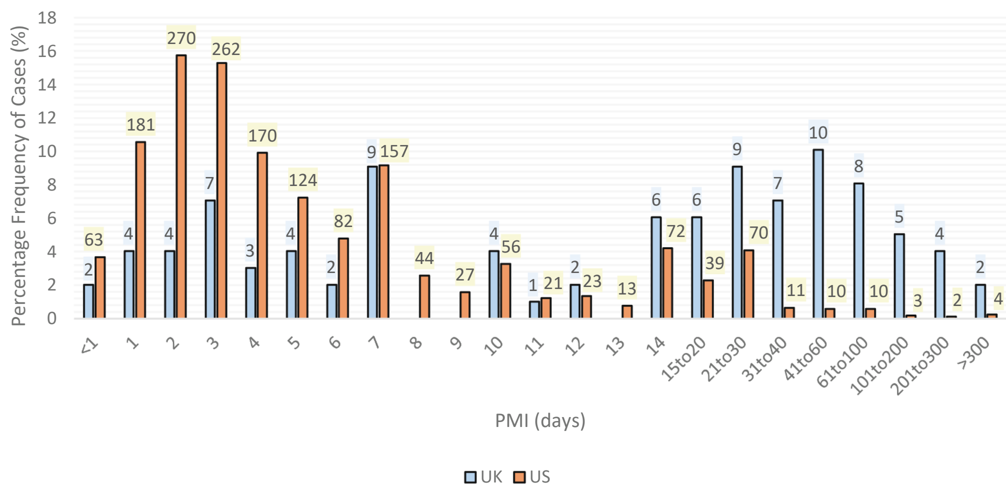

Fig. 2. Percentage Frequency Distribution of PMI days for the UK (n = 99) and US (n = 1714) datasets. While PMI was a continuous variable it is presented categorically here in order to create sub-groups for PMIs greater than 14 days that showed decreasing frequency. Number in box above each bar presents the frequency of cases (n).

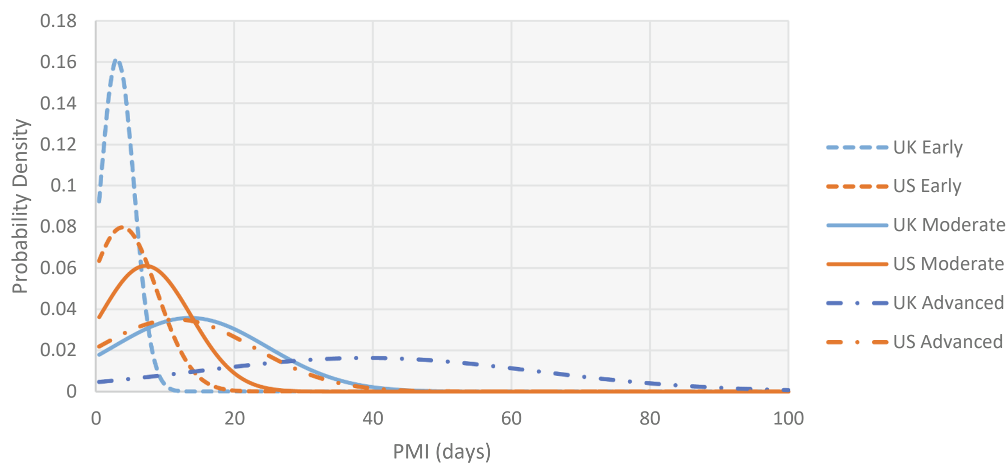

Fig. 3. Frequency distribution of PMI by decomposition stage for UK (blue) and US (orange) datasets (n = 1737 cases). Graph excludes the following cases from both datasets: >100 PMI days (n = 20), mummification (n = 36) and skeletonization (n = 20).

the means (Fig. 3). The UK peak for early decomposition cases was higher than the comparative US peak as indicated by these excess kurtosis values (Table 2). However, the K-S test revealed no significant differences in the PMI distribution of early decomposition cases between the UK and the US (D = 0.033, p ≥ 0.05, n = 951). Since the D value was close to 0, this indicated comparable variability in the PMI for early decomposition between the UK and US.

The curves for moderate decomposition shifted slightly to the right for both UK and US cases but were still positively skewed. UK cases had a greater mean PMI for moderate decomposition (14 PMI days ± 11) compared to the US (7 PMI days ± 6.5). The excess kurtosis of the moderate decomposition curve for the UK indicated a platykurtic distribution, reflected by the lower and broader central peak, with greater variability in PMI ranges between 2 and 46 days, compared to early decomposition cases (Table 2). Conversely, the excess kurtosis of the moderate curve for US cases indicated a leptokurtic skewness characterised by the narrower, taller peak, with less PMI variability (2 to 31 days) (Fig. 3). Despite these observable differences, the K-S test

Table 2
Normal Distribution Data for Decomposition Stage by the PMI for the UK (n = 99) and US (n = 1714) cases.

	UK				US			
	Mean PMI (days (±SD))	PMI Range (days)	Excess Kurtosis	Distribution	Mean PMI (days (±SD))	PMI Range (days)	Excess Kurtosis	Distribution
Early	3 (±2)	<1–10	+12.2	Leptokurtic	4 (±5)	<1–88	+5.2	Leptokurtic
Moderate	14 (±11)	2–46	−0.5	Platykurtic	7 (±6.5)	2–31	+2.2	Leptokurtic
Advanced	39 (±24.5)	6–97	−1.3	Platykurtic	12 ± 11.4	3–47	−0.4	Platykurtic
Mummification	160 (±11.1)	90–224	0.00	Normal	144 ± (535.5)	12–2920	−1.1	Platykurtic
Skeletonization	227 (±180.7)	41–575	−1.2	Platykurtic	296 ± (560.5)	15–2190	−1.2	Platykurtic

revealed that the PMI distributions of moderate decomposition between the UK and the US were statistically insignificant ($D = 0.064$, $p \geq 0.05$, $n = 498$), meaning the PMI variability of moderate cases was indistinguishable between the UK and the US.

Both UK and US advanced decomposition cases presented platykurtic distributions with lower and wider central peaks than their respective moderate curves. However, advanced decomposition in the UK and the US represented the greatest variation in PMI compared to the early and moderate stages. The broader range of PMIs reflected this for advanced decomposition in both the US (3 to 47 days) and the UK (6 to 97 days) (Fig. 3). The mean PMI for advanced decomposition cases was much higher in the UK (39 ± 24.5 days) compared to the US (12 ± 11.4 days). The K-S test found statistically significant variation in the PMI distribution of advanced decomposition cases between the UK and US ($D = 0.196$, $p \leq 0.05$, $n = 308$).

Interestingly, the platykurtic distribution of advanced decomposition in the US was similar to the platykurtic distribution of UK moderate decomposition (Fig. 3) with a mean PMI of UK moderate cases (14 ± 11.1 days) close to the mean PMI of US advanced decomposition (12 ± 11.4 days) (Table 2). This was likely due to environmental differences between both countries, meaning advanced decomposition is reached more quickly in the humid, continental climate of Allegheny County compared to the UK's milder, temperate climate.

Mummification (n = 36) and skeletonization cases (n = 20) presented the greatest variability in PMI distribution (Table 2). Mummification had a higher mean PMI for the UK (160 ± 11.1 days) compared to the US (mean PMI 144 ± 535.5 days), whereas skeletonization cases had a higher PMI for the US (296 ± 560.5 days) than the UK comparative (227 ± 180.7 days). However, there was greater variability in the PMI range for US cases in both mummification (12 to 2920 days) and skeletonization (15 to 2190 days) than in the UK (mummification 90 to 224 days and skeletonization 41 to 575 days). The K-S test showed statistically significant differences between the PMI distribution of mummification cases ($D = 0.621$, $p \leq 0.05$, $n = 36$) and skeletonization cases ($D = 0.865$, $p \leq 0.05$, $n = 20$) between the UK and US. The higher D statistic for skeletonization cases indicated that the PMI varied to a greater extent than in mummification cases.

3.2. PMI sources

Each case had at least 1 PMI source in the UK (n = 99) and US (n = 1714). In the UK, 62% of cases used more than 1 PMI source, attributed to 45 cases of 2 PMI sources and 17 cases of 3 PMI sources. Conversely, in the US, only 5% of cases used more than 1 PMI source (n = 79). Of these 79 cases, 78 used 2 PMI sources, and only 1 case used 3 PMI sources.

The most common source of PMI information originated from the 'people' category accounting for 55% of the UK sample (n = 73) and 70% of the US sample (n = 1270). The least common PMI source used was 'forensic specialists' accounting for approximately 1% of the total sources used in both datasets (n = 2, UK and n = 12, US). Compared to the US, UK cases had a higher percentage of PMI sources derived from 'scene evidence' (34%, n = 55 v 10% n = 187), 'digital evidence' (10%, n = 16 v 3%, n = 16) and 'missing persons reports' (6%, n = 10 v 2%, n = 28), whereas the US had a higher proportion of PMI sources derived from 'organisations' (14%, n = 250 v 3% n = 5).

'Social contact' (2C) was the most frequent source of PMI information in both the US (70%, n = 1247) and the UK (40%, n = 65) (Fig. 4). Within each category, the frequency of PMI information sources was unevenly distributed. For example, 'mail' (4B, n = 121 US, and n = 18 UK) was the most common source of PMI information of 'scene evidence' sources, whereas 'diary' (4E), 'calendar' (4F), 'TV guide' (4 J) and were far less frequently used (Fig. 4). In cases relying on forensic specialists to estimate the PMI, the 'forensic pathologist' (5A) was used more frequently than the forensic entomologist (5B) or forensic anthropologist (5C) in both the UK and US. Mobile phone records (1B) were the most frequent source of digital PMI information for the US (n = 32) and the UK (n = 6), along with CCTV (1A) (n = 6). PMI information derived from organisations was more frequent in the US dataset, with the last sighting by colleagues (3F) used in 101 cases, whereas the UK had no cases of this. The UK also did not attain PMI information from swipe card access (1F), bank transactions (1G), 3d (colleagues) to 3G (hotel staff), and the forensic entomologist (5B). Conversely, the US used a greater number of PMI sources but did not aquire PMI information ANPR (1E) or shelf life of food and drink items (4D) (Fig. 4).

Fig. 4 also displays the mean PMI by the codes of PMI information sources (Table 1). Except for missing persons, the US had a lower mean PMI for all information sources than the UK. Forensic pathologists had the lowest mean PMI of 2 days (n = 13, STD ± 0.7) for the UK and US. Similarly, 'organisations' were used between 1 and 60 days and had a shorter mean PMI of 5 days (UK, STD ± 4.8) and 7 days (US, STD ± 7.5). Conversely, PMI information derived from missing persons reports were used across extensive PMI ranges (1 to 2190 PMI days) and had the second-highest mean PMI of 90 days (UK, n = 10, STD ± 97) and 101 days (US, n = 28, STD ± 403) when compared to all other PMI sources. In the US, suspect confessions conferred the longest mean PMI of 975 days (n = 3), whereas, in the UK, receipts presented the longest mean PMI of 104 (n = 7) (Fig. 4).

PMI sources derived from social contact were used between 1 and 365 days in both datasets; however, social contact conferred a longer mean PMI in the UK (34 ± 52 days) compared to the US: 7 PMI days (n = 1247, STD ± 19). Digital sources and scene evidence were used across extensive PMI ranges in the UK: 1 to 240 days (digital) and 1 to 575 days (scene). The mean PMI of all digital sources in the UK was 23 (STD ± 57 days) compared to 9 (STD ± 13 days) in the US (data not shown). 'Social contact' was combined with at least one other PMI source in 83% of cases (n = 105) and was most commonly combined with 'scene evidence' codes (4A-4E) (n = 81), of which 'mail' (4B) was the most frequent (n = 53) (Fig. 4). Interestingly, different sources of PMI information contained within the 'scene evidence' category were combined with each other in 13% of cases (n = 18). For example, 'newspapers' (4A) and 'mail' (4B) were common to the 'scene evidence category' and were combined in 5 cases. Furthermore, in the 18 cases with 3 PMI sources, 'scene evidence' codes were present as one of the corroborating PMI sources in 77% of cases (n = 14).

When assessing cases that used multiple PMI sources, it was found that social contact was combined with at least one other PMI source in 81% of the US cases of >1 PMI source (n = 84) and 60% of UK cases of >1 PMI source (n = 37). In both the US and UK, social contact was most commonly combined with 'scene evidence codes' (4A-4E), of which 'mail' (4B) was the most frequent substantiating source in both the US (n = 40) and the UK (n = 10).

3.3. PMI source and decomposition stage

As the decomposition stages progressed from 'early' to 'skeletonization', fewer PMI sources were used; however, this could be due to the decreasing frequency of cases represented at each decomposition stage. Early decomposition was fairly evenly distributed across 'digital', 'people' and 'organisations' in the US, accounting for 55 to 60% of cases in these categories. 'Scene evidence' was most frequently used as a PMI source for moderate decomposition cases (35%, n = 66). 'Forensic specialists' had the highest proportion of 'early' decomposition, with 75% of the cases representing this decomposition stage (n = 9). No forensic specialists were used for mummification or skeletonization cases in the US. 'Missing person's accounted for the greatest proportion of 'advanced' decomposition (43%, n = 12) and 'mummification' (21%, n = 6). Digital sources were used for all US skeletonization cases (n = 7), representing 3% of the US digital category. The 'people' category was the only PMI source that represented every decomposition stage in the US data.

Conversely, in the UK, 'people', 'scene evidence' and 'missing

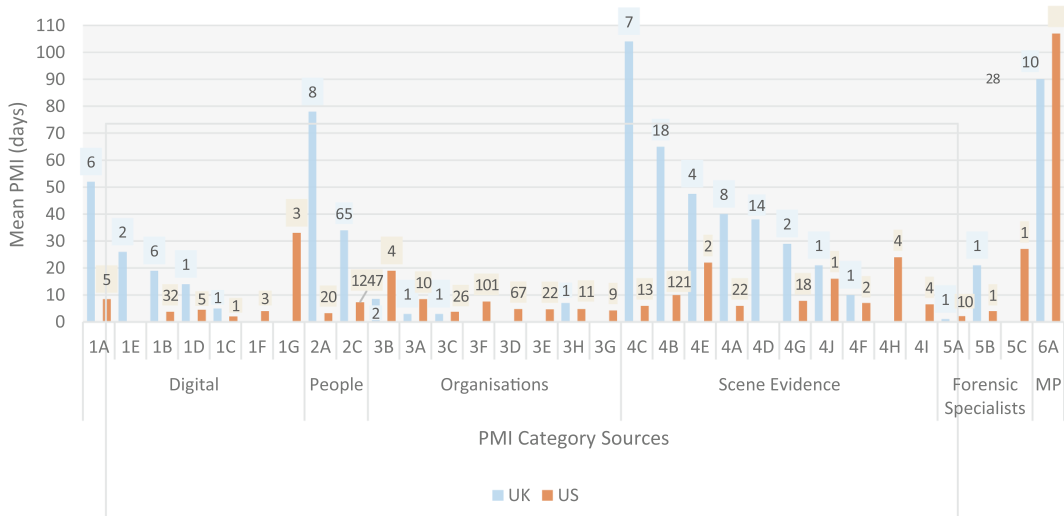

Fig. 4. Mean PMI of PMI information sources for the UK (n = 161) and US (n = 1793). Code 2B 'suspect confessions' excluded as mean PMI was 975 days (n = 3, US cases). The number in the box above each bar shows frequency of cases by PMI source code for UK (blue) and US (orange). Code Definitions: 1A = CCTV, 1B = Mobile Phone Records, 1C = Internet Access, 1D = Email, 1E = ANPR, 1F = Swipe Card Access, 1G = Bank Transaction, 2A = Witnessed Death, 2B = Suspect Confession, 2C = Social Contact, 3A = Police Incident, 3B = GP Appointment, 3C = Hospital Discharge, 3D = Colleagues, 3E = Community Services, 3F = Building Manager/ Landlord, 3G = Hotel Staff, 3H = Other Professional Service, 4A = Newspapers, 4B = Mail, 4C = Receipts, 4D = Food & Drink. 4E = Diary, 4F = Calendar, 4G = Dated Suicide Notes, 4H = Dated Cheque, 4I = Marked Medication Packet, 4 J = Television Guide, 5A = Forensic Pathologist, 5B = Forensic Entomologist, 5C = Forensic Anthropologist. 6A = Missing Persons (MP).

persons' were the only PMI source categories to represent every stage of decomposition. Moderate decomposition was uniformly distributed between the digital, people, organisations, and scene evidence categories, ranging between 38 and 41%. However, there were no cases of moderate decomposition (along with mummification and skeletonization) in the 'forensic specialists' category. Forensic specialists presented the highest proportion of early and advanced decomposition (50%, n = 2), whereas missing persons conferred the greatest proportion of skeletonization cases (40%, n = 4).

3.4. PMI source and manner of death

The frequency of PMI sources was assessed by the manner of death (natural, homicide, accidental, suicide, and undetermined). PMI information derived from 'people' was the most frequently used source across all manners of death in both the UK and US. Unsurprisingly, forensic specialists were exclusively used for homicide cases; however, they provided a PMI in only 33% of all UK homicide cases (n = 2) and 26% of all US homicide cases (n = 11). PMI information derived from digital sources was used most frequently in UK suicide (28%, n = 5) and accidental deaths (26%, n = 5), and were used for every manner of death except for UK undetermined deaths. US natural and accidental deaths had an even distribution of the 'organisations' PMI category (44%: n = 167 natural, accidental n = 52, respectively). Scene evidence was used in every manner of death, except for UK homicide cases, and was most frequently used in both UK and US natural deaths (43%, n = 47 v 12%, n = 137). PMI information derived from missing persons reports were associated with all manners of death, except US accidental deaths, and had the highest frequency in UK undetermined deaths (25%, n = 2) and US homicide cases (17%, n = 7).

3.5. Source evaluation

The first stage of the adapted 3x5 National Intelligence Model (NIM) required a 'source evaluation' to establish the reliability of the PMI information source. 'Reliable' sources accounted for the highest number of PMI sources in this study (63%, n = 20) by comprising: digital evidence (1A-1G), witnessed deaths (2A), suspect confessions (2B), the majority of organisations (3A-3C, 3E, 3G, 3H), dated suicide notes (4G), forensic specialists (5A-5C), and missing persons (6A). Each PMI category, therefore, contained at least one or more PMI codes defined as 'reliable'. 'Untested' sources were comprised of the fewest PMI sources (9%, n = 3): social contact (2C), colleagues (3D), and building manager/ landlord (3F) but presented the greatest proportion of cases in both the US (79%, n = 1410) and the UK (42%, n = 68) (Fig. 5). 'Unreliable' sources accounted for 9 PMI sources (28%) and included sources exclusively from the 'scene evidence' categories (4A – 4F, and 4H – 4 J). The UK had a more even distribution of reliable, untested, and unreliable sources, and a greater proportion of reliable sources (27%, n = 44) than the US (11%, n = 209). However, the US used less unreliable sources (10%, n = 174) than the UK comparative (30%, n = 49) (Fig. 5).

Reliable, untested, and unreliable sources presented asymmetrical and positively skewed curves when distributed by the PMI in both the UK and US (Fig. 6). Reliable PMI sources followed a similar platykurtic distribution pattern in both the UK (excess kurtosis −2.2) and the US (excess kurtosis −3.7), characterised by low and wide central peaks (Fig. 6). The mean PMI for reliable cases was higher in the UK (49 days, SD ± 76) than in the US (33 days, SD ± 249). Reliable PMI sources were used across 1 to 240 PMI days in the UK and even broader ranges in the US (1 to 2920 days). Untested PMI sources in the US had a leptokurtic (high and narrow) peak with an excess kurtosis of + 1.51 and a mean PMI of 7 days (SD ± 18). In contrast, the UK comparative showed a platykurtic distribution (excess kurtosis −1.04) with fewer cases clustering around the mean PMI of 36 days (SD ± 52). The greatest variation between the US and UK was seen in unreliable PMI sources, where the US had the highest leptokurtic peak (excess kurtosis of + 16.1), with cases densely populated around the mean PMI of 10 days (STD ± 9) and a narrower PMI range of 1 to 75 days. Conversely, unreliable PMI cases in the UK presented a wider platykurtic distribution with more variation around the mean PMI of 56 days (STD ± 110) and a broader PMI range of 1 to 575 days. The K-S results indicated statistically significant differences in the PMI distribution curves of reliable ($D = 0.5$, $p \leq 0.05$, $n = 253$), untested ($D = 0.425$, $p \leq 0.05$, $n = 1478$), and unreliable PMIs ($D = 0.862$, $p \leq 0.05$, $n = 223$) between the UK and US. The higher D statistic for unreliable PMI cases ($D = 0.862$), compared to the other source grades, further confirmed that the PMI variation between the UK

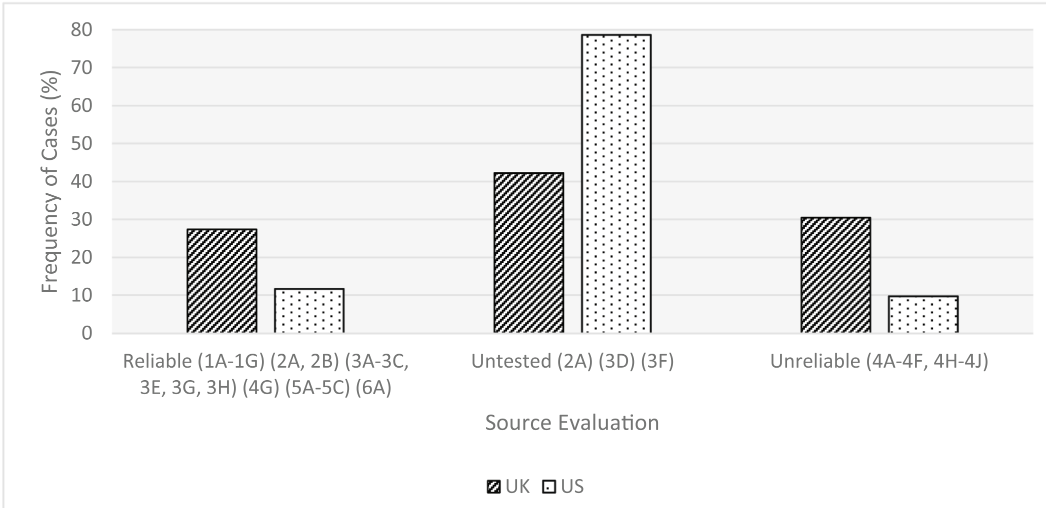

Fig. 5. Frequency of UK (n = 161) and US (n = 1793) cases by Source Evaluation (n = 1813). Frequency count is based on number of PMI sources used per case and are therefore inclusive of cases with multiple PMI sources. Code Definitions: 1A = CCTV, 1B = Mobile Phone Records, 1C = Internet Access, 1D = Email, 1E = ANPR, 1F = Swipe Card Access, 1G = Bank Transaction, 2A = Witnessed Death, 2B = Suspect Confession, 2C = Social Contact, 3A = Police Incident, 3B = GP Appointment, 3C = Hospital Discharge, 3D = Colleagues, 3E = Community Services, 3F = Building Manager/Landlord, 3G = Hotel Staff, 3H = Other Professional Service, 4A = Newspapers, 4B = Mail, 4C = Receipts, 4D = Food & Drink. 4E = Diary, 4F = Calendar, 4G = Dated Suicide Notes, 4H = Dated Cheque, 4I = Marked Medication Packet, 4 J = Television Guide, 5A = Forensic Pathologist, 5B = Forensic Entomologist, 5C = Forensic Anthropologist. 6A = Missing Persons.

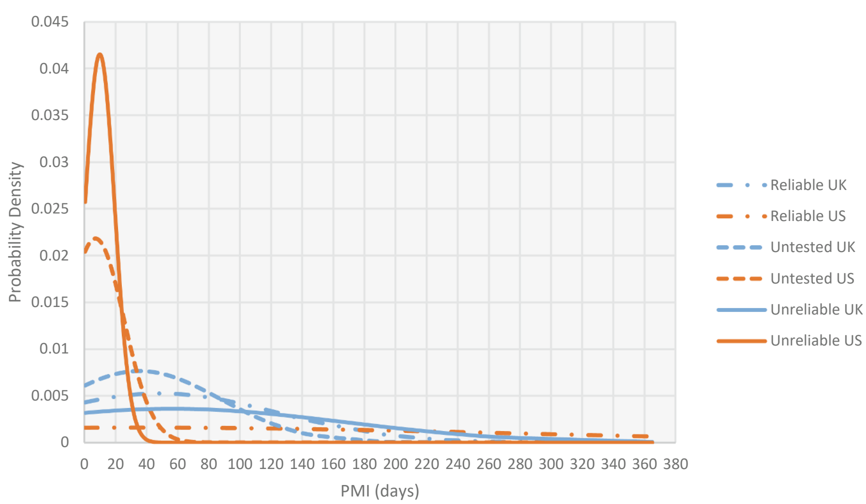

Fig. 6. Frequency distribution of PMI by the PMI source evaluation for UK (n = 160) (blue) and US (n = 1791) (orange) datasets (n = 1811 cases). Graph excludes cases that are greater than >365 PMI days (n = 3).

and the US was most pronounced in unreliable cases.

Reliable, untested, and unreliable PMI sources were used at every decomposition stage, except for US cases of skeletonization which had no unreliable sources. Untested sources had the highest frequency across all decomposition stages (likely due to social contact being the most common PMI source), except for UK cases of early decomposition, which was most prevalent in reliable PMI sources (56%, n = 14) (results not shown). Conversely, in the US, early decomposition presented the lowest proportion of reliable sources (14%, n = 133), with skeletonization accounting for the highest proportion of reliable PMI sources (46%, n = 6). Untested sources of PMI decreased in frequency as the decomposition stage increased, with early decomposition having the highest frequency of untested PMI sources in the US (80%, n = 771), compared to 54% in skeletonization cases (n = 7). In the US, mummification cases had the highest proportion of 'unreliable' cases than any other decomposition stage (25%, n = 7), whereas the UK comparative found unreliable PMI cases most prevalent in advanced decomposition (41%, n = 9) (results not shown).

When considering the effect of intrinsic and extrinsic variables on the PMI source evaluation, there were apparent differences between the distribution of reliable, untested, and unreliable sources (Fig. 7). Reliable PMI sources were more frequently used in homicide cases for both the UK (83%, n = 5) and the US (69%, n = 29), and were least common in natural manners of death for the UK (15%, n = 43) and the US (7%, n = 141). The UK had higher proportions of reliable PMI sources across every manner of death than the US, whereas the US had more untested PMI sources across all manners of death (Fig. 11). Unreliable PMI sources were most common in natural manners of death for the UK (39%, n = 43) and the US (12%, n = 141). There were no unreliable PMI sources in UK or US homicide cases.

While the study dataset consisted predominantly of indoor deaths, the proportion of reliable sources of PMI was significantly greater in

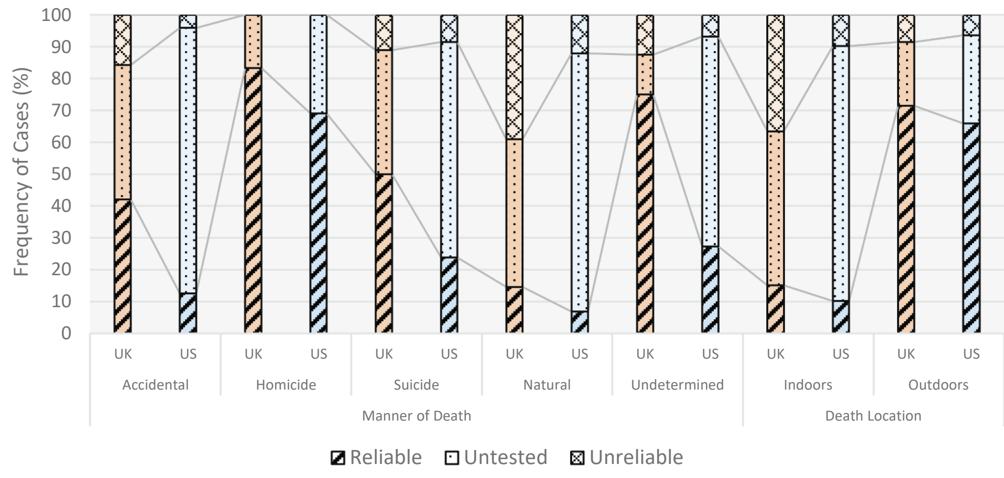

Fig. 7. Frequency (%) of PMI source evaluation (reliable, untested, unreliable) in the UK (n = 161) and the US (n = 1793) by the manner of death and death location.

outdoor deaths for the UK (71%, n = 25) and the US (66%, n = 31) (Fig. 11). Indoor deaths predominantly used untested sources of PMI information in the UK (48%, n = 61) and the US (80%, n = 1397). Both indoor and outdoor deaths had comparably low uses of unreliable PMI sources in the US. In contrast, the UK had a greater proportion of unreliable PMI sources used in indoor cases (40%, n = 46) than outdoor cases (9%, n = 3) (Fig. 7).

PMI source evaluations were evenly distributed between the meteorological seasons in both datasets, with 'untested' sources accounting for the highest proportion across each season with comparably lower frequencies of reliable and unreliable sources (results not shown).

3.6. Intelligence assessment

The second stage of the adapted two-stage 3x5 National Intelligence Model (NIM) required an 'intelligence assessment' to establish the reliability of the PMI information in terms of how it was collected or known to the source. In total, 88% of all PMI sources were assigned a 'Grade A' intelligence assessment, which meant that the PMI information was known directly to the source. Grade A sources included all categories of PMI information: digital, people, organisations, forensic specialists, and missing persons (n = 1604), except for 'scene evidence' (n = 209).

'Grade B' intelligence was assigned to 4% of the overall sample (n = 74) and referred to cases where the PMI information had been obtained indirectly but could be corroborated by an additional, independent source of PMI information that had been graded A. Interestingly, out of the 144 cases that had > 1 PMI source in this study, approximately half (51%, n = 74) were assigned Grade B, meaning that the additional corroborating source(s) were graded A. Of these 74 cases, 100% were corroborated by directly known social contact. Grade B exclusively included 35% (n = 74) of cases from the overall 'scene evidence' category (n = 209). Grade B cases were present across every scene evidence code, except for 'dated cheques' (4H) and 'daily medication packets' (4I), which had no substantiating PMI source.

'Grade C' accounted for the remaining 7% (n = 135) of the total sample and represented cases where PMI information was 'known indirectly to the source' in the absence of corroborating Grade A sources. Grade C cases exclusively included 65% (n = 135) of cases in the remaining 'scene evidence' category (n = 209). Grade C cases were also present across every scene evidence code (4A – 4 J). 'Mail' (4B) accounted for the highest proportion of Grade C cases (n = 74) (Fig. 11). No cases were assigned grades D (no means of assessing the PMI information) or grade E (suspected to be false).

In both the UK and the US, 'Grade A' (directly known to the source) was the most frequently assigned intelligence code, accounting for 65% (n = 105) of UK cases and 90% (n = 1605) of US cases. The UK had a higher proportion of 'Grade B' cases where the PMI information was corroborated (22%, n = 37) than the US (3%, n = 56). 'Grade C' cases, where the PMI information was indirectly known to the originating source, accounted for the lowest proportion of UK (12%, n = 19) and US cases (7%, n = 132).

3.7. Confidence matrix

The confidence matrix indicated the level of confidence (high, medium, or low) in the reported PMI information, based on the source evaluation and intelligence assessment results (Fig. 8). High confidence PMI sources accounted for 13% of the overall sample and included all sources of digital evidence, missing persons, forensic specialists, witnessed deaths, suspect confessions, and most organisations (all graded 1A, n = 227). Dated suicide notes were also assigned high confidence (graded 1B) when corroborated by an additional grade A source (n = 2) (Fig. 8). Medium confidence PMI sources graded 2A comprised 81% of the total sample and included the last known social contact, and PMI information derived from the remaining two categories organisations: colleagues and building manager/landlord (n = 1467). Except for dated suicide notes, the remaining scene evidence categories were primarily assigned low PMI confidence (grade 3C, n = 123), which improved to medium confidence (grade 3B, n = 72) when the scene evidence was corroborated by an additional grade A source. Low confidence PMI sources accounted for just 6% of the overall sample (n = 123).

Medium confidence PMI sources accounted for the majority of UK (54%, n = 54) and US (82%, n = 1413) cases (graph not shown). This was followed by high confidence PMI sources which represented 36% of UK cases (n = 36) and 11% of US cases (n = 191). Low confidence PMI cases were comparably low between the UK (9%, n = 9) and the US (6%, n = 110).

High confidence PMI sources in the UK had the greatest mean PMI of 67 days (±SD 118) when compared to the mean PMI of 'medium' (35 days ± SD 50) and 'low' (32 days ± SD 37) confidence sources. The US comparative found 'medium' PMI sources presented the highest mean PMI of 10 days (±SD 82), followed by a mean PMI of 8 days for both 'high' (±SD 17) and 'low' sources (±SD 9). High and medium confidence PMI sources were used across a broad PMI range in both the UK (high: 1 to 575 days, medium: <1 to 240 days) and the US (high: <1 to 200 days, medium: <1 to 2920 days). Conversely, low confidence PMI sources had the least variability in PMI with use between 1 and 122 days (UK) and 1 to 74 days (US).

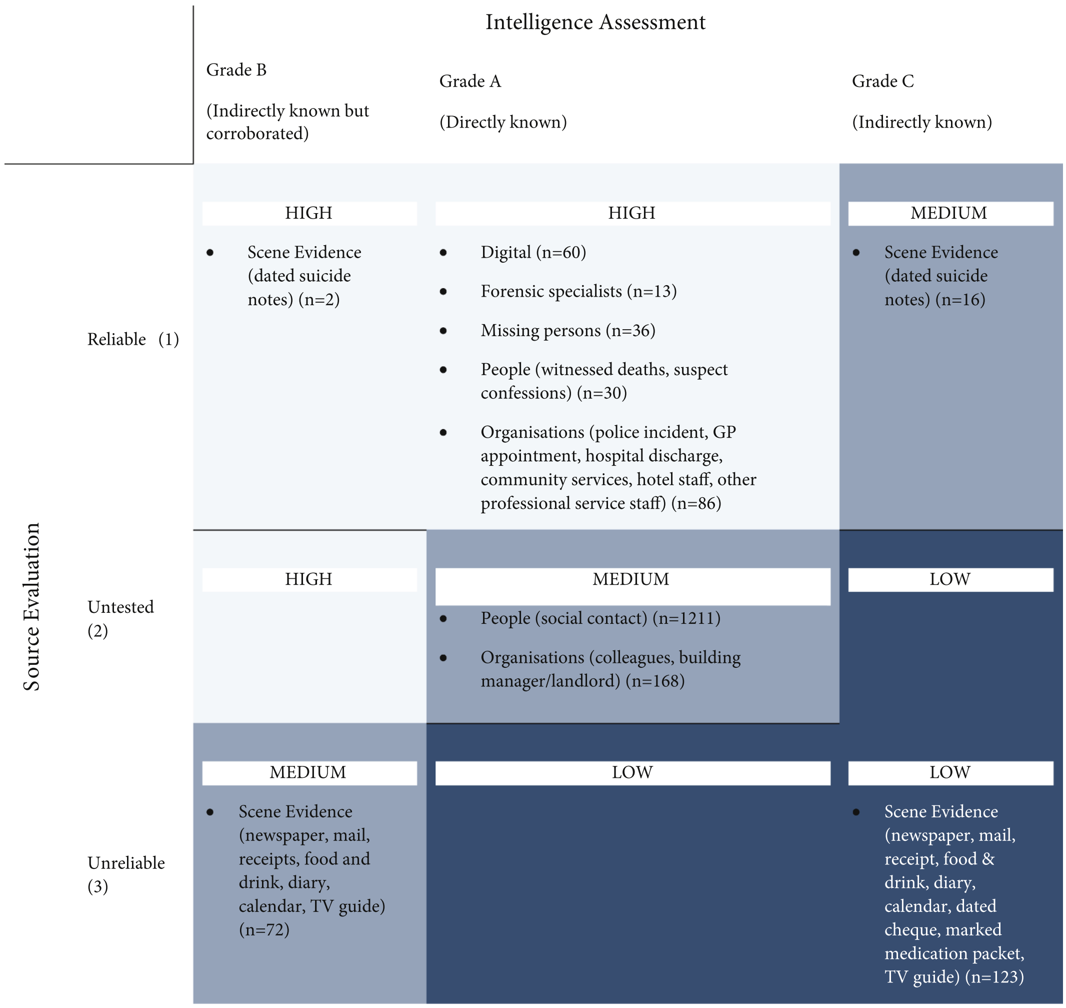

Fig. 8. Confidence Matrix of PMI Information for both UK and US (n = 1813).

High, medium, and low confidence PMI sources were present across every decomposition stage, except for skeletonization which used no low confidence PMI sources in both datasets. Medium confidence sources had the highest prevalence across all decomposition stages, except for UK skeletonization cases (n = 7) which had a higher proportion of ‘high’ PMI confidence cases (71%, n = 5). Conversely, low confidence PMI sources made up the smallest proportion of all decomposition stages, except for US moderate decomposition cases (n = 454), which had a lower proportion of high confidence PMI cases (7%, n = 3) compared to low confidence cases (9%, n = 40).

The PMI confidence varied according to the intrinsic and extrinsic variables. High confidence PMI sources were most prevalent in homicide cases in the UK (67%, n = 2) and the US (58%, n = 18). Medium confidence PMI sources accounted for the remaining homicide cases in the UK (33%, n = 1) and the US (39%, n = 12). Medium confidence PMI sources represented the highest proportions in all manners of death, except for homicide cases and UK undetermined deaths. In the US, medium confidence PMI sources were predominantly used for 83% of natural (n = 927) and accidental deaths (n = 298), and 82% of suicide cases (n = 138). The UK comparative found medium confidence PMI sources accounted for 58% of natural deaths (n = 36), 42% of accidental deaths (n = 6), and 67% of suicides (n = 8). There were no low confidence PMI sources used in UK homicide or undetermined deaths, and only 3% of US homicides used low confidence sources (n = 3). Low confidence PMI sources consistently accounted for the lowest proportion of the remaining manners of death.

The distribution of PMI confidence by indoor and outdoor death locations found that indoor deaths predominantly conferred medium PMI confidence in the UK (58%, n = 43) and the US (83%, n = 1379). However, when the death occurred inside a public building (e.g., hotel), high PMI confidence was conferred in 73% of these US cases (n = 11). There were no deaths inside public buildings in the UK dataset. High confidence PMIs accounted for 31% of UK indoor deaths (n = 23) and 11% of US indoors deaths (n = 177). Low confidence PMIs were sparse and accounted for the remaining 11% of the UK indoor deaths (n = 8) and 7% of the US comparative (n = 113).

Outdoor deaths had a greater proportion of ‘high confidence’ PMIs (compared to other confidence levels) in every outdoor location for both the UK and US, except US road deaths which represented more medium confidence PMIs (89%, n = 8). Burials were the only death environment to exclusively confer high PMI confidence in the US (n = 2). No outdoor cases in the US presented low confidence PMIs, and only one outdoor woodland death in the UK conferred a low confidence PMI. US vehicle deaths predominantly conferred high PMI confidence (80%, n = 8), with the remaining 20% of cases consisting of medium PMI confidence (n = 2).

PMI confidence levels were evenly distributed between the meteorological seasons, with ‘medium’ sources accounting for the highest proportion across each season and considerably lower frequencies of ‘high’ and ‘low’ PMI confidence for both datasets (data not shown).

4. Discussion

4.1. The National intelligence model

This study sought to apply an adapted version of the NIM (3x5x2) model to sources of reported PMI information to establish parameters from which a level of confidence could be ascertained regarding the reliability of PMI source information. Applying the 3x5 aspect of NIM to evaluate the veracity and integrity of PMI information from the US and the UK proved quick and simple to implement. Our study demonstrated that subjecting PMI information to the evaluation process of the 3x5 aspects of the NIM streamlined the reported PMI information so that it could be easily graded according to the source evaluation and intelligence assessment codes. Furthermore, while an array of PMI information sources was examined, the list provided is not exhaustive and could easily be amended to reflect additional PMI sources not represented in this study (e.g., last known social media access).

The level of PMI confidence (high, medium, low) was based on an evaluation of the PMI source (reliable, untested, unreliable) and an intelligence assessment of the origin of PMI information (directly known, indirectly known but corroborated, indirectly known). The model was flexible in enabling the overall confidence in the PMI to increase if an additional independent source corroborated the original PMI information. In this study, scene evidence was the only PMI information source that increased from a 'medium' to 'high' confidence when the PMI information was substantiated with directly known social contact information. Interestingly, the UK conferred a higher proportion of cases where the PMI source was corroborated. The US data spanned 10 years, compared to only 5 years in the UK; therefore, one might expect the UK to have 50% fewer cases if the datasets were equal. However, the US ME system exclusively investigates medico-legal deaths on a daily basis, whereas the UK CSI attends all different crime types. Given the higher throughput of cases in the US, this could have resulted in more confidence being applied to a single PMI source (since 95% of US cases had only one PMI source). However, it is advised that corroborating PMI information should always be sought to confirm the validity of the original PMI source information [25].

The NIM also has the added advantage in its universality to PMI recording. In this study two geographically different PMI datasets were graded with the 3x5 aspects of the NIM. The standardisation of this methodology facilitated a direct and rigorous comparison between PMI information sources used in both countries and also in the assessment of the decomposition stage in relation to the PMI. Variability in the PMI distribution between the UK and the US increased as the decomposition stage progressed, as measured by the increasing D statistic, where the greatest effect on PMI variation was evident in skeletonization cases. Conversely, no statistical differences were found in the PMI distribution of early and moderate decomposition between the UK and the US. It is possible that the effect of taphonomic variables, that become more pronounced as the PMI increases [1], contributed to the greater PMI variation seen in the later stages of decomposition between these two countries.

4.2. PMI sources

This study confirmed that a variety of PMI information sources are available to record an initial PMI in cases of decomposition. The PMI information can be derived from technical sources (e.g., digital evidence), people (e.g., social contact, organisations), professionals (e.g., forensic specialists), circumstantial scene evidence, or police reports (e.g., in missing persons cases). Importantly, this study found that specific PMI sources were associated with different levels of reliability and used at different PMIs, stages of decomposition, and manners of death.

4.3. High confidence PMI sources

Of all the PMI sources evaluated in this study, the majority (63%) conferred a high level of reliability. These sources included digital evidence, forensic specialists, missing persons reports, people (witnessed deaths, suspect confessions), organisations (those pertaining to professional services), and scene evidence (dated suicide notes). In the 3x5 model, it is essential to note that reliable sources are not necessarily graded as 'high confidence' since this also depends on the provenance of the information. For example, dated suicide notes were only assigned high confidence when the evidence was substantiated by a corroborating PMI source (e.g., directly known social contact), whereas the remaining aforementioned PMI sources were graded high confidence due to their combination of directly known provenance and high reliability.

Reliable PMI sources had the highest mean PMI in both datasets, compared to untested and unreliable sources, and were used at every decomposition stage (except for US skeletonization cases). Importantly, reliable PMI sources were used across extensive PMI ranges in both the US (1 to 2920 days) and the UK (1 to 240 days). This contests the ethos that the longer the PMI, the more likely the estimation will be unreliable [9,26]. These findings are reassuring and confirm that reliable PMI information sources are applicable beyond the early post-mortem period. Reliable PMI sources also had the lowest incidence in natural deaths and highest incidence in homicide cases in both the UK and the US, which is not surprising given the critical need to estimate the PMI with accuracy in homicide investigations [8]. The incidence of reliable PMI sources was also higher in outdoor death locations for both countries, where the array of extrinsic taphonomic variables arguably requires more reliable means to estimate the PMI [2–4]. However, while these reliable PMI sources proved valuable in their diverse application, the frequency of their overall use was relatively low and was superseded by 'untested' and 'medium' confidence PMI sources (e.g., social contact). To explore possible reasons for this, it is necessary to interpret the respective PMI sources comprising high reliability.

The time-stamped footprint of digital sources such as mobile phone communications, online email, internet, and bank transactions, provided reliable PMI information. Since these digital sources are now so abundantly used and centralised to individual lives, they are undoubtedly pertinent to the provision of PMI information. The UK had a higher incidence of digital evidence being used in accidental and suicide deaths, whereas the US had a lower reliance on digital evidence across all manners of death. This can partly be explained by the investigative requirement to establish a PMI when determining if the death is non-suspicious [42]. However, the yield of digital PMI information was also comparably low for homicide and undetermined deaths in both the UK and the US, where it would be appropriate to seize communication devices for further investigation [20]. Therefore, the scene examination of digital devices to establish the last known electronic communication from the deceased, should be encouraged as it contributes a factual, reliable means to establishing an initial time frame for the PMI.

Other technical sources of PMI information such as CCTV and ANPR can also reliably narrow down the PMI time frame but were infrequently used in this study. This is most likely due to the sample predominance of indoor residential deaths in both datasets, where there would simply be a lack of opportunity to recover CCTV and ANPR evidence. As with mobile communication data, these digital sources of PMI information were used in early decomposition cases and were limited to determining shorter PMIs. While CCTV has no set retention time, a 31-day retention period has been previously recommended [28], and ANPR is accessible to police staff for 30 days [28]. The absence of these digital sources beyond these short retention times could also explain their association with shorter PMIs in this study.

Forensic specialists (encompassing the fields of pathology, anthropology, and entomology) were exclusively consulted to estimate the PMI in homicide cases and no other manner of death. In the UK, this is consistent with their recommended appointment by the CSM in consultation with the senior investigating officer (SIO) [30]. Despite the credibility and reliability of forensic expert opinion [31,32], forensic specialists were the *least* used PMI source in this study, and 65% of all homicide cases had PMI information derived from means other than forensic specialists. Furthermore, forensic anthropologists were not used for PMI estimations on any cases of mummification or skeletonization in this study, contrary to the literature consensus [32]. The low frequency of forensic specialist consultation for PMI estimations in this study could be due to several reasons. These may include limited resourcing budgets, police delays in determining a suspicious death and subsequent requesting of the specialist, the rapid removal of the deceased to the mortuary in favour of evidence preservation, or limitations with the *accuracy* of their methods used to derive longer PMI estimations [20,31–34]. When forensic specialists were used to estimate the PMI, this was associated with early decomposition cases at shorter PMIs and was predominantly conducted by forensic pathologists, consistent with early post-mortem indicators that can be used to estimate the PMI [35].

PMI information derived from missing persons police reports conferred long mean PMIs of 101 days (US) and 90 days (UK) and was the most frequent PMI source used in US mummification and UK skeletonization cases. Previous research has established a strong association of missing persons cases being found in the advanced stage of decomposition [36,37]. The missing persons reports contained highly detailed information about the last known sighting and were deemed reliable, having been obtained by the law enforcement in both countries. However, estimating the PMI remains a significant challenge due to the pronounced effect of taphonomic variables manifested in the advanced decomposition stage which can also preclude identification of the deceased. Processes such as adipocere formation, that are associated with late-stage decomposition, further complicates PMI estimations by inhibiting putrefactive bacteria [21]. The missing persons PMI information is therefore, only valuable once the identity of the deceased has been confirmed. In both countries, missing persons PMI information was frequently associated with homicide, undetermined, and suicide manners of death, which is characteristic of such cases [38].

Under the 'people' category of PMI information, witnessed deaths (most common in accidental deaths) and suspect confessions (homicide cases) also conferred high reliability but very low incidence in the UK and the US. Most deaths are not witnessed, which presents significant challenges in PMI estimations [37,38]. Witnessed deaths associated with delayed reporting (i.e., where the witness lives with the deceased and does not report the death) is a common law offence in England and Wales, albeit the prosecution of this offence is rare and complicated by mental health issues [39,40]. Similarly, the incidence of suspect confessions was low and only present in the US dataset, where they harboured the longest mean PMI of 975 days, given the prolonged delay in attaining them [35]. Suspect confessions have previously served to independently corroborate other forms of PMI evidence [35].

Professional organisations such as the emergency services (police and medical) and community services proved to be reliable sources of PMI information and were associated with early decomposition, consistently short mean PMIs (UK: 5 days, US: 7 days), and natural manners of death. The US had a higher reliance on PMI information derived from organisations than the UK. The incidence of deaths in police custody or following police contact is relatively low in England and Wales, with 19 deaths reported in 2020 [41]. Given the short time period between the last known police contact and the discovery of the deceased to classify the death as 'following police contact', it is not surprising that such deaths were associated with shorter PMIs and early decomposition. Similarly, with community services (e.g., healthcare professionals) providing routine home care services, the failure of regular contact or engagement of the deceased in these services apply to narrowing down shorter PMIs [42].

4.4. Medium confidence PMI sources

Medium confidence PMI sources were used in most UK and US cases and were predominantly attributed to determining the last known 'social contact' across all manners of death. In the US, social contact PMI information was most commonly used in indoor cases of early decomposition with a mean PMI of 7 days. This finding appears logical when considering research that shows the reverse, social isolation associated with Diogenes syndrome, is a marker of advanced decomposition associated with prolonged discovery times [25,43]. However, it cannot be excluded that this could be due to the large number of early decomposition cases present in the US dataset. In the UK, social contact was distributed more evenly across all stages of decomposition and conferred a longer mean PMI of 34 days. This finding was unsurprising, given that it is routine practice for police investigations to reconstruct the deceased's last known movements by speaking to those who maintained regular contact with the deceased when alive (e.g., family, friends, neighbours) [42].

Members of the public (including family, friends, colleagues, landlords) providing last known contact information were deemed to confer 'untested' reliability since they are giving information to the police for the first time [25]. However, given that the PMI information was directly known to the source (e.g., through an eyewitness account) this resulted in 'medium' level confidence in the PMI. Arguably, this is an acceptable level of confidence for non-suspicious deaths, given that PMI estimations are widely considered most critical for homicide investigations [4,8]. Furthermore, the current practice guidance suggests that factual information of the last known sighting derived from people may be more reliable than estimating the PMI from decomposition and the array of associated extrinsic variables [33,44,45]. While this may be true, there are still undetermined limitations of authenticity, competence, and accuracy of the PMI information derived from the 'people' category.

Research investigating the reliability of eyewitness accounts in criminal investigations recommends that asking witnesses open questions when obtaining information will improve the reliability of witness reporting and prevent bias [46–48]. Furthermore, it is best policing practice to ensure information gathering from witnesses complies with the 5Ws (who, what, when, where, and how) to obtain detailed, relevant information [25]. Adhering to these principles when obtaining PMI information from witnesses of the deceased's last known sighting, may also improve the reliability of the reported PMI information.

Medium confidence in PMI sources could also be achieved if the source was indirectly known but reliable, as demonstrated by dated suicide notes. Research examining the content of suicide notes suggests that the inclusion of dates affirms their authenticity [49], rendering them reliable PMI sources. However, as with all scene evidence, the attending police officers or forensic investigators would not have witnessed the note being written; hence the PMI information contained in the note is 'indirectly known'. If, however, the dated suicide note is substantiated by a directly known PMI source (e.g., social contact in this study), this increased the PMI confidence of these cases to 'high'.

Scene evidence in the form of newspapers, mail, receipts, food and drink items, diary and calendar entries, and TV guide dates, although ubiquitous at death investigation scenes, were deemed unreliable sources of PMI information. This is likely due to their inconclusive subjectivity surrounding the PMI, which is consistent with previous findings [8]. However, when such evidence was corroborated by independent means of directly known PMI information (e.g., by last known social contact or other scene evidence sources), medium level confidence was achieved. Circumstantial scene evidence should not be discarded as it may infer value when substantiated by corroborating sources and could still prove useful in establishing initial parameters of the PMI time frame.

4.5. Low confidence PMI sources

Most PMI sources of scene evidence were not corroborated, which resulted in low confidence PMI. The incidence of PMI source corroboration was overall very low in this study (4%). It is possible that PMI sources were simply not substantiated because of an absence of other corroborating evidence or because it was beyond the scope of the scene assessment to investigate additional PMI sources, as in the case of natural deaths [4].

Low confidence PMI sources represented the lowest frequencies of both UK and US cases and were exclusively comprised of unreliable PMI sources from the scene evidence category. Incidentally, the unreliable sources between the UK and the US showed the greatest variation in the PMI distribution compared to reliable and untested sources, as measured by the higher D statistic. This revealed significant differences in the application of unreliable PMI sources between the US and UK, with the UK using unreliable PMI sources at statistically longer PMIs compared to the US. This could be due to the higher proportion of longer PMIs in the UK sample. However, we also cannot exclude differences in the approaches of PMI information collection between UK and US medico-legal death investigation practices. The US dataset still comprised longer PMIs, but unreliable sources were mainly used at shorter PMIs. It is recommended that unreliable PMI sources should only be used at as a last resort, regardless of the suspected PMI duration.

Importantly, no low confidence PMI sources were used for homicide cases, reiterating the requirement of only recording reliable PMI sources for cases of this nature. Indoor deaths had a greater proportion of low confidence PMI sources than outdoor deaths. Since most scene evidence codes (e.g., newspapers, mail, receipts) were primarily located inside residences, this finding was expected. Low confidence PMI sources were also non-specific to the decomposition stage and used between 1 and 575 PMI days. Given that shorter PMIs and their association with early decomposition are deemed to be more reliably estimated, it was interesting that low confidence PMI sources were not primarily used at longer PMIs and more advanced stages of decomposition. This could be due to low confidence PMI sources being sufficient to satisfy natural causes of death, which is where most 'unreliable' sources were used in the absence of corroborating PMI information. However, there may still be instances where suspicious deaths are only subsequently determined at the post-mortem examination [27]. Therefore, it is recommended that higher confidence PMI sources should always be sought and recorded from the scene wherever possible.

4.6. Limitations

The NIM application to PMI information serves a novel purpose in categorising the reliability of PMI information sources that are commonly encountered in the investigation of decomposition scenes. However, it is not without limitations since a high confidence level for the PMI source is not the same as the PMI source being accurate. The 3x5 aspects of the NIM are bound by determining the reliability and provenance of source information and cannot be used as a tool to determine the PMI accuracy. Methods of PMI estimation and their accuracy remain a challenging area of ongoing research [50–52], but the limitations and error rates of specific PMI estimation methods were not within this study's scope.

It is, however, recognised that source accuracy, alongside competence and authenticity of the source, may still influence the reliability of the reported PMI information. These factors are not explicitly incorporated in the 3x5 model; rather it is advised that the assessor should rely on their objective professional judgement when evaluating the source [25]. This is arguably most applicable when determining the reliability of the PMI information from untested sources of people (e.g., last known social contact). Therefore, it is recommended to ascertain the provenance of the source by considering how the person came to know the PMI information, whether they are in a position to know the information, whether it was obtained first-hand, or if there is a motive to mislead the investigation [17]. The latter may occur in cases where decomposition is a marker of social isolation and relatives, friends, or neighbours of the deceased provide falsified PMI information to resolve guilt [43].

In homicide cases, witness testimony of PMI information plays a significant role in suspect identification. Research has previously assessed the accuracy of witness testimony, finding that asking open questions and asking the witness how confident they are in their information improve the accuracy of witness memory recall [44]. In relation to obtaining PMI information, an open question would be 'when did you last see the deceased alive?', as opposed to 'did you see the deceased alive yesterday?' (a closed question). In addition, it is recommended to adhere to the 5Ws (what, when, who, where, and why) to gather detailed PMI information for'during the investigation [17].

The challenge of determining the accuracy of PMI information is not limited to 'people' sources. For example, ANPR cannot identify the vehicle driver; therefore, PMI information obtained from this digital source (although reliable) may not be accurate (i.e., a third party could be driving the deceased's car). In cases where there is any degree of doubt regarding the integrity of the PMI source, corroboration should always be sought from an additional, independent PMI source [25].

A further limitation of this study lies within the homogeneity of some PMI information categories that may have concealed variability in the PMI reliability. For example, the 'forensic specialists' category, combined forensic pathologists, forensic entomologists, and forensic anthropologists. While the mean PMI was compared between these groups, the overall confidence matrix considered only the PMI source categories and not their individual components. Variation may exist in the reliability between these different forensic specialists that could not be confidently explored in our study due to their limited sample sizes ($n = 14$). Therefore, it is recommended to include a greater number of cases that are specifically representative of different forensic specialist groups and the other components of the PMI source categories to identify and further explore any variation in PMI reliability.

Arguably, the most detrimental limitation of the 3x5x2 intelligence model is the incorrect application of intelligence and source evaluation codes by the individual recording the information [26]. Therefore, it is essential that the police officer or civilian member of staff should be trained and competent in using the NIM to ensure that the PMI reliability can be graded correctly.

5. Conclusion

This study differentiated between the reliability of different sources of PMI information currently used in medico-legal death investigations of decomposition scenes. Applying the 3x5 aspects of the NIM model to the PMI considers both the reliability and provenance of PMI information and communicates an associated level of confidence in the PMI information that quantifies uncertainty. Arguably, the most critical application of reliable PMI information is in criminal investigations, where PMI information can assist in suspect identification, confirm, or refute suspect alibis, identify the deceased, and inform suspect and witness interview strategies [20]. This study has demonstrated that reliable PMI sources, such as digital evidence, can be acquired for different manners of death and used across all stages of decomposition to establish the initial parameters of the PMI.

The majority of PMI sources conferred 'untested' reliability in non-suspicious deaths. There is currently no requirement to establish the PMI for non-suspicious deaths, and it does not form part of the England and Wales guidance on death investigation practice of sudden deaths [27]. However, there may still be instances where suspicious deaths are only subsequently determined at the post-mortem examination [29,30]. Therefore, it is recommended that acquiring PMI information from reliable sources, which were available across all PMI categories in this study (e.g., digital, people, organisations, scene evidence), should be collected regardless of the suspected manner of death. In cases where reliable PMI information is not available, substantiating any 'untested' PMI information with corroborating evidence can improve its overall validity. In doing so, this could inadvertently assist in determining a suspicious or non-suspicious manner of death, but most importantly will mean that in instances where a suspicious death is only determined at the post-mortem, important PMI information has already been collected which may have otherwise been lost if the scene was released.

Conversely, the US Medical Examiner's medico-legal death investigation system will conduct complete autopsy examinations on all cases, even if the death is interpreted to be natural at the scene by attending forensic investigators [19]. However, the application of this research also recommends forensic investigators extract PMI information from reliable sources and seek corroborating PMI sources, to prevent the loss of scene or witness evidence to acquire PMI information if the autopsy determines a homicide manner of death.

While this research has primarily concentrated on the reliability of PMI sources, evaluating the accuracy of such sources was beyond the scope of this study and remains undetermined. As forensic taphonomy research continuously seeks to improve the accuracy of PMI estimation models, the extremely low incidence of forensic pathologists using early post-mortem decomposition markers to derive a PMI demonstrates the widening gap between research and subsequent implementation of valuable PMI estimation models into practice. When taphonomy research develops PMI estimation models using PMI information from forensic cases as their basis, establishing the reliability of the derived information may serve to improve model validity. The reliable PMI sources identified in this study confer valuable application to the practice of medico-legal death investigation by communicating a standardised level of confidence for the originating PMI information.

Ethical statement

Permission was granted by the Allegheny County Office of the Medical Examiner (ACOME) to access and utilise the Medical Examiner's Information Management System (MEIMS) to conduct this study. All cases were processed anonymously in accordance with ACOME policy. Permission was granted by the Head of Southwest Forensics (SWF) Crime Scene Investigation Unit to access and utilise the Socrates forensic case management system to conduct this study. All cases were processed anonymously in accordance with SWF policy. Ethical approval was also obtained from the Cranfield University Research Ethics System (CURES).

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CRediT authorship contribution statement

Stephanie B. Giles: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **David Errickson:** Supervision, Writing – review & editing. **Nicholas Márquez-Grant:** Supervision, Writing – review & editing.

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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