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Technical Note

# An examination of the spatial distribution of the tissue fragments created during a single explosive attack

E. DuBois[a,*], K. Bowers[a], C. Rando[b]

[a] University College London, Department of Crime and Security Science, 35 Tavistock Square, London WC1H 9EZ, United Kingdom
[b] University College London, Institute of Archaeology, 31-34 Gordon Square, London WC1H 0PY, United Kingdom

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ABSTRACT

Throughout the course of a forensic investigation following an explosive attack, the identification and recovery of tissue fragments is of extreme importance. There are few universally accepted methods to achieve this end. This project aims to explore this issue through the examination of the spatial distribution of the tissue fragments resulting from an explosive event. To address this, a two stage pilot study was conducted: first, a series of controlled explosions on porcine carcases was undertaken. Second, the data produced from these explosions were used to chart the spatial distribution of the tissue debris. In the controlled explosions, 3 kg military grade explosive was chosen to create the maximum amount of fragmentation; this level of explosive also prevented the complete disappearance of forensic evidence through evaporation. Additionally, the blast created by military grade explosive is highly powerful and would mean that the maximum possible distance was achieved and would therefore allow the recorded distances and pattern spread to be a guideline for forensic recovery of associated with an explosive amount of an unknown size and quality. A total station was employed to record the location of the resulting forensic evidence, with the collected data analysed using R Studio. The observed patterns suggested that the distribution of remains is fairly consistent in trials under similar environmental conditions. This indicates potential for some general guidelines for forensic evidence collection (for example, the distance from the explosion that a search should cover).


## 1. Introduction

With acts of terrorisms on the rise, the ability to react and appropriately handle these situations effectively is of critical importance within the field of forensic science [1–4]. This includes the search and recovery of tissue fragments from victims on the scene at the time of the explosion. In the forensic literature, research on explosions has been primarily examined from two different perspectives: chemical and trauma analysis. Firstly, from a chemical analysis perspective the focus has been on the examination of the particles created by the explosive device to predict potential distance ranges expected from the explosive chemicals in a variety of situations [5,6]. Secondly, within the fields of forensic medicine and anthropology the focus instead has been on the types of trauma that occur to the victims of explosions: in particular, the emphasis with has been on the injuries obtained by members of the military serving in Iraq or Afghanistan [7–9]. However, while these two areas have been well addressed, there appears to be a lack of information regarding the pattern and spatial distribution of the tissue fragments that are created as a result of a (likely fatal) explosive event. This dearth is surprising considering how critical it is to know how far (and where) to search for potential fragments. The ability to quickly and efficiently search for evidence fragments is a requirements of any successful search and recovery operation.

The purpose of this current research is to address this gap in the literature with an aim to provide a more complete understanding of the spatial distribution of human tissue fragments specifically focusing on those produced by single-bomber (or suicide bomber) explosive events [10–12]. By having access to this data, experts will be able to conduct searches in a more efficient manner (quicker and more coherently), limiting unnecessary searches and reducing cost. Further, this will ensure that the critical forensic evidence can be collected in such a way that facilitates faster identification process of those tissue fragments.

In order to fully address this gap in the literature and produce concrete data which future forensic specialists can use and apply, it

* Corresponding author.
*E-mail addresses:* erin.dubois.12@ucl.ac.uk (E. DuBois), kate.bowers@ucl.ac.uk (K. Bowers), c.rando@ucl.ac.uk (C. Rando).

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is important to establish a universally applicable framework and set guidelines which recovery personnel can implement effectively. Following the National Academy of Science report (2009), the importance of developing a database that can be drawn upon in conducting forensic investigations and in the later evidence interpretation has become a main focus in the field of forensic science. This research aims to contribute to the slowly expanding forensic evidence base [13–15].

## 2. Methods and materials

### 2.1. Explosion parameters

In order to create an acceptable replication of a real world explosive attack event, this experiment needed to use an explosive material that would both create the necessary shockwave resulting in the fragmentation of the tissue and be a common explosive element used by terrorist groups [16–18]. From a fragmentation standpoint, the aim was to have sufficient separation of the material whilst not obliterating the forensic evidence entirely. In other words, the goal was to create small to medium sized fragmentation. Considering this, plastic explosive 4 or PE4, was chosen; this is a military high-brisance crystalline explosive known to be used in terrorist attacks, especially in the cases of state-sponsored terrorism where there is more access to military grade equipment [19,1,2]. The amount of explosive was based on a previous run of experiments and case studies that examined only the tissue injury and damage following a blast [20–22]. Pilot explosions were also performed in which the weight of the explosive was gradually increased until complete fragmentation of the target was obtained. The optimal amount was judged to be 3 kg of explosives, as this appeared to result in the desired complete fragmentation of the porcine test specimens; pigs (*Sus scrofa*) as commonly used as a human substitute in many fields, particularly within forensic science [23]. The deceased pigs used in the course of this experiment were purchased for 150 pounds per pig directly from a local farmer who raised them to sell as meat produce.

**Fig. 1.** A photograph demonstrating the composition of the explosive prior to detonation.

### 2.2. Experimental set-up

For these experiments, the explosive materials that comprised the bomb were placed together and wrapped with duct tape (Fig. 1). The finished bomb was then placed on the front and centre of the pig. This composition of the bomb was chosen for two reasons. The first was that by having the explosive material bound closely together, the resulting forces are produced in a central location that then spread outwards from the centre point. This was the easiest way to create the most powerful force that would produce the maximum tissue fragmentation. Secondly, it was also less expensive as it only used one primer charge to create the explosive train that produces the explosive force. The explosives were purposely not placed in any type of container or device, allowing for the examination of what happens to the tissue fragments with no other material involved.

The pigs were placed directly upright onto a wooden stake to resemble a suicide bomber (Fig. 2). As observed in Fig. 2, the position of the both the pig and the explosive of both the pig and the explosive was chosen as it allowed for the examination of the maximum distance obtained by the resulting tissue fragments as all of the force of the explosion was position in one direction against the pig tissue. The overall direction that the pig and the explosive faced varied due to the difficulty in getting the pigs

**Fig. 2.** A photograph representing the completed experiment set-up prior to detonation.

upright on the stake. As soon as the pig was in a position to be secured to the stake, the opportunity was taken. Although the direction between the different tests differed, the statistical program that will be described in greater detail later on allowed for the tests to be compared by rotating the data sets. It should be noted that before each of the test was performed, the wind speed was recorded to document how the overall distribution is impacted by the weather (see Table 1).

As mentioned above, the motivation for this research was in producing an empirical evidence base of the expected distribution of tissue fragments. The experiments were necessarily resource intensive – they required expensive material (pig cadavers, explosive, hire of technical equipment), locations which were suitable experimental sites and input from expert personnel (explosive experts). The number of explosions undertaken needed to be carefully balanced; each additional explosions adds to the validity of the resulting evidence base, but also adds to the expense. In practice, we were able to conduct nine explosions of large pig cadavers which we describe in more detail in the results section.

### 2.3. Recovering and plotting the fragments

This study employed the Waldron Springs Protocol [23–26] and is described in detail below. This method is designed for fast recovery of evidence and for plotting of fragments in mass disasters, which are complicated scenes with many moving parts. The acquired data was then uploaded to a Global Imaging System (GIS) program [23–26]. This data was then used to create a map of the distribution, which produces an empirical database that can be used by investigators in both the forensic examination of the scene and in the later evidence interpretation [25]. This process substantially reduces the risk of human error in the recording of the tissue fragmentation distribution.

The Waldron Springs Protocol for evidence recovery is split into four parts [23–26]

- The first step is to search for and locate the physical evidence, which in the case of this research is the tissue fragments;
  - In the case of these experiments, the researcher and the explosive engineer were the only two present. In order to practically search the scene within the week time frame, the two searchers worked from two ends of the space and worked towards the blast centre. When a fragment was located, it was marked with a flag. Although it is not realistic to except to recovery all fragments (e.g. become blood splatters and fluid stains); when the search area was completed and the large fragments identified (parts of the four limbs and the head), it was determined that area was fully searched.
- Secondly a total station is employed to collect the data and assign a field specimen number;
  - Once the fragment had be recorded using the total station, the flag that was used to mark it was removed to reduce the risk of fragments being marked twice.
- The third step is to photograph the evidence in situ;
  - A range of fragments from each test was photographed to give an example of the types of tissue that was present throughout the experiments.
- Lastly, the evidence is collected, preserved, and removed from the scene.
  - This step was not conducted as there was no cold storage space to store the fragments long term.

**Table 1**
A table outlining the recorded wind speeds during each of the 9 tests.

| Test number | Recorded wind speed (MPH) |
|---|---|
| Test 1 | 30 |
| Test 2 | 20 |
| Test 3 | 6 |
| Test 4 | 7 |
| Test 5 | 7 |
| Test 6 | 6 |
| Test 7 | 3 |
| Test 8 | 3 |
| Test 9 | 4 |

### 2.4. Data analyses

Once the data was collected, it was transferred from the total station and downloaded. The data points were then processed through Excel and imported into R Studio to produce completed spatial maps of the collected data points and for statistical analysis. As a first step, the data was plotted on a scatterplot centred at 0,0 to look at the shape of the distribution of fragments. These plots revealed that the data conformed to a roughly circular distribution around the point of the explosion. Therefore, to describe their distributions a special class of statistic, known as circular statistics, are needed here [27]; circular statistics are highly useful as they can be applied to many types of inherently circular data such as magnetic fields, winds direction, migration patterns and temporal crime frequencies [28]. It is useful in describing data like this to look at the degree the data conforms to a circular distribution. This adds to the ability to make references about likely distribution shapes of future events. In this case, the input data was the number of degrees (from 0 to 360) from which each segment's position deviated from a reference line originating from the centre of the blast. This data was plotted and its continuous distribution was estimated employing a Kernel Density Estimation technique. In order to explore distribution shape, Rayleigh's Test of Uniformity was applied for each experiment in order to reject or accept the null hypothesis that the tissue fragments conformed to a uniform circular distribution (i.e. fall in all directions with equal likelihood around the centre point of the blast). A further circular statistics test, known as the Watson–Wheeler test, was performed to explore the relationship between two circular data distributions. In this case, the null hypothesis was that the two samples were from the same underlying distribution [29]. These comparisons were useful in establishing how similar or distinct the shape of the tissue fragment distribution was across the various experimental blasts.

In addition to comparing the relative distributions of the tissue fragments, it is important to examine the actual spatial patterns emerging from the blast. Expanding on the point mapping of the spatial locations of the fragments, we were interested in the direction of the blast and in visualising the density of the segment distribution. In estimating the blast direction we wished to draw a line which could represent the main thrust of the blast. Since we were unable to identify a prior method for doing this, we conceptualised that one method of doing this would be to minimise the total deviation of the set of points from the blast line. This is the equivalent of fitting a line of best fit in a linear regression of the spatial x co-ordinates against the y co-ordinates anchored at the centre of the blast (0,0). Since all of the best-fit lines pass through (0,0) it is possible to compare the angular deviation of any two distributions or of each distribution against the aggregated picture across all multiple experiments. In terms of visualising the density of the tissue segments distribution, we produced Kernel Density Estimation (KDE) plots which identify any visible clustering of the tissue fragments. Furthermore, cumulative density plots were produced to visually demonstrate

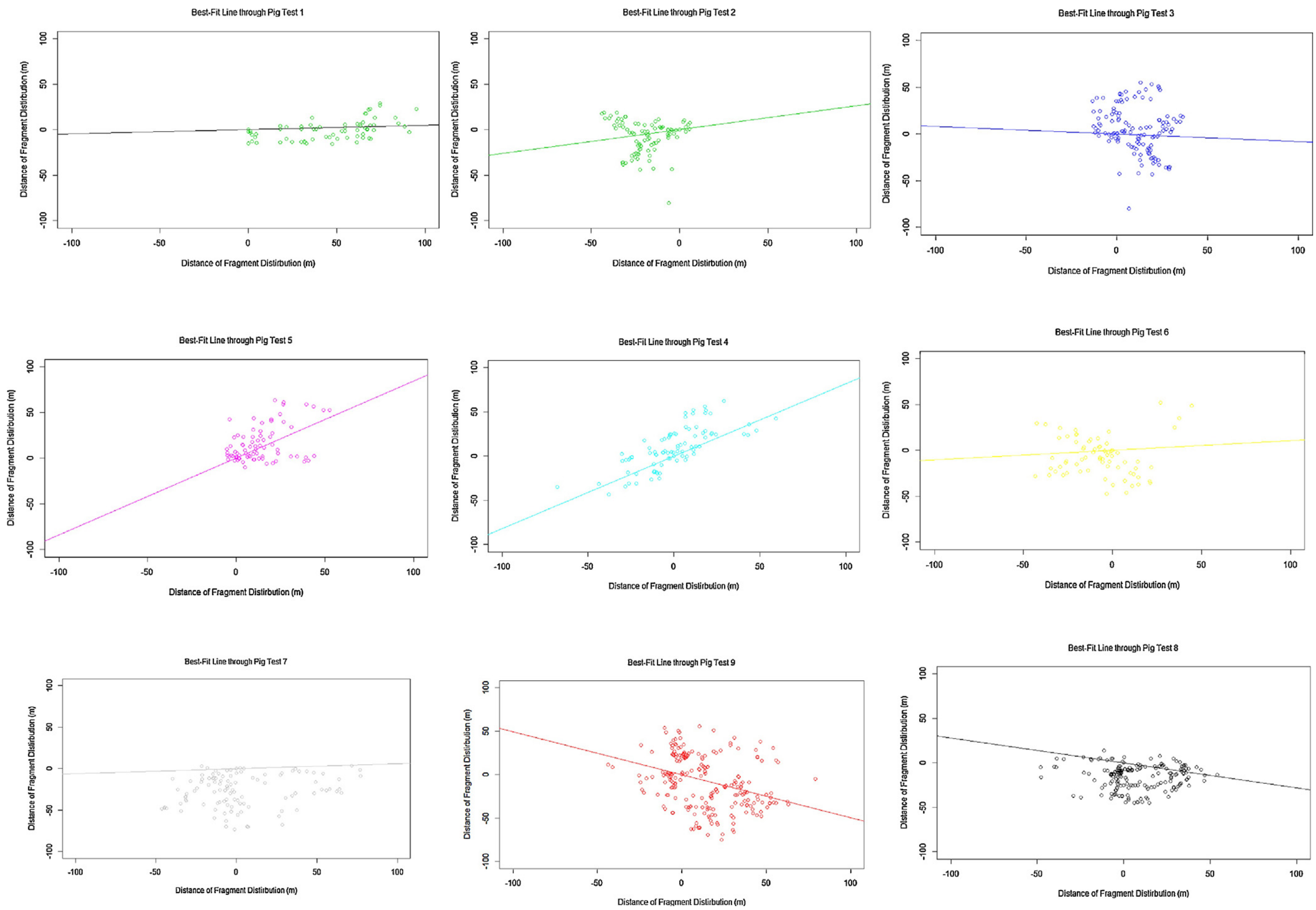


**Fig. 3.** The collected data points with the resulting linear regression line that was used to anchor the data points so that a later data they could be compared to other data sets.

the density of the fragmentation moving out from the blast centre [30,31].

## 3. Results

The collected spatial data from the nine tests illustrated certain patterns that the resulting tissue fragments took following the explosion (Fig. 3). Although the patterns from each test differ to some degree, there appears to be a common characteristic in that, according to the lines of best-fit, they appear to be fairly directional. This is particular in the case with some experiments (e.g. Test 1) whereas in other cases this is less defined (e.g. Test 9). The blast lines tends to demonstrate a left to right of the blast centre when examined on the data plot. Further, points appear to distribute at negative co-ordinates rather than positive ones, indicating a tendency for the fragments to fall behind the blast

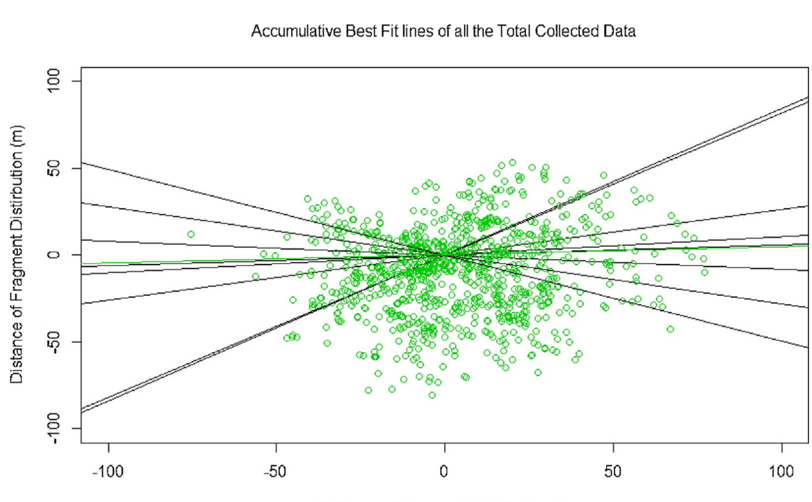


**Fig. 4.** The accumulative best fit lines of all of the collected data sets across the nine tests. The green line is the constant best-fit line, with the black lines illustrating the original best fit line for each test. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Table 2**
Summary statistics for the collected test data.

| Test number | Q1 distance | Median distance | Q3 distance | Maximum distance | Number of fragments recovered | Rayleigh test of uniformity |
|---|---|---|---|---|---|---|
| 1 | 30.01 | 51.39 | 67.20 | 97.71 | 69 | 0.8593* |
| 2 | 12.85 | 26.26 | 36.37 | 81.02 | 91 | 0.598* |
| 3 | 13.54 | 24.84 | 36.37 | 80.54 | 127 | 0.366* |
| 4 | 13.11 | 24.75 | 34.13 | 76.35 | 89 | 0.3178* |
| 5 | 7.84 | 19.45 | 34.28 | 74.44 | 78 | 0.6658* |
| 6 | 14.87 | 26.67 | 38.24 | 66.03 | 70 | 0.4554* |
| 7 | 21.96 | 41.55 | 55.66 | 77.68 | 109 | 0.6562* |
| 8 | 13.59 | 25.89 | 36.61 | 55.57 | 187 | 0.6242* |
| 9 | 21.78 | 34.67 | 50.47 | 79.34 | 225 | 0.2952* |

* $p < 0.01$.

centre (the stake on which the pig is placed). Fig. 4 indicates the change in direction of the line of best-fit as data points are accumulated across the nine experiments. This demonstrates that accumulating data across experiments causes only small changes in the direction of the overall best-fit line and hence indicates little deviation in directionality across data sets. The final accumulated blast direction best-fit line is illustrated in green in Fig. 4.

The mean maximum distance that a fragment travelled throughout the entire experiment was 76.5 m, with a standard deviation 18.78 m. Table 2 gives summary statistics for each experiment individually. There appears to be reasonable consistency in terms of maximum distances, with some experiments deviating from this general picture (e.g. experiments 1 and 8).

Table 2 also provides information on the outcome of Rayleigh's Test for Uniformity for each experiment. The results demonstrate that in all cases, the shape of a continuous KDE estimated from the point data deviates from a uniform circular distribution. The visual circular statistic distributions, reflecting the Rayleigh results, show

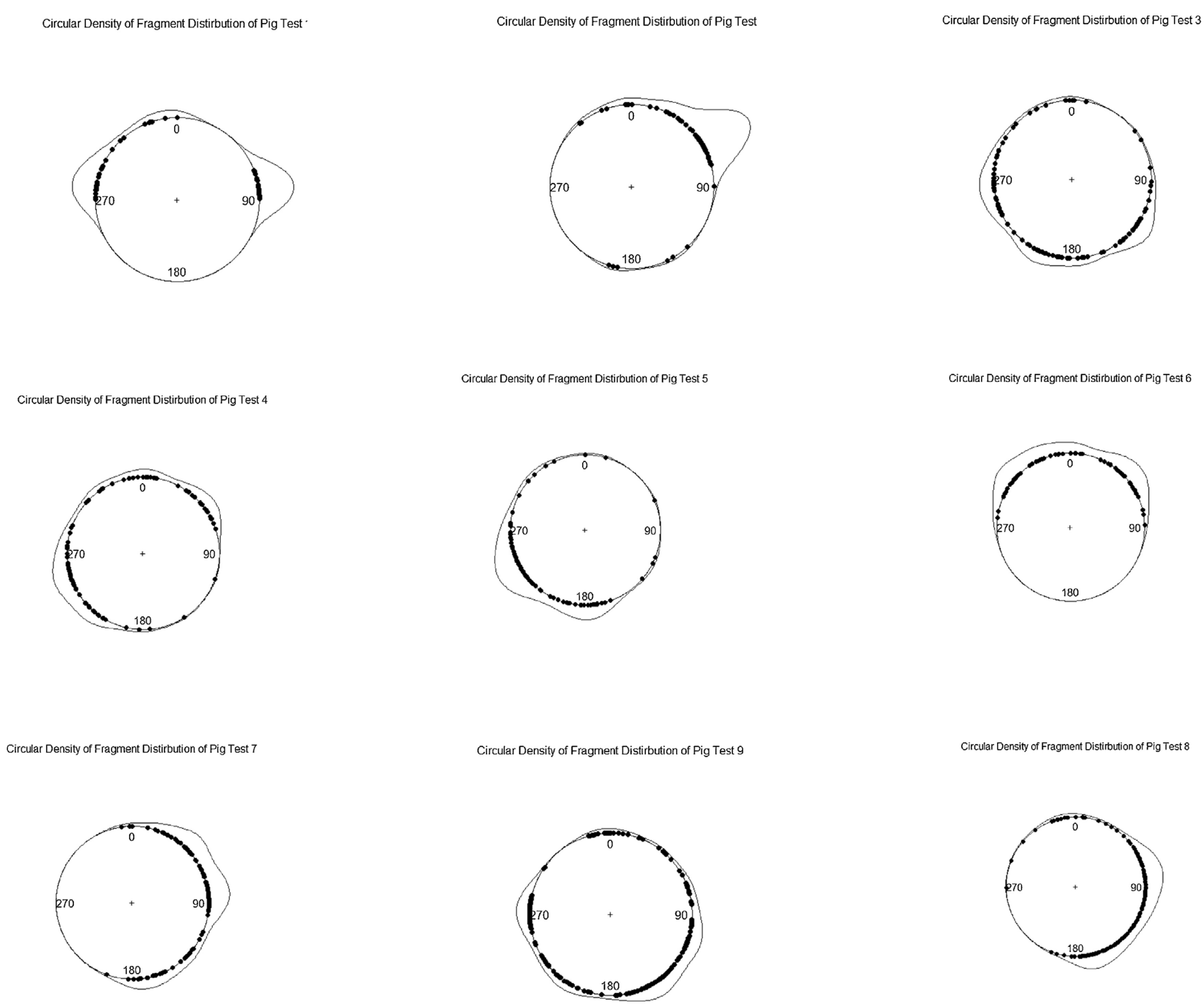


**Fig. 5.** The directionality observed in the course of the experiments, represented in a circular static graph.

**Table 3**
The Watson–Wheeler results, with stars demonstrating results with a significant p-value.

| Test number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | | 100.74* | 76.34* | 2.03 | 73.17* | 48.64* | 2.81 | 19.84* | 68.24* |
| 2 | 100.74* | | 166.99 | 79.21* | 140.11* | 42.25* | 54.53* | 162.79* | 191.60* |
| 3 | 76.34* | 166.99* | | 17.32* | 20.91* | 101.10* | 61.03* | 50.03* | 7.14* |
| 4 | 2.03 | 79.21* | 17.32* | | 17.33* | 29.46* | 75.72* | 116.67* | 38.92* |
| 5 | 73.17* | 140.11* | 20.91* | 17.33* | | 90.58* | 107.23* | 118.54* | 56.82* |
| 6 | 48.64* | 42.25* | 101.10* | 29.46* | 90.58* | | 45.87* | 95.03* | 110.92* |
| 7 | 2.81 | 54.53* | 61.03* | 75.72* | 107.23* | 45.87* | | 11.32* | 39.90* |
| 8 | 19.84* | 162.79* | 50.03* | 116.67 | 118.54* | 95.03* | 11.32* | | 22.95* |
| 9 | 68.24* | 191.60* | 7.14* | 38.92* | 56.82* | 110.92* | 39.90* | 22.95* | |

* p value $<0.05$.

the deviance in degrees from a centre line originating at (0,0) for each experiment are shown as Fig. 5. The KDE distribution approximations (shown diagrammatical as a continuous line surrounding the inner circle) appear to reflect directionality as they have distinctive wedge shaped pieces indicating clustering. Although the nature of this research was directional due to how the explosive was placed on the pig, the circular statistics played an important role in understanding the overall distribution.

Table 3 shows the results of the Watson–Wheeler tests which examine differences between the experimental distributions. The comparisons reveal that the majority of the experiments showed some significant deviation from each other in terms of their overall shape. The exception to this is that Test 1 was not significantly distinct from Tests 4 and 7 according to this statistic.

In terms of density of fragments, KDE mapping demonstrates that the fragments tended to cluster around the centre of the blast, and become sparser as the distance increases from the centre of the blast sites (Fig. 6). These maps also visually demonstrate similarities and differences between the experimental distributions, reflecting the results of the Watson–Wheeler test. Cumulative density analysis shows the clustering of the fragmentation in each of the experimental tests (Fig. 7) [26–28]. Fig. 7 indicates that within 40 m at least 50% of more of the fragmentation is recovered in all cases. Notably, Fig. 7 also speaks to variation in

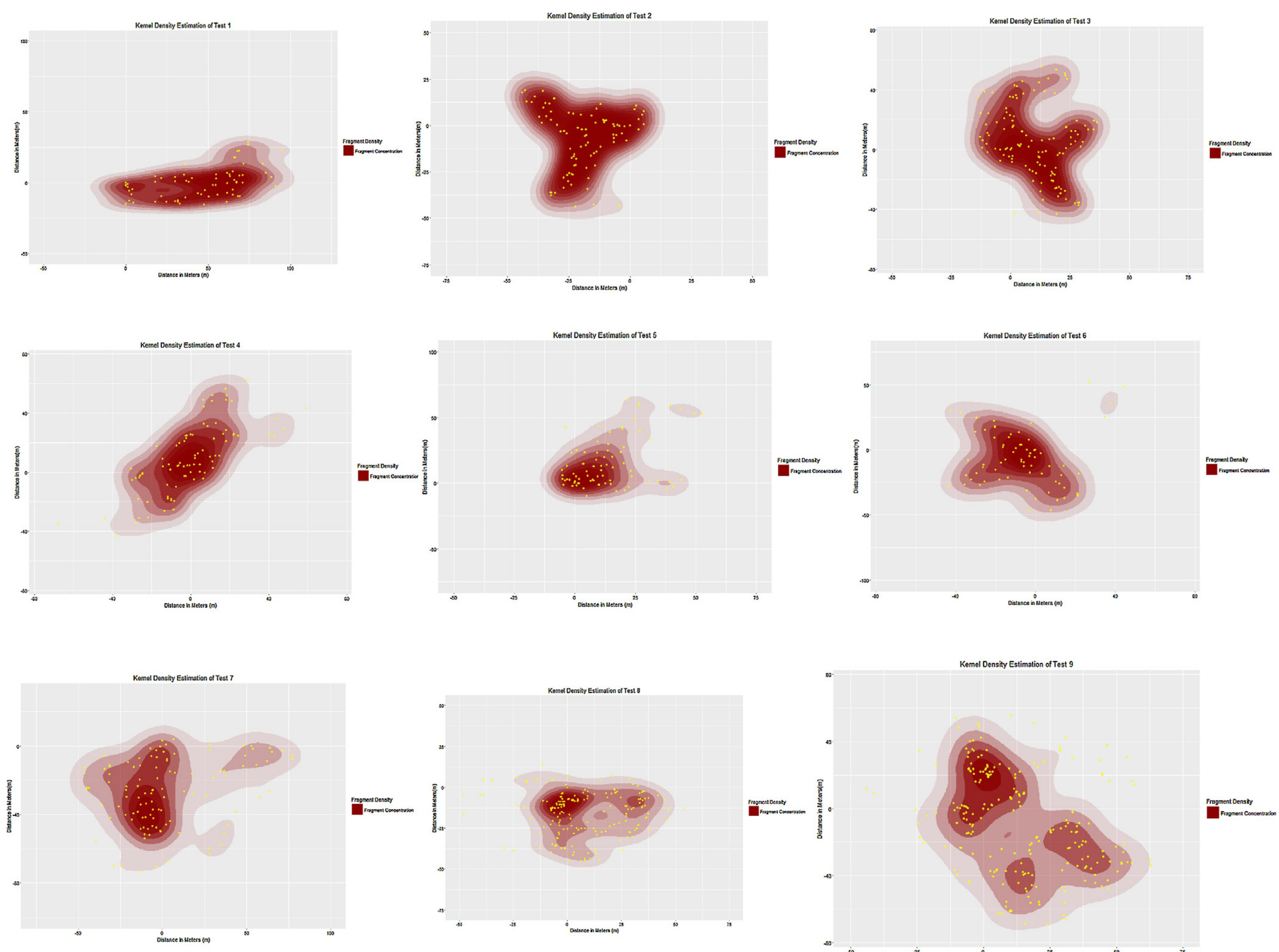


**Fig. 6.** The fragment clustering observed in the course of the experiments, represented in a KDE tests.

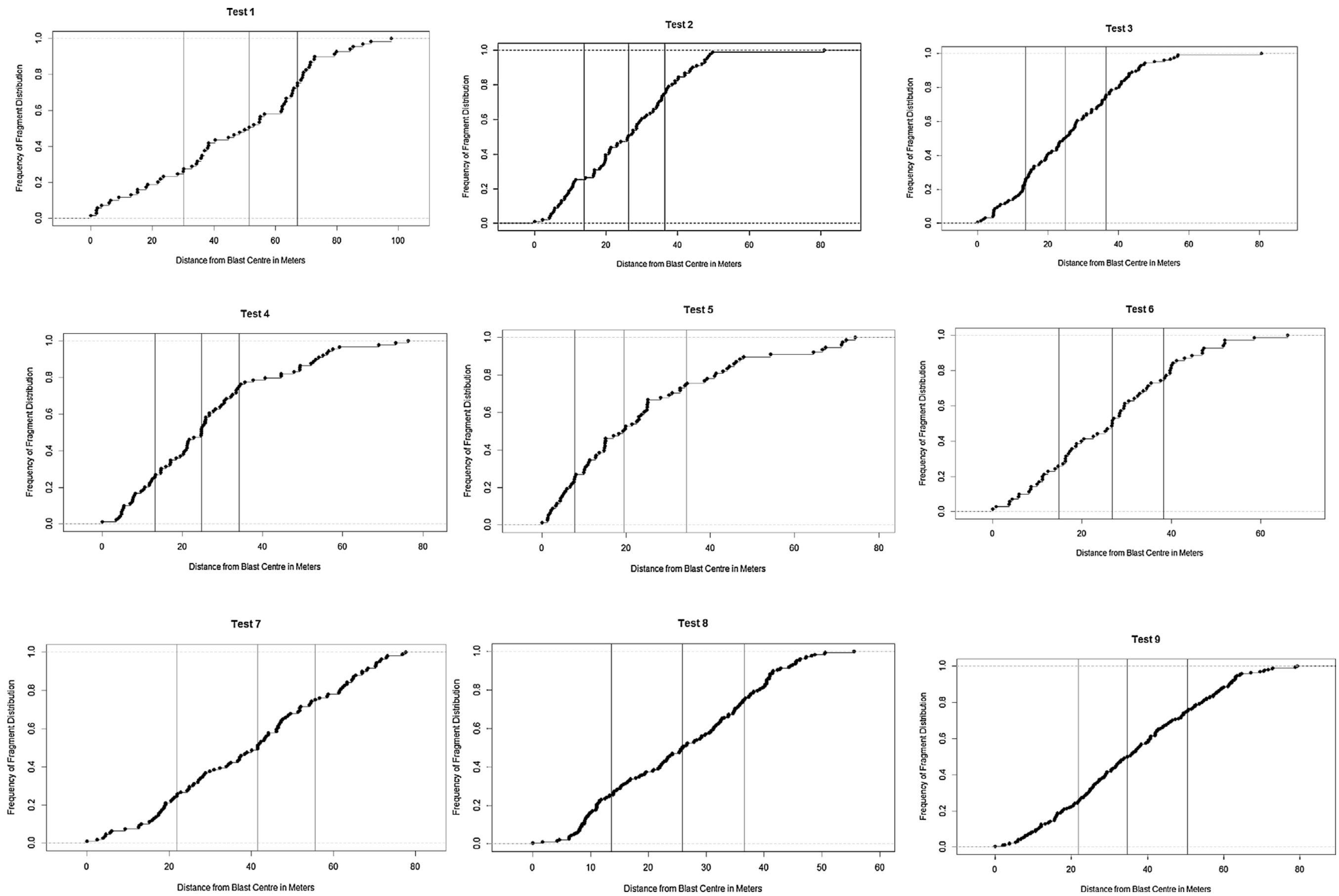


**Fig. 7.** The cumulative density graphs, with the vertical lines showing the Q1, Median, and Q3 fragment percentages per distance.

environmental conditions. Recorded wind speed was higher than average for Tests 1, 7 and 9. The charts demonstrate that in all three cases, the first 25% of fragments were distributed further from the blast centres-approximately 20 m than the remainder of the experiments, which recorded this quantity at the 10–15 m mark.

## 4. Discussion

The observed fragment distances that this study recorded differed from the distances outlined in similar published sources examining the chemical spread of the explosive material [5,32]. The fragments observed over the course of this experiment never exceed 80 m, even with employing 3 kg of military grade explosive. One reason behind this discrepancy is likely to be that the explosive experiments in these previous studies were designed to examine the chemical distribution and not the biological components. Biological fragments are impacted by the stress-strain relationship that the body will undergo under the extreme forces of the explosion [33–36]. These fragments are also impacted by the resulting vacuum that follows as the surrounding environment aims to return to normal pressure levels, essential acting to pull objects back towards the blast centre [37,7–9]. Hence, when the explosions were observed in video taken from the initial blast, the created force can be seen sending many of the tissue fragments into the air before directly falling to the ground.

The mean maximum distance of 76.5 m makes additional sense in the context of how the force that is produced by the explosion decreases after the initial chemical reaction. The chemical reaction that is created during the initial explosion results in a blast wave [10]. It is within this blast wave that there is that huge increase in surrounding air pressure as it moves away from the blast centre at supersonic speeds, with the leading edge of this wave called a blast front [7] creating the tissue fragmentation. This increase in pressure soon decreases as the blast wave moves away from the centre of the blast [7]. It is here that the momentum of the tissue fragments ends and they began to fall to the ground. Although the initial force produced by the explosive blast is strong enough to create maximum fragmentation of the pig, the distance the blast wave was able to allow the tissue fragments to travel was still below the 100 m distance. Within the literature there are few examples about how far forensic evidence associated with these types of explosive events will travel. With most either having a focus on the chemical distribution or case studies [5–6,10–12], the ability to scientific examined how far the tissue fragments with travel is an important step in adding to the forensic evidence base.

Another pattern that can be observed from the data collected from the nine tests is that the positioning of the bomb on the centre-front of the pig has an impact on the resulting tissue fragment distribution. This resulted in the creation of a blast force directionally ‘pushing’ the tissue away and back from the centre of the blast, causing the wedge-shaped pattern observed in the spatial maps.

This research aimed to assist in the production of an evidence base describing the behaviour and the distribution of biological tissue when placed at the centre of the blast during an explosive event. The results demonstrated that consistency can be expected across distributions associated with this type of explosive scenario. In addition to being limited in terms of the distance of travel, the tissue fragments also tend to be directional as demonstrated by the Rayleigh’s R statistics and the distribution visualisations. These imply the influence that the placement of the bomb will have on the resulting spatial spread of the fragments [38]. The Watson–Wheeler results along with the KDE visualisation reveal conditional variation between tests. For example, Tests 1, 7 and 9 were obviously impacted by higher wind speeds, while Tests 1, 4 and 7 appeared to have a more similar shape. One explanation for the latter is that they had similar overall placement of both the pig and the explosive when compared to the other tests. It is obvious that account for these variations is important in interpreting the resulting forensic evidence.

The characterisations produced by the research described here should prove helpful in alerting forensic practitioners regarding what to expect from a biological tissue perspective in the wake of an explosion. It is also possible that with further experimentation this research could be applied to other areas e.g. accidental explosions. However, these results can only be applied to the particular conditions of these experiments, meaning that the external validity of the process is likely to be fairly limited [13]. There are also issues with the low sample size in such forensic experimentation, a problem that has been highlighted elsewhere in the literature [13,39–40].

Building upon this, albeit small study, there are a number of ways in which this research could be explored further. The first could be to examine the viability of using ballistic gel and downsized experiments in continuing this research. If these moderations do prove viable this will greatly increase the capacity and the ability of further pursuits to add to the overall evidence database. The second could focus on exploring methods to identify interesting deviations depending on conditions. For example, do military grade bombs result in a different distribution to homemade ones? If reliable conditional variation is found this should assist with the production of forensic intelligence.

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