Influence of muzzle gases on blood droplet backspatter

Nathaniel D. Sliefert

Iowa State University

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Influence of muzzle gases on blood droplet backspatter

by

Nathaniel D. Sliefert

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Mechanical Engineering

Program of Study Committee:
James B. Michael, Major Professor
Sarah A. Bentil
Thomas Ward III

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University

Ames, Iowa

2020

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ABSTRACT

Bloodstain pattern analysis (BPA) has been widely used for the forensic analysis of crime scenes, and recent attention has focused on patterns formed from blood drops in backspatter produced from a gunshot. However, much of the BPA literature lacks rigorous uncertainty estimates and is disconnected from the controlling physical processes resulting in bloodstain formation—in particular, fluid breakup and propagation mechanisms have only recently been addressed in literature. A detailed understanding of the droplet behavior in flight and the importance of competing processes is key to quantifying the uncertainty in a forensic bloodstain pattern analysis. Forces such as muzzle gases expelled from the barrel of the firearm can be very important for cases where the shooter is at close range. In this dissertation, a study of forward projected droplet tracks compared with blood stain patterns as well as the influence of muzzle gases blood backspatter is presented. Droplets were tracked in three-dimensional space using digital in-line holography coupled with high-speed imaging at kHz rates for global visualization of the backspatter. The Sandia HOLOSAND code was used to identify and link droplets over multiple frames which produced position and size of the in 3D space. Calculating associated error and velocity of these tracks prepared them to be compared with physical stains through a forward propagation model.

Muzzle gas interactions with blood backspatter were observed through shadowgraphy and critical distances for ligament and fully formed drop interaction were identified. In conjunction, blood stain patterns for various firearm distances were also observed to show obvious differences in stain patterns. Particle tracking velocimetry was applied to the shadowgraphy to analyze larger droplets entering particle breakup regimes during interactions with the muzzle gas flow field. A retroreflective shadowgraphy technique was used to visualize the expansion of muzzle gases for
various firearms. The gas expansion was captured and processed to extract the position of the leading edge and radial expansion over time. This data was then compared to a numerical model characterizing the expansion of gases leaving the firearm as self-similar vortex rings. Confirmation of an analytical theory allows for the generalization of muzzle gas interactions across a range of firearms and standoff distances, which may be key in analyzing bloodstain patterns in a range of scenarios.
CHAPTER 1. INTRODUCTION

The purpose of this dissertation is to enhance understanding of blood backspatter experimentally, while specifically analyzing the influence muzzle gases can have on the blood droplets in flight. Exploring the nearfield of blood droplets provides another avenue of research to connect the controlling fluid mechanical processes to the forensic field of bloodstain pattern analysis (BPA).

1.1 Motivation

BPA has the potential to become a highly influential asset to the forensic science field, and to help ensure correct judgment in the courtroom for violent crimes. Many efforts towards reconstructing crime scenes using only the knowledge of the blood stain patterns left behind have resulted in significant error when predicting point of origin. This is not unexpected as the backspatter of blood droplets is a phenomenon nearly impossible to replicate one test to another. In addition, external forces such as air drag and gravity have been well documented\textsuperscript{1–3}, while the addition of including the influence of muzzle gases at short distances has become another factor.

To better understand the backspatter, the formation of droplets has been of interest in recent years. Models predicting the primary breakup of a bloodletting events have shown that numerical analysis is getting more accurate when estimating number of droplets as well as stain pattern distributions. Even models characterizing the muzzle gases expelled from a firearm to interact with synthetic droplets has been generated.

However, the common denominator has been comparisons to experimental data, and even lack of experimental data to improve or validate models. In an attempt to satisfy this need, this work is based on the analysis of blood droplets in the nearfield while they are still in-flight, as well as the influence muzzle gases have on these droplets based on imaging and the stain patterns left
from the gunshot. The following literature review covers important work in BPA including models predicting the influence of muzzle gases. Additionally, introducing an oncoming flow field to the droplet field brings breakup of these drops into play, so a short overview of droplet atomization is also covered.

1.2 Literature Review

Some of this work will be submitted for publication in *Physics of Fluids* and is shown in an extended version here.

1.2.1 Bloodstain Pattern Analysis

Bloodstain pattern analysis is the use of blood spatter patterns from a crime scene to extract information pertaining to the nature of the crime committed. Attempting to determine what caused the patterns observed is the overarching motivation behind BPA. Estimating the origin of the blood spatter is a common expectation from the BPA forensics field, but the techniques may neglect key fluid mechanical forces including air drag or the effect of gravity. Over short time spans, assuming that drag and gravity do not have an impact on blood droplets may provide sufficient results, depending on the effective inertia of droplets. However, over full droplet flights, these external forces need to be taken into consideration. Specifically, the method of strings or the trigonometric method from the 1950s, which was known for attaching strings from the stains and seeing where they intersected to estimate the point of origin. Commercial software packages such as BackTrack utilize this straight line trajectory assumption. However, straight line trajectories are not very realistic, in turn causing significant error that is well documented. A commonly used example is that this method can overestimate the origin of the blood by 50%. The difference between straight line trajectories is nicely portrayed by Attinger et al. in Figure 1.1, where the influence of drag and gravity are clearly necessary to account for trajectories over paths of meter-length.
Figure 1.1 Blood droplet trajectory comparison between straight line trajectories and when external forces drag and gravity are taken into consideration.

In considering the physical breakup and propagation behavior of blood, it was been recognized that blood is a non-Newtonian, complex, shear thinning fluid consisting of suspended particles being blood cells and proteins in the plasma$^{14-16}$. Blood is a shear thinning (or pseudoplastic) fluid resulting in a decreasing viscosity with increasing shear rate. This behavior results in different regimes for slow phenomena like dripping versus the high shear rate which may be encountered during high-force blunt trauma or gunshot impacts. Additionally, the rheological properties of blood can depend on temperature and hematocrit$^{14,17}$. Hematocrit, or the percentage of red blood cells, has a measurable impact on viscosity.

In light of these difficulties, multiple models have been created in hopes of accurately representing blood droplet travel. The systematic approach of including both gravity and air drag
in to the model showed a four-fold improvement in estimating the origin location of the blood droplets as compared to the straight line approximation \(^1\). Models like these take the pattern formed by the bloodletting event and back-propagate the droplet flight without considering the formation of the blood droplets. To consider the formation mechanisms of droplets, the Rayleigh Taylor instability was shown to be a prominent mechanism of atomization \(^2,3\). This instability the result of high-density fluid splashing towards the air being lower density fluid. From this, blood drop size and velocities from a source impacted with a conical shaped bullet were predicted for backward blood spatter. Experimental bloodstain measurements were compared to the numerical simulations and showed a good fit when it came to number of droplets produced, while the pattern of blood stains was more difficult to correlate \(^2\). Comiskey et al. also performed a similar study for the forward spatter of blood to predict the number of stains, however there was a large variation in the average stain area as a function of distance from the blood source over the various experiments \(^19\).

The full three-dimensional trajectories of droplets have been examined using 3D laser scanners. Buck et al. showed a ballistics software that takes images captured by photogrammetry and three-dimensional laser scanning of the surrounding stain patterns to reconstruct the bloodletting event \(^20\). The use of ballistic software demonstrated the short preparation time at the crime scene, non-intrusive technique, and high accuracy even for small droplets. However, drawbacks included the need to take these 3D images quickly after the crime is reported. If the scene is tampered with, the results from the scan will be impacted.

High-speed video capturing the formation of blood drops was performed by Laber et al.\(^19\) and were used for BPA training where students were taught pattern recognition for violent bloodletting events with a firearm. These videos were documented on Midwest Forensics Resource
Center (MFRC) website \(^{20}\). The phenomena that was muzzle gas influence on blood drops was apparent to researchers but wasn’t reported in literature until Taylor and Laber directly observed this impact muzzle gases had using shadowgraphy\(^{21}\). The retroreflective technique they used provided a large field of view (FOV) for the global blast and muzzle gas interaction to be visible. Even with previous work on optically measuring the expansion of muzzle gasses by Schmid and Shear in 1975 \(^{22}\), and Klingenberg in 1976-77 \(^{23,24}\), there still hasn’t been qualitative conclusions on the when and how the muzzle gases expelled from the gun influence the field of blood backspatter droplets.

Comiskey and Yarin 2019 presented the propellant gases exiting the gun muzzle as self-similar vortex rings \(^{21}\). In doing this, a velocity field of the muzzle gases was generated and was modeled influencing an artificial set of flying blood droplets. The model does show a difference in numerical results for muzzle gas interaction versus a normal blood stain pattern, however there is a lack of experimental data to validate the model. Some previous work on optical measurements of muzzle gases include Schmid and Shear in 1975 \(^{22}\), and Klingenberg in 1976-77 \(^{23,24}\).

### 1.2.2 Secondary droplet breakup

With the analysis of droplets in flight and especially involving the influence of oncoming muzzle gas flow fields, droplet atomization is important to highlight. Once a droplet from the bloodletting phenomena that is backspatter is introduced to an ambient air flow field, aerodynamics forces can cause the drop to react in various ways. This is referred to as secondary atomization. The primary atomization of the droplet was breaking away from the bulk fluid that was the blood source in the form of ligaments, then as individual drops. How the droplet reacts to an external flowfield is dependent upon droplet size, droplet velocity, fluid of droplet, and velocity of external flowfield relative to the droplet. These parameters combine to makeup important non-dimensional values such as the Weber number and Ohnesorge number. The Weber number relates
the drag force on the drop using relative velocity between the drop and external flow with the cohesion force of the droplet. Namely, the surface tension of the droplet. So, when the drag force overcomes the cohesion force denoted by the surface tension, the droplet will likely enter a breakup mode. Figure 1.2 shows a breakup map for critical Weber numbers. These regime transitions remain relatively constant for Ohnesorge numbers less than 0.1. The Ohnesorge number relates the viscous forces to the inertial and cohesion force. The viscosity of a fluid can largely impact its tendency to breakup, so the breakup transitions map in Figure 1.2 is most consistent for \( Oh < 0.1 \).

Vibrational and oscillatory reaction without breakup are observed from \( 0 < We < 11 \), bag breakup from \( 11 < We < 35 \), multimode breakup \( 35 < We < 80 \), and shear breakup \( We > 80 \). Figure 1.3 shows corresponding examples of these modes.

![Figure 1.2 Breakup regime map for droplets. Reproduced from Hsaing and Faeth with permission.](image-url)
Figure 1.3 Visual of breakup modes depicted in Figure 1.2. Reproduced from Guildenbecher et al. with permission.$^26$

**1.3 Research Objectives**

The overall goal of this thesis is to assist the advancement of the BPA field using experimental techniques to analyze droplets in the nearfield as well as the influence of muzzle gases on droplets and the global stain pattern left behind.

Considering previous work and the unpredictability of blood backspatter from test to test, this thesis will address the following objectives:

1. Compare droplet tracks observed using holography to the stain pattern left on the floor using a forward propagating model.

2. Compare the experimental expansion of muzzle gases for various firearms to a theoretical model characterizing the gas expelled from the muzzle as self-similar vortex rings.

3. Evaluate the influence of muzzle gases on blood backspatter, analyzing critical distances as well as blood stain location distributions.
1.4 Thesis Summary

The following depicts what will be covered in each chapter of this thesis.

Chapter 2 goes over the experimental setup of holography combined with shadowgraphy and backlit imaging to observe individual droplet tracks in three-dimensional space. Additionally, the analysis of that large set of tracks compared to the blood stains utilizes forward propagation model.

Chapter 3 covers the visualization of muzzle gas expansion of various firearms and compares the expansion to a numerical model. Additionally, the visualization of the effects of muzzle gases on blood backspatter and an analysis of large individual drops tracked while under muzzle gas influence.

Chapter 4 provides a summary of the work completed for this thesis and a discussion on future directions for this research.
CHAPTER 2. DROPLET TRAJECTORY AND SPATTER COMPARISON

Some of this work will be submitted for publication in *Experiments in Fluids* and is shown in an extended version here.

2.1 Holography

2.1.1 Experimental setup

The experimental configuration for the study of near field blood atomization and trajectory estimation was setup at the Izaak Walton Indoor Range in Ames, IA as seen in Figure 2.1. A suppressed L-AR15 was used to shoot Full metal jacket (FMJ), 5.56 caliber XM193 rounds into a 10mL cavity of blood mounted on a vertical target. Blood properties are depicted in Table 2.1, and for all experiments in this thesis animal (swine) blood at 20 °C was used. The pattern of blood droplets projected back towards the origin of the bullet were caught by butcher paper laid out perpendicularly to the vertically mounted blood source. The paper extended 4 m from the target to the gun muzzle, and 1.5 m left and right of the target. For this experiment, no external influences on the droplet trajectories were desired so a screen was placed 4m away from the target and 0.9 m in front of the rifle muzzle. Imaging systems used were located beyond the sides of the butcher paper. Both backlit imaging and shadowgraphy were used in conjunction with holography in order to provide a global visualization of the initial blast (backlit) and the particles crossing the holography field of view (FOV) (shadowgraphy).
Table 2.1 Properties of blood as specified in Attinger et al. For purposes of these experiments, animal blood at room temperature (20 °C) was used.

<table>
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<th>Liquid Properties</th>
<th>Human Blood</th>
<th>Animal Blood</th>
</tr>
</thead>
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<tr>
<td>Viscosity, ( \mu ) (10^{-3} Pa.s)</td>
<td>20 °C = 6.3</td>
<td>20 °C = 8.6</td>
</tr>
<tr>
<td></td>
<td>37 °C = 4.4</td>
<td>37 °C = 5.5</td>
</tr>
<tr>
<td>Surface tension between air and blood, ( \sigma ) (10^{-2} N/m)</td>
<td>20 °C = 6.1</td>
<td>20 °C = 6.5</td>
</tr>
<tr>
<td></td>
<td>37 °C = 5.2</td>
<td>37 °C = 5.1</td>
</tr>
<tr>
<td>Density, ( \rho ) (at 37 °C) (kg/m^3)</td>
<td>1060</td>
<td>1062</td>
</tr>
<tr>
<td>Hematocrit (%), ( H )</td>
<td>0.4 - 0.45</td>
<td>0.39 – 0.46</td>
</tr>
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</table>

The backlit imaging was comprised of two 500 W halogen lamps the projected onto a large 1.5 m screen. This imaging system was used to visualize the bullet impact and ensure repeatability for consistent blood backspatter. The illuminated image was captured on a high-speed CMOS sensor (Photron SA-Z) with a zoom lens to capture the target spatter plane. Similarly, shadowgraphy was used to visualize the droplets in a larger FOV as they interfere with the holography beam. This setup is shown in Figure 3.10.
Figure 2.1 Experimental setup (not to scale) consisting of backlit imaging for global visualization of the blast, holography for particle tracking through 3D space, shadowgraphy to show another visualization of the projectile spatter overlaying the holography FOV, and the butcher paper to capture the spatter pattern of blood from the blast.

The holography setup utilized a 15 mW Helium Neon (HeNe) laser beam of 632.8 nm (Melles Griot 25-LHP-171-249) to provide a collimated light field. The beam was expanded by a telescope using a +50 mm and +300 mm focal length plano-convex lenses, followed by a second telescope consisting of a +20 mm and +150 mm focal length plano-convex lens. The final lens was a 2-in. diameter, allowing for a collimated beam diameter of approximately 50mm. To conserve space on the optical board two Ag mirrors redirected the beam opposite that of the laser source directions as shown in Figure 2.2.
Figure 2.2 Holography beam layout to expand the beam to a 50 mm diameter.

The collimated beam of light generated crossed through the shadowgraphy field of view at the target plane and holograms were captured directly on a high-speed CMOS sensor (Photron SA-X2) with a quartz window to protect the sensor from droplet splashing and flying debris. Figure 2.3 presents the bullet impact and initial backspatter visual using the backlit imaging system. This imaging setup is necessary to confirm that each backspatter that is analyzed was a successful impact to the middle of the blood source. As shown in Figure 2.1, the holography and shadowgraphy imaging systems are located farther away from the blood source than the backlit imaging. The holography beam is located 630 mm down range from the blood source crossed with holography shown in Figure 2.4, where the holography is displayed inset in each shadowgraphy frame. For both Figure 2.3 and Figure 2.4, the same time instances are shown, specifically 3.8 ms, 15.8 ms, 27.8 ms, and 39.8 ms. These range of times displayed the initial spatter for times 3.8 ms and 15.8 ms in the backlit imaging shown in Figure 2.3(a)(b), then as the spatter continues to form and droplets travel farther the holography begins to identify droplets as show in the inset of Figure 2.4(c)(d).
Figure 2.3 Backlit imaging to visualize the blood backspatter spray and droplet formation near the blood source target. Image timestamps (a) 3.8 ms, (b) 15.8 ms, (c) 27.8 ms, and (d) 39.8 ms.
Figure 2.4 Shadowgraphy sequence with holography inset corresponding to the backlit images observed in Figure 2.3. (a) 3.8 ms, (b) 15.8 ms, (c) 27.8 ms, and (d) 39.8 ms post bullet impact. Holography frames showing particle identification and depth designation using a color bar.
Camera settings and field of view for both imaging systems can be seen in Table 2.2.

Table 2.2 Imaging specifications for shadowgraphy and holography setups.

<table>
<thead>
<tr>
<th></th>
<th>Shadowgraphy (large field)</th>
<th>Holography (small field)</th>
<th>Backlit (large field)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frame rate (kHz)</strong></td>
<td>25</td>
<td>12.5</td>
<td>25</td>
</tr>
<tr>
<td><strong>Exposure (µs)</strong></td>
<td>5</td>
<td>1.25</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Magnification (µm/pixel)</strong></td>
<td>200</td>
<td>20</td>
<td>400</td>
</tr>
<tr>
<td>Field of view (mm x mm)</td>
<td>200 x 200</td>
<td>20 x 20</td>
<td>300 x 300</td>
</tr>
<tr>
<td>Feature resolution</td>
<td>~ 1 mm</td>
<td>~50 µm</td>
<td>~ 2 mm</td>
</tr>
<tr>
<td>Downrange Distance (mm)</td>
<td>520</td>
<td>630</td>
<td>0</td>
</tr>
</tbody>
</table>

The holography imaging was purposefully set to half of the shadowgraphy frames per second in order to synchronize them, which allowed a time-synchronous holography frame from alternating shadowgraphy frames. The camera image acquisition was initialized by an acoustic trigger mounted 120 cm from the barrel of the rifle. The acoustic trigger sensitivity was adjusted to only trigger on the sound of a gunshot. After the rifle triggered the cameras to start, each camera saved frames both before and after the trigger was acquired. Specifically, holography saved frames -200 to 3000 while shadowgraphy saved -400 to 6000 frames relative to the timing trigger. Due to the supersonic bullet speed and signal delays, it was necessary to save frames before the trigger to capture the entire event.

### 2.1.2 Optical depth uncertainty

A potential shortcoming for digital holography as an experimental technique is the significant uncertainty in the optical depth resolution as compared to the in-plane resolution. The finite aperture of the hologram, meaning the diffraction patterns generated by the interference of the particle field reach the edge of the digital sensor, limits the depth where particles can be numerically reconstructed into focus\textsuperscript{27,28}. This depth is proportional to \(d^2/\lambda\), where \(d\) is the diameter
of the particle and $\lambda$ is the wavelength of the illuminating laser beam \(^{29}\). With the goal of determining three-dimensional droplet position following bullet impact, the accuracy of the calculated velocity is important. To successfully determine particle depth, various processing algorithms have been developed utilizing image amplitude and edge sharpness \(^{30,31}\).

### 2.1.3 Image processing with HOLOSAND code

#### 2.1.3.1 Methodology

The experiments involving holography utilized a Helium-Neon (He-Ne) laser to illuminate the droplet field. The particles passing through the beam of light created a diffraction pattern which is characterized by scalar diffraction theory. A discrete hologram $h(m,n)$ ($m$ and $n$ being the horizontal and vertical axis of the hologram respectively) is created by the interference between the reference beam and the light diffracted from the droplets. The digital sensor of a Photron SA-Z high-speed camera captured this hologram. Reconstruction of the hologram to desired droplet depths in the $z$-direction was performed numerically with the HOLOSAND code maintained by Sandia National Laboratories \(^{32}\). To reconstruct the droplet field, the code evaluated the Rayleigh-Sommerfeld diffraction integral equation for specified $z$ depth locations in three-dimensional space. The reconstructed hologram amplitude was solved numerically in the frequency domain by

$$A(x, y; z) = \left| F^{-1} \left\{ F \{ h(m, n) \} G(m', n', z) \right\} \right|$$

(2.1)

where $F$ and $F^{-1}$ indicate the fast-Fourier transform and inverse fast-Fourier transform, and $G(m', n', z)$ is the analytical solution to the Fourier transform. For the Rayleigh Sommerfeld kernel, this is given by \(^{29}\)

$$G(m', n', z) = e^{jkz\sqrt{1-(\lambda m/M\Delta\xi)^2-(\lambda n/N\Delta\eta)^2}}$$

(2.2)

Here, $k$ is the wavenumber, $M$ and $N$ are the pixel extents in the horizontal and vertical directions and $\Delta\xi$ and $\Delta\eta$ are the pixel size in the respective directions.
Following reconstruction over a range of planes, the HOLOSAND implementation of the Hybrid method introduced by Gao et al.\textsuperscript{33} was used to identify particle boundaries that consists of selecting pixels with minimum intensity and maximum edge sharpness. Each hologram is reconstructed at specified incremental depths and scanned for particles using the Hybrid method. Eventually, a volumetric reconstruction is attained mapping out the minimum intensity pixels, which then based on intensity thresholds, particle edges are identified. Sharpness of these particle edges are gauged based on the Tenengrad operator

\[ \tau(x, y; z) = [A(x, y; z) \ast S_x]^2 + [A(x, y; z) \ast S_y]^2 \]  \hspace{1cm} (2.3)

where $S_x$ and $S_y$ represent the horizontal and vertical Sobel kernels respectively and the two-dimensional convolution is indicated by the $\ast$ operator. Droplets are considered in focus at the depth with a maximum Tenengrad value. For an identified droplet, an initial $z$-depth is approximated by averaging the depth of each edge observed by the Tenengrad operator. Then a final $z$-depth is estimated by implementing two refinement steps where a new local window that is twice the size of the identified particles is used alongside new optimal thresholds that are determined for that localized window for that droplet\textsuperscript{33}.

2.1.3.2 \textit{Processing routine}

Utilizing the above method, the HOLOSAND code (in MATLAB) was used to read in saved hologram image files, normalize the image using the background light field, and sweep through $z$ depths searching for objects of minimum amplitude and maximum edge sharpness. The hybrid method was then applied to detect position and particle likeness in the reconstructed hologram. Minimizing the intensity and locating maximum edge sharpness already on the reconstructed hologram helped further refine particle depth. Advantage of the hybrid refinement is that the optimal thresholds for particle detection are numerically determined minimizing the
guesswork of thresholds to apply to the dataset. After the first refinement, a second localized refinement for each particle is performed. A sub-window is created around identified particles, and separate thresholds are set for edge sharpness and a final depth is determined for that individual particle.

The steps of DIH processing for particle identification are highlighted in Figure 2.5, where the steps all the way from panel (a) showing the raw hologram to panel (f) showing the reconstructed hologram with distinguished particles and their respective depths. These droplets range from 200-400 µm observed at a distance of 630 mm from the target. Figure 2.5(a) and (b) show the background light field and hologram, with the normalized hologram shown in Figure 2.5(c). In Figure 2.5(d) the reconstructed field amplitude is shown at a depth of 855 mm, and the Tenengrad at the same depth is shown in Figure 2.5(e), indicating regions of high sharpness. Finally, Figure 2.5(f) shows sub-windows for each identified object refocused to the optimal depth. The colored circles show the equivalent diameter of these objects, and the color indicates the optimal depth (via the Hybrid refinement method) for each droplet.
Figure 2.5 Hologram processing steps indicating the (a) background reference light field, (b) the raw hologram amplitude, (c) the normalized hologram, (d) the reconstructed hologram at depth $z = 855\,\text{mm}$, (e) the Tenengrad at same optical depth, (f) and the identified drops with overlaid depth scaling defined by the color bar.

Following track identification, several additional filtering steps were taken to rule out spurious particle tracks. The droplet size was defined using the size of the two-dimensional area of the identified object. The area having the same as that of an equivalent circle determined the droplet diameter $d$. Minimum droplet size was set to $100\,\mu\text{m}$ because that is the smallest stain that can be reliably counted on the butcher paper used to collect bloodstain patterns. The identified objects were then linked using a Hungarian particle linking algorithm$^{34}$, as introduced by Guildenbecher et al. for DIH measurements at high-repetition rates$^{35}$. Identified tracks were filtered iteratively to select improved tracks. The primary direction of the droplets should was in
the $x$-direction assuming minimal change vertically, so a maximum linking distance of 2.5 mm and a maximum vertical change of 0.5 mm were applied for the initial linking. Not every particle is successfully linked in the first step, so the linked tracks were then ran through a multiframe filtering function with the following filters: 25% diameter tolerance, 25% $x$-direction tolerance, 25% $y$-direction tolerance, and a minimum track length of 5.

An example of the particle linking outcome is shown in Figure 2.6 for the region highlighted in panel (a). Successive droplets identified in frames are shown in Figure 2.6(b), indicated by the varying colors. The successfully linked particles are shown Figure 2.6(c), where 4 tracks are identified. Note that no track is identified for the lower center particles as there are two overlapping sets of identified objects corresponding to two distinct droplets.

Figure 2.6 (a) Single frame of reconstructed hologram, (b) particle linking 6 frames after hologram, (c) multiframe filtered tracks and all identified objects indicated by the open circles.

In order to shift the holography reference frame for particle tracks to the lab frame, a coordinate transform was performed. Figure 2.7 depicts the coordinate transform orientation,
taking the holography sensor coordinate system \((\xi, \chi, \eta)\) and transferring it to the lab coordinate system \((x, y, z)\) located beneath the blood source on the floor.

<table>
<thead>
<tr>
<th>Label</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>980 mm</td>
</tr>
<tr>
<td>b</td>
<td>657 mm</td>
</tr>
<tr>
<td>(\Theta)</td>
<td>12 deg.</td>
</tr>
</tbody>
</table>

Figure 2.7 Coordinate transform for holography data to transfer the sensor coordinates to the lab coordinates origin located on the floor underneath the blood source.

The matrix transforms required were two translation transforms and one rotational transform defined as

\[
T_1 = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & a \\
0 & 0 & 0 & 1
\end{bmatrix};
R = \begin{bmatrix}
\cos(\Theta) & 0 & -\sin(\Theta) & 0 \\
0 & 1 & 0 & 0 \\
\sin(\Theta) & 0 & \cos(\Theta) & 0 \\
0 & 0 & 0 & 1
\end{bmatrix};
T_2 = \begin{bmatrix}
1 & 0 & 0 & b \\
0 & 1 & 0 & \text{height} \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}. \tag{2.4}
\]

Here \(a, b\) and \(\Theta\) correspond to the measurements in Figure 2.7. Then to determine the coordinate transform the translation and rotational transforms are multiplied as follows,

\[
[x; y; z; 1] = [T_2][R][T_1][I]] * [\xi; \eta; \chi; 1] \tag{2.5}
\]

2.1.4 Track Error Analysis

As previously mentioned, optical depth uncertainty is a limitation for the digital inline holography technique. To quantify this uncertainty for the droplets position, size, and velocity an
error analysis was performed for each individual track. Figure 2.8 shows an individual track with a least-squares fitted track based on the linked objects. These tracks consist of a modeled $x$, $y$, and $z$ position as well as the diameter of the particle over multiple frames. Each coordinate track was fitted with a linear position model and constant diameter highlighted by the blue lines shown in the left column of panels in Figure 2.8. The fits result in an analytical derivative to model the three-dimensional velocity. The velocity vector, position and diameter represent the main characterization for each track.

Figure 2.8 An individual track depicting $x$-position, $y$-position, $z$-depth, and particle size as the droplet was tracked in three-dimensional space.
Each tracked object was fitted with a linear trend and the mean squared error was computed by

$$MSE = \frac{1}{n} \sum_{i=1}^{n} \left( y_i - \hat{f}(x_i) \right)^2$$

where $y_i$ is the data value, $\hat{f}(x_i)$ is the predicted function, and $n$ is the number of data points. The square root of the MSE is the unbiased value of standard deviation $\sigma_{\text{MSE}}$. Each track then had defined standard deviation values (assuming normal distributions) of $\delta_x$, $\delta_y$, $\delta_z$, and $\delta_D$ using this technique. Incorporating the spatial errors, uncertainty for the velocities are related to the standard deviation by

$$\delta v_x = \sqrt{\frac{2(\delta_x)^2}{\Delta t}} ,$$

where $\Delta t$ is the time the droplet was tracked for, and $\delta x$ was the standard deviation in the $x$-direction. A three-dimensional velocity error can then be estimated from

$$\delta V_{3d} = \sqrt{2(V_x \delta_x)^2 + 2(V_y \delta_y)^2 + 2(V_z \delta_z)^2} \over \Delta t .$$

Additionally, Re and We errors for each particle are estimated by

$$\delta Re = \sqrt{\left( \frac{\rho_a D \delta V_{3d}}{\mu_a} \right)^2 + \left( \frac{\rho_a V_{3d} \delta D}{\mu_a} \right)^2}$$

and

$$\delta We = \sqrt{\left( \frac{2\rho_a V_{3d} D \delta V_{3d}}{\sigma} \right)^2 + \left( \frac{\rho_a V_{3d}^2 \delta D}{\sigma} \right)^2} ,$$

where $\rho_a$ is the density of air, $\mu_a$ is the viscosity of air, and $\sigma$ is the surface tension of blood at room temperature.
2.1.5 Results

Using the above strategy, we observed the backspatter of a gunshot with the holography beam 630 mm from the blood source and approximately one meter off the ground. Providing a buffer between the target and holography FOV (as shown in Figure 2.1) does slow down the particles, but also provides a more fully formed, sparse droplet field. This makes holography data less cluttered and provides more confident particle tracks.

Even with a slightly sparser field and fully formed drops, the initial set of tracks presents inconsistencies. These include measurement accuracy, biased data, and outright unnatural values. In order to combat these, filters were used to extract these tracks and present a realistic set of droplet trajectories to analyze.

Two parameters specifically, were used to provide constrain on the data set. More precisely, the depth error $\delta_z$ and depth velocity $V_z$ were chosen because of the accuracy of the depth measurement as well as the physical biased values seen in the depth velocity. The momentum of the majority of particles analyzed is in the $x$-direction so $V_y$ and $V_z$ should have similar velocity distributions, however the depth uncertainty presented in holography doesn’t fully allow this.

Table 2.3 shows the results of various filters applied to the full dataset of 2506 tracks which is found in the first row of the table. The $\pm V_z$ filter places positive and negative bounds on the $z$-velocity distribution as the values should hover around zero. This bound is justified by the distribution of $V_y$ which barely breaks 2 m/s as seen in the raw data distributions shown in Figure 2.9 and Figure 2.10. The $>\delta_z$ filter erases tracks with calculated depth error higher than the threshold set.
Table 2.3 Holography track filters utilizing depth velocity constraints both positive and negative of the tabled value, as well as calculated depth error extracting tracks with error higher than the tabled value. Important results include the mean velocity, diameter, $Re$, and $We$ number as well as the number of tracks remaining after applying the filter.

<table>
<thead>
<tr>
<th>±$V_z$ filter [m/s]</th>
<th>&gt;$\delta z$ filter [mm]</th>
<th>Tracks</th>
<th>$\delta V_x$ [m/s]</th>
<th>$\delta V_y$ [m/s]</th>
<th>$\delta V_z$ [m/s]</th>
<th>$\delta D$ [μm]</th>
<th>$\delta Re$</th>
<th>$\delta We$</th>
</tr>
</thead>
<tbody>
<tr>
<td>n/a</td>
<td>n/a</td>
<td>2506</td>
<td>5.14E-03</td>
<td>6.68E-03</td>
<td>1.651</td>
<td>11.722</td>
<td>165.692</td>
<td>5.566</td>
</tr>
<tr>
<td>5</td>
<td>n/a</td>
<td>2233</td>
<td>4.27E-03</td>
<td>5.43E-03</td>
<td>1.313</td>
<td>11.276</td>
<td>41.479</td>
<td>0.245</td>
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<tr>
<td>2</td>
<td>n/a</td>
<td>1716</td>
<td>3.52E-03</td>
<td>4.60E-03</td>
<td>1.110</td>
<td>11.300</td>
<td>17.186</td>
<td>0.082</td>
</tr>
<tr>
<td>n/a</td>
<td>5</td>
<td>2440</td>
<td>4.92E-03</td>
<td>6.29E-03</td>
<td>1.401</td>
<td>11.335</td>
<td>96.030</td>
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</tr>
<tr>
<td>n/a</td>
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<td>2197</td>
<td>4.82E-03</td>
<td>5.86E-03</td>
<td>1.203</td>
<td>11.114</td>
<td>73.603</td>
<td>0.637</td>
</tr>
<tr>
<td>n/a</td>
<td>2</td>
<td>1591</td>
<td>4.98E-03</td>
<td>5.80E-03</td>
<td>1.046</td>
<td>10.917</td>
<td>64.594</td>
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</tr>
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<td>5</td>
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<td>4.18E-03</td>
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<td>1.057</td>
<td>10.984</td>
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</tr>
<tr>
<td>5</td>
<td>3.5</td>
<td>2078</td>
<td>4.20E-03</td>
<td>5.03E-03</td>
<td>1.110</td>
<td>11.048</td>
<td>34.819</td>
<td>0.209</td>
</tr>
</tbody>
</table>

It is observed in Table 2.3 that $x$ and $y$-velocity error along with error in particle diameter do not vary significantly with the application of the filters in comparison to $z$-velocity error and the non-dimensional parameter error in $Re$ and $We$. Notice that without any filters the Reynolds and Weber number error is significantly high, this is due to the error propagation of the three-dimensional velocity, that $Re$ and $We$ require, blowing up with unrealistic track values. Majority of individual filters returned the non-dimensional error to a respectable value. Individually, each filter did assist the dataset in deleting unwanted tracks, as well as nearing $\delta V_z$ closer to 1 m/s. However, when used in combination, less tracks were loss with a similar results in $\delta V_z$, $\delta Re$, and $\delta We$. That is why the filter of ±$V_z$ = 5 m/s and $\delta z < 3.5$ mm was selected to further analyze this data. Distributions and errors for the original unfiltered data set are depicted in Figure 2.9 and Figure 2.10, while the same distributions and errors are presented with the chosen filter in Figure 2.11 and Figure 2.12. It is important to note that the distribution patterns do not change when the filter is applied.
Figure 2.9 Original raw data distributions of holography droplet track parameters. Specifically (a) x-velocity, (b) y-velocity, (c) z-velocity also known as optical depth velocity, and (d) droplet diameter. Each histogram is also accompanied by a mean error bar depicting the mean error for one track in that distribution.
Backspatter blood droplet’s momentum was directed primarily in the $x$-direction, explaining the minimal movement in both the $y$ and $z$-directions. For the filtered set of data, particle diameters ranged from 100-500 µm with a few droplets pushing 1 mm in diameter. At 630 mm away from the blood source, many of the larger droplets have either fell below the field of view or have experienced secondary breakup from the initial impact phenomena. This is why many of the droplets being less than 500 µm makes sense. Droplet velocities in the $x$-direction ranged from 0-15 m/s, while the bulk of the droplets were 150-250 µm going 0-10 m/s. Velocity in the $z$-direction, as expected, was very close to zero. The distribution in the $z$-direction should be similar to the $y$, however it stretches past ±5 m/s. This is due to the optical depth uncertainty discussed in section 2.1.2.
Figure 2.11 Filtered set of holography track data distributions. Specifically (a) x-velocity, (b) y-velocity, (c) z-velocity also known as optical depth velocity, and (d) droplet diameter. Each histogram is also accompanied by a mean error bar depicting the mean error for one track in that distribution.
Additionally the Reynolds and Weber number distributions and error were also showcased to clarify that the droplets fall into the intermediate Reynolds number range \((0.1 < \text{Re}_d < 2000)\), as well as stay out of the first breakup region with \(\text{We} < 11^{25}\).

Figure 2.12 Filtered distributions of non-dimension parameters (a) Reynolds number and (b) Weber number.

An additional reason to the use of a filter was analyzing the droplet speed versus size over time. Figure 2.13 shows the trend of three-dimensional velocity plotted against droplet size over time, comparing the full original data set and the filtered set of tracks. The trend of larger droplets moving faster holds true throughout the 102 ms shown, however it is obvious that as time increases the trend starts to flatten with most late droplets moving 6 m/s or slower. This is a good way to show the impact of air drag on blood droplets and how quickly they are affected in a tenth of a second post impact. It is observed that Figure 2.13(a) does show the trend previously discussed
but there are many stray droplets not adhering to the predicted fit. Majority of the stray droplets were taken care of by the chosen filter, providing additional support behind the filtered data set outputting realistic tracks.

![Graphs showing 3D particle velocity versus size over time.](image)

Figure 2.13 3D particle velocity versus size over time. Comparing (a) Original set of raw data to (b) the filtered data set.

This data set of holography tracks consisting of position, size, and velocity were then propagated forward using a blood droplet trajectory model similar to that depicted in Attinger et al. 2019 37. So now the droplet information obtained in flight is no represented as physical blood stains on the ground. With this, a direct comparison of these stains to the physical pattern of blood stains generated from the gunshot backspatter can be observed in Figure 2.14. With the forward propagated stain size, distance from blood source, and projection angle are seen on top in Figure 2.14(a), and the same distributions are shown for the real blood stain pattern in Figure 2.14(b).
Comparing the stain diameters of propagated holography tracks to the blood stains, a similar distribution is observed despite the extreme count difference. Holography tracks having counts on the order of thousands while the blood stains from the backspatter have stain counts in the tens of thousands. The holography tracks cover the size distribution well, including the strong bias of stain sizes at 200 μm. Overall, the size distribution does show good comparisons between the data sets.

More significant differences appear when comparing the stain distance from blood source. The initial peak of smaller stains around 100 cm from the blood source is captured, however the holography tracks lack stains observed 250-500 cm from the blood source. This is inherently due to the limited FOV of the holography imaging system. Many droplets were not observed that were located above the holography beam. These droplets would travel farther and account for the distinct difference in the distance distributions. The holography tracks to not properly represent the stain data for stain distance from blood source.

Lastly, droplet projection angle was compared between the projected holography tracks and the blood stain pattern. The physical stains show a very strong bias towards the zero angle that is slightly represented by the holography tracks. The bias is not as strong for the holography, and the distribution is much thicker. This difference is partially due to the sheer number of stains the physical pattern has to emphasize that zero angle bias. Additionally, when considering angular projection, the uncertainty in the depth measurement does become relevant. The accuracy of the depth measurement could also be contributing to the wider distribution.
2.2 Conclusion

In this chapter, holograms were reconstructed to identify droplets in three-dimensional space. The droplets were then linked from frame to frame and filtered for realistic particle tracks using the HOLOSAND code. Due to the fact that holography presents a large uncertainty in the depth location, an error estimation was performed to provide clarity on the accuracy of this data. The original set of tracks displayed a large error for the of over 1.5 m/s for \( z \) velocity and an unreal
error for non-dimensional parameters $Re$ and $We$ relative to the distributions shown. This meant there were still multiple unreal tracks still present in the data set, so multiple filters were applied to extract the unreal data. Two parameter that filters were applied to include the depth position error $\delta z$ based on the inconsistent accuracy of the measurement in comparison to the other coordinate directions, as well as a physical constraint on $V_z$. Velocity distributions in the $z$ and $y$-directions should have been similar with the majority of the droplet momentum in the $x$-direction, therefore constraining the allowed $V_z$ values would also filter unwanted tracks. Through a comparison analysis a filter of $\pm \delta V_z = 5$ m/s and $\delta z < 3.5$ mm was selected. $\delta V_z$ was decreased to 1.1 m/s and $\delta Re$ went from 166 to 35. The filter was better visualized in Figure 2.13 looking at the trend of droplet velocity versus size over time. The original set of data consisted multiple values significantly straying from the obvious trend while the filtered data presented nice clean trend of droplet velocity versus size decreasing over time.

Propagating the holography tracks forward and representing them as stains did provide comparisons to the physical stain patterns collected from the blood backspatter. The stain size distributions showed close comparisons despite the difference in stain count. The holography tracks did not properly represent the stains observed farther from the blood source, and the projection angle was similar but lacked a stronger bias towards the zero angle.

Moving forward, the axisymmetric shape of blood backspatter will be used in hopes of better representing physical stain patterns using holography track data. The tracks collected can potentially be rotated about the bullet axis to synthetically simulate the cone shape that backspatter inherently creates from a gunshot. If rotated at multiple angles this would assist in observing stains farther from the blood source, as well as a stronger bias towards zero-degree projection angle due to the number of stains that would be added.
CHAPTER 3. THE ROLE OF MUZZLE GASES ON BLOOD BACKSPATTER

In this chapter, the influence of the forward-propagating and expanding muzzle gases on droplet backspatter is investigated. High-speed imaging of the blood backspatter is used to capture the dynamics for individual blood backspatter events, allowing comparison with collected backspatter patterns on the floor and on vertical spatter targets. In addition, the muzzle gas expansion is characterized using large field shadowgraphy for comparison with self-similar turbulent vortex theory.

Publications including these data are in preparation for submission\(^1\),\(^2\) but this chapter presents an expanded discussion of the experimental methods.

3.1 Expanding gas field from muzzle gases

3.1.1 Experimental setup

Muzzle gas imaging experiments were performed to capture time-resolved muzzle gas plumes over the relevant temporal and spatial extent where experiments indicate interactions of the expanding plume with blood back spatter. Experiments were performed at an indoor shooting range (Izaak Walton Indoor Range in Ames, IA), with a retroreflective shadowgraphy configuration as experiment shown in Figure 3.1 and Figure 3.2. The firearms used were a Rock River Arms 0.223-in. caliber rifle with a muzzle flash suppressor and XM193 0.223 caliber rounds (5.56 mm diameter); as well as, a Smith and Wesson 9 mm pistol with 4.25 in. barrel length and AE9AP rounds. The muzzle was held at height of 1 m off the floor, as with blood spatter experiments and rounds were fired at a fixed 1 m height target down range. The shadowgraphy

\(^1\) To be submitted to Physics of Fluids ‘Different Senarios of Interaction of Blood Backspatter with Propellant Gases’, Gen Li, Nathaniel D. Sliefert, Alexander L. Yarin, James B. Michael

\(^2\) To be submitted to Experiments in Fluids ‘Experimental and Numerical Study of Blood Backspatter Interaction with Propellant Gases’, Nathaniel D. Sliefert, Gen Li, Alexander L. Yarin, James B. Michael
sequences were triggered using an acoustic trigger (Sound Trigger-1505 produced by Kapture Group Inc.) placed 0.5 m from the muzzle exit.

To visualize the muzzle gas expansion in a large field of view, a retroreflective shadowgraphy setup similar to that of Taylor and Labor\textsuperscript{38,39} was used. The optical system, shown in the diagram of Figure 3.1, consisted of a 75W Xenon short arc lamp (USHIO 75-XO) which was focused onto a 45-degree, 5 mm diameter rod mirror using a 2-in. diameter, 2-in focal length spherical mirror. The rod mirror was fixed on an optical flat and mounted on an objective lens. The expanding beam was then projected onto two retroreflective steel placards (3M Diamond Grade acquired from Iowa Department of Transportation). The centerline plane of the retroreflective shadowgraphy was captured using a high-speed CMOS camera (Photron SA-Z) at a frame rate of 20 kHz and an exposure of 2.5 μs. The objective lens was 35 mm and resulted in a field of view of 1 m by 0.9 m, with a magnification of approximately 1 mm/pixel. To capture the full range of relevant muzzle gas motion, sequences were captured for two positions downrange from the muzzle centered at zero and 0.7 m. 20 shots were taken for both the rifle and the pistol in the FOV (shown below) and offset 0.7 m out of the FOV.

The arrangement of the optical system, firearm location, and firing target location are shown in Figure 3.1. For each firearm, shadowgraphs were acquired for 20 separate shots. The image processing routine will be discussed in the subsequent section.
Figure 3.1 Experimental setup for large field of view observation of muzzle gas expansion, showing the light source, retroreflective placard, firearm location, and the imaging camera.

Figure 3.2 The configuration for muzzle gas expansion tests showing the relative position of the retroreflective placards, the shadowgraphy illumination, the acoustic trigger, and the positioning of the firing target and firearm.
3.1.2 Image processing

Shadowgraphs of the muzzle gas expansion were processed in MATLAB to extract the muzzle gas front for each frame. Representative frames for the pre-processing steps are shown in Figure 3.3. First, each raw muzzle gas image (Figure 3.3(b)) was normalized by a mean background taken prior to the shot (Figure 3.3(a)). The resulting light-field normalized image shows improved contrast, and a typical example is shown in Figure 3.3(c).

Figure 3.3 Image pre-processing steps showing the (a) background light field image, (b) raw shadowgraphy image of muzzle gases, and (c) normalized muzzle gas image of the suppressed LAR-15 5.3 ms after the bullet left the muzzle showing improved contrast.
Next, a Canny edge detection algorithm was applied to the light-field normalized image to identify contours in the muzzle gas shadowgraphy field. The typical sensitivity threshold in the edge finding algorithm was 0.2-0.3 for the normalized images but required adjustment as the muzzle gas field expanded and density gradients decreased. The edge detection resulted in a binary set of contours, as shown in Figure 3.4(a).

In order to track the extent of muzzle gas expansion from the detected edges, the image was first dilated to fill voids between edges, and subsequently eroded to return the outer physical edge to the original position. The dilation and erosion steps are depicted in Figure 3.4(b) and (c), respectively. This process was implemented using the ‘imdilate’ and ‘imerode’ functions in MATLAB, and a disk geometry was used with a pixel radius ranging from 7-14 pixels. In addition, the image was filtered to only retain the largest object (the muzzle gas extent). The main muzzle gas region is highlighted by the bounding box shown in Figure 3.4(c).

Using the bounding box, the muzzle gas front was identified pixel by pixel and overlaid onto the normalized image shown by the red contour in Figure 3.4(d). As this is just a two-dimensional view of the muzzle gasses, the information extracted from each individual shot was the leading-edge position and radial edge expansion positions relative to the end of the firearm muzzle. This was done over multiple frames ranging in time from approximately 0 to 40 ms post bullet exit from the muzzle. An example sequence showing the tracking of the muzzle gas leading edge is shown for a suppressed LAR-15 rifle case in Figure 3.5.
Figure 3.4 (a) Binarized edge detection, (b) dilated edges to fill muzzle gas feature, (c) eroded the dilated image to return the edge to real gas edge location in addition to filtering features to identify the muzzle gas region shown by the red box, (d) and the muzzle gas front identified and overlaid on the normalized image.
3.1.3 Self-similar vortex rings

This section contains a brief overview of self-similar vortex rings formed from a gunshot and how they may subsequently interact with backspatter droplets. The approach was introduced by Comiskey and Yarin \(^{21}\), and the nomenclature below is consistent with their approach.

Muzzle gas interactions can result in significant impact on the trajectory and landing location of blood backspatter drops. The experimental approach just described provides a characterization of the muzzle gas expansion, but for completeness this section will compare some results for the expansion with the theory of self-similar turbulent vortex ring expansion to describe the muzzle gas evolution.

The self-similar vortex evolution is given in terms of a non-dimensional stream function \(\tilde{\psi}\) and non-dimensional vorticity \(\tilde{\Omega}\) by solutions present in the vortex rings are depicted as

\[
\tilde{\psi}(r, z) = \frac{r^2}{64\sqrt{2\pi}l_0^{3/2}s^3} \left[ \text{erf}(s) - \frac{2s}{\sqrt{\pi}} \exp(-s^2) \right]
\]

and

\[
\tilde{\Omega}(r, z) = \frac{r^2}{64\sqrt{2\pi}l_0^{3/2}s^{5/2}} \exp(-s^2)
\]

Figure 3.5 Muzzle gas shadowgraphy sequence for the suppressed LAR-15, where the front of the gas expansion is overlaid by the red contour curve.
These expressions are parameterized in terms of $r_m$ and $z_m$ denoting the radial and axial location of maximum vorticity, while $\lambda_0$ is an empirical constant without dimension and s is a placeholder variable. All depicted as,

$$s = \sqrt{\frac{(z-z_m)^2 + r^2}{8\lambda_0}}, \hspace{1cm} (3.3)$$

$$r_m = 2\sqrt[2]{\lambda_0}, \hspace{1cm} (3.4)$$

and

$$z_m = \frac{1}{2\sqrt{2\pi}(\pi\lambda_0)^{3/2}} \left[ 1 - \frac{\sqrt{e\pi}}{8\sqrt{2}} \text{erf} \left( \frac{\sqrt{2}}{2} \right) \right] \hspace{1cm} (3.5)$$

The single empirical constant $\lambda_0$, appears and is related to the ratio of the radial expansion to the axial expansion, $\alpha = \frac{r_m}{z_m}$. The constants are related by,

$$\lambda_0 = \sqrt{\alpha} \left[ \frac{1 - \sqrt{e/8\text{erf}(1/\sqrt{2})}}{4\sqrt{2\pi}^{3/2}} \right]^{1/2} \hspace{1cm} (3.6)$$

Lastly, to dimensionalize the self-similar parameters and allow comparison with the experimental data, the following relationships can be used:

$$\tilde{r} = \frac{r}{(P_0 t)^{1/4}}, \hspace{0.5cm} \tilde{z} = \frac{z}{(P_0 t)^{1/4}}, \hspace{0.5cm} \Omega = \frac{1}{\Omega}, \hspace{0.5cm} \psi = \frac{P_0^{3/4}}{t^{1/4}} - \psi \hspace{1cm} (3.7)$$

where $P_0$ is the initial vortex impulse ($\text{cm}^4 \text{s}^{-1}$). From the self-similar theory, there are two constants necessary to describe the evolution of the turbulent vortex expansion: the ratio of radial to axial expansion $\alpha$ and the impulse for the muzzle gas, $P_0$. It should also be noted that the dimensional axial and radial expansion scale with $(P_0 t)^{1/4}$, meaning that the radial and horizontal displacement of the vortex rings is expected to follow this power law trend.
3.2 Results

For the retroreflective shadowgraphy setup, five different modifications of firearm setups were captured. Table 3.1 lists the range of firearms used, including (a) the suppressed rifle, (b) the rifle with a compensator, (c) the rifle with a muzzle brake, (d) the pistol, and lastly (e) the pistol with a suppressor. For the purpose of this work, only (a) and (d) were analyzed for power-law trends as mentioned, but example sequences are shown for each firearm case.

Table 3.1 List of firearms imaged using the retroreflective setup. For the purpose of this dissertation, only (a) and (d) were analyzed.

<table>
<thead>
<tr>
<th>Firearm</th>
<th>Modification</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Rock River Arms Rifle</td>
<td>Yankee Hill Phantom 223 suppressor</td>
</tr>
<tr>
<td>(b) Rock River Arms Rifle</td>
<td>Yankee Hill Phantom muzzle brake</td>
</tr>
<tr>
<td>(c) Smith &amp; Wesson 9mm pistol</td>
<td>n/a</td>
</tr>
<tr>
<td>(d) Smith &amp; Wesson 9mm pistol</td>
<td>Creative arms suppressor</td>
</tr>
<tr>
<td>(e) Rock River Arms Rifle</td>
<td>KX3 compensator</td>
</tr>
</tbody>
</table>

Each firearm case setup can be seen visually in Figure 3.6 and Figure 3.7. By eye the only case that might be tough to compare to the self-similar vortex theory would be Figure 3.7(e) a rifle with a compensator. At least in this FOV, it is not obvious that vortex rings are forming and may need to be analyzed later in time. Note the time for the compensated rifle’s muzzle gas expansion compared to every other case. Nearly reaching the bound of the FOV in a couple milliseconds, while the other cases do look to possibly fit the power-law dependence suggested by Comiskey and Yarin. The suppressed rifle (Figure 3.6(a)) expands faster axially than the muzzle brake and both pistol cases, while the muzzle brake (Figure 3.6(b)) expands radially at a similar rate. Both the pistol (Figure 3.6(c)) and suppressed pistol (Figure 3.6(d)) expand slower radially in comparison.
An additional observation of Figure 3.6 and Figure 3.7 is the difference between case (a), (b), and (c), being the same exact rifle and ammunition specified in section 3.1.1 but with different modifications. A suppressor, compensator, and muzzle brake respectively show very different muzzle gas formation in time. Speed and formation of the self-similar vortex rings varies significantly, which highlights the importance of knowing firearm attachments when trying to apply muzzle gas interactions to a gunshot case.

Notice the difference of muzzle gas color in (b) (c) and (e) compared to the suppressed cases (a) and (d) in Figure 3.6 and Figure 3.7. The dark shadowgraphs can be attributed to the gunpowder being expelled from the muzzle of the gun along with the gases, the gases can then carry these particles in-flight. The powder can add to the density of the flowfield and is also the reason for muzzle flash. When incomplete combustion occurs in the bore of the gun, there is combustible propellant powder leaving the muzzle which in turn can end up in flashes. The implementation of gunpowder particles was also incorporated Comiskey and Yarin where they model the number of particles carried in the self-similar turbulent vortex and predict the impact this has on blood backspatter. Gun powder particle density was found to decrease over time, but at close distances was important to consider.
Figure 3.6 Corresponding shadowgraphy montages to the firearms and modifications specified in Table 3.1 for time instances 1.5 ms, 5 ms, and 9 ms post bullet leaving the muzzle. (a) The suppressed rifle, (b) rifle with muzzle brake, (c) pistol, (d) suppressed pistol. Again, for this work, only cases (a) and (c) were analyzed. Hence, the red outline of the gas front per the image processing described previously.
Figure 3.7 Shadowgraphy montage of the (e) rifle with a compensator specified in Table 3.1. The expansion speed of the muzzle gases exceed that of the firearms in Figure 3.6, so separate time instances 0.4 ms, 1 ms, and 1.6 ms were shown.

As mentioned above, Equation (3.7) describes a power-law expansion for the leading edge and radial expansion of the self-similar turbulent vortex ring. From the retroreflective shadowgraphy, the leading edge and radial maxima/minima were determined from each time instance and averaged over the 20 shots for both respective firearms. The time-evolution of the mean leading edge expansion and radial expansion for the LAR 15 (XM193 rounds) are shown in Figure 3.8(a) and (b), respectively. The three solid contours represent the mean value at each time-instant averaged over 20 sequences (blue solid line) and the variation is represented by two curves indicating a 4 standard-deviation spread over all 20 sequences (black curves representing ±2σ). In addition, a power-law fit is shown for $P_0 t^{1/4}$ as a red dashed line. For times greater than ~10 ms, both the leading edge and radial expansion approach the predicted power-law dependence.
Figure 3.8 (a) Radial and (b) leading edge expansion of the LAR-15 (suppressed 0.22 caliber rifle) compared to the $t^{1/4}$ power law.

Corresponding leading edge and radial expansion data for 20 sequences with the pistol (AE9AP rounds) are shown in Figure 3.9. As with the rifle muzzle gas expansion, the early expansion grows rapidly, but approaches the predicted $n=0.25$ power law dependence. The pistol muzzle expansion approaches the power law dependence at ~6 ms. Considering the two gas expansions, the suppressed rifle has an extended impulse resulting from the extended blowdown time, while the pistol at early time better approximates the small extent source captured by the theory of self-similar turbulent vortex rings to capture the muzzle gas expansion.
3.3 Interaction of muzzle gases with backspatter drops

Given the high gas velocities produced in the muzzle gas expansion, and the significant extent of muzzle gases (exceeding 1 m), the influence of the muzzle gas field on the produced backspatter of blood was investigated in a series of experimental studies. In this section, the influence of muzzle gases on droplet backspatter is made apparent and presented in various ways. These include image sequencing, blood stain patterns, and droplet location distributions.

3.3.1 Experimental Setup

Experiments were performed at an indoor shooting range (Izaak Walton Indoor Range in Ames, IA), and the experimental configuration is shown in Figure 3.10. A Rock River Arms 0.223-in. caliber rifle with a muzzle flash suppressor was used with 0.22 caliber (5.56 mm diameter) XM193 rounds. The blood source was a hollow foam cavity filled with 10 mL of swine blood at 20 °C was used (Table 2.1). It was covered with a single piece of adhesive tape and mounted on a vertical target. The blood-filled cavity target was located at a height of 1 m, and the rifle muzzle was also held at 1 m to ensure a 90-degree angle of entry for the bullet. The pattern of blood
droplets projected back towards the origin of the bullet (termed backspatter) fell on butcher paper laid out horizontally (on the floor). The paper extended 5 m from the target to the gun muzzle direction, and 1.5 m left and right of the blood source. Imaging systems used were located beyond the horizontal extent of the butcher paper.

To capture the global interaction of muzzle gases with the expanding backspatter drop a shadowgraphy system captured the bullet impact and backward-directed blood spray formation. The shadowgraphy system consisted of a point light source and two parabolic mirrors arranged in a z-type configuration. The light source was a 75 W Xenon short arc lamp (USHIO 75-XO) which was collimated with an 8-in. diameter parabolic mirror with a focal length of XX mm as depicted in Figure 3.10. A second parabolic mirror was used to image the centerline plane on a diffuser, which was subsequently captured using a high-speed CMOS camera (Photron SA-Z) with a f/2.8, 60 mm objective lens (Nikon). To increase the light level, an additional concave spherical mirror (50 mm diameter, 50 mm focal length) was placed behind the lamp. The camera frame rate was 25 kHz with a 5 μs shutter exposure. The magnification for the shadowgraphy system was ~200 μm/pixel with a corresponding field of view of 200 mm x 200 mm. An acoustic trigger (Sound Trigger-1505, Kapture Group Inc.) placed 0.5 m from the muzzle was used to start the acquisition of the camera at the time of the gunshot. For each event, 6400 frames were recorded spanning a timescale of 256 ms.

Before each shot, or set of shots, three 1 m wide and 5 m long sheets of butcher paper were laid out directly underneath the blood source which was located at 1 m height above the floor. Blood spatter patterns were allowed to dry for 5 minutes before moving from the test location. Spatter patterns were digitized using a flatbed scanner at 600 dots per inch (dpi) and composite
digital scans were reassembled for analysis. Additional spatter patterns were collected on a vertical screen placed at the same plane as the blood source.

3.3.2 Determining the region of muzzle gas interaction

3.3.2.1 Imaging the interaction of blood spray with muzzle gases

A series of experiments with blood, as described in Chapter 2 were imaged in the near field using the collimated shadowgraphy system. These consisted of the muzzle position of the
suppressed AR-15 rifle varying from 65-300 cm, which resulted in a variation in the arrival time of the muzzle gases in the field of view and the velocity magnitude of the arriving gases.

A visual representation of muzzle gas interaction for the suppressed rifle over various distances is shown in Figure 3.11. Case (a) being a close case of 65 cm rifle muzzle to blood source where the muzzle gasses appear in the near FOV at 7 ms post bullet impact, while the ligaments are forming. Case (b) is a 125 cm difference showing fully formed droplet interaction with oncoming muzzle gas field. Secondary atomization of larger droplet is observed, and a full reverse of velocity is observed for many droplets. Lastly, case (c) is observed with an offset distance of 300 cm. The muzzle gases do not appear in frame and this is representative of a normal backspatter formation for the experiment performed.

These results do provide a range of distances of significant influence on different stages of blood backspatter for this specific firearm in the nearfield. The early times shown in Figure 3.11 are where the backspatter is relatively compact and where the majority of droplets can be impact similarly before the blood droplets disperse in their separate directions far away from the blood source.
Figure 3.11 Muzzle gas interaction cases over increasing muzzle offset distances. Distance from muzzle to blood source being (a) 65cm, (b) 125 cm, and (c) 300 cm.
3.3.2.2 Backspatter distributions

Bloodstain patterns with a muzzle offset distance of 30 cm, 60 cm and 300 cm were collected on butcher paper as described in Section 2.1. Couple with the imaging experimental results summarized in Figure 3.11, blood spatter distributions were intended to determine the range of significant influence for muzzle gases for the suppressed LAR-15 rifle. In particular, at distances greater than 150 cm, shadowgraphy results showed minimal influence but these measurements are biased towards large droplet deflection due to the resolution limits of the shadowgraphy imaging system.

The blood spatter was collected and scanned spatters were used to identify droplets using the procedure outlined by Attinger et al. The scanned and identified backspatter bloodstains from single events are represented by the scatter plots shown in Figure 3.12 for three muzzle gas standoff cases: 30 cm, 60 cm, and 300 cm. First examining the distribution of 11,000 blood stains collected for 300 cm shown in Figure 3.12(a), there are clusters of stains near the target (which fall vertically onto the floor), a wide angular distribution, and a significant number of droplets reaching out to approximately 4 m. Along the centerline, there are fewer droplets at close distances. This can be attributed to the prominent high-momentum jets evident in shadowgraphy images and the gravitational force which collapse a near-cylindrical geometry of initial spray onto the floor.

Examining the blood stain pattern distribution for cases of 60 cm or 30 cm, there is evidence of a distinctly different behavior driven by the interaction with muzzle gases. At a 60 cm muzzle standoff shown in Figure 3.12(b), the number of stains recorded decreased from 11,000 to 2,000. The axial displacement of drops decreased to nearly 100 cm with most of the droplets falling near the target. A number of large stains were recorded underneath the target, suggesting a large portion of the blood reversing flow and attaching to the target where it proceeded to drip, forming puddles of blood. Then at 30 cm muzzle standoff depicted in Figure 3.12(c), the number of
recorded stains decreased from 11,000 to 7,000. Even with significantly more droplets recorded than the 60 cm case, notice the particle sizes are all very small. The angular distribution was much wider than any case yet, with droplets recorded traveling perpendicularly to the bullet plane. This could be attributed to the strong impact of muzzle gases atomizing all droplets and ligaments present at arrival into multitudes of smaller drops. The angular distribution was possibly a product of the muzzle gases deflecting from the target sideways and taking clouds of small droplets along with. However, this is difficult to claim outright without a control case.
Figure 3.12 Bloodstain pattern distributions for single gunshots impacting a 10 mL blood-filled cavity at a 1 m height. Patterns were collected on the floor (0 m height) for muzzle standoff distances of (a) 300 cm, (b) 60 cm, and (c) 30 cm.
Histograms for the bloodstain pattern distributions for muzzle standoff distances of 30 cm, 60 cm, and 300 cm are shown in Figure 3.13 showing the number of bloodstains for each horizontal distance (measured on the floor where the spatter patterns are collected). The 300 cm muzzle standoff distribution is characteristic cases with no muzzle gas influence on the backspatter droplet distribution. These distributions show bimodal distributions, with a significant number of droplets located within 20 cm of the target location, and a main peak centered at approximately 1.75 m.

The distributions show the number of stains counted from the scanned spatter patterns. Neither the 60 cm or 30 cm muzzle standoff cases show distributions without obvious bimodal features. Both distributions show significant reductions in the total and peak number of stains, which suggest a significant number of droplets are either (1) deflected back towards the target or (2) fragmented due to muzzle gas interactions and subsequently reversing direction or reaching sizes below the threshold for counting in the scanned blood spatter patterns. Considering these results combined the shadowgraphy results, the most likely outcome seems to be the reversal in direction. In the subsequent section, additional trajectories are shown for flow reversal and instances of secondary droplet breakup due to muzzle gas interactions.
Figure 3.13 Backspatter stain distance from the blood source (in the x-direction) for muzzle offset distances of 30cm, 60 cm and 300 cm.

3.3.3 Particle tracking velocimetry of individual drops

Utilizing the same shadowgraphy setup, particle tracking velocimetry (PTV) is applied to shadowgraphy images where individual droplets that are impacted by the oncoming muzzle gasses are analyzed.

3.3.3.1 Methodology

Particle tracking velocimetry was implemented on the shadowgraphy images to track particle motion as the muzzle gases influenced the droplet trajectories. A gunshot 125 cm away from the blood source provided optimal timing for the rifle to expel muzzle gases that appeared into the shadowgraphy field of view as the blood particles atomized into fully formed droplets as seen in Figure 3.14. At the time the muzzle gases appeared in frame, particles were not moving
fast enough to provide a clear positional displacement from frame to frame on the camera sensor. Therefore, a frame interval of 10 was used to allow the particles more time to travel between frames.

Larger individual blood droplets (>1 mm) were identified by binarizing the shadowgraphy image and implementing an object identifier embedded in the HOLOSAND code that tracks the position and size of the droplet per frame. The objects were then linked from frame to frame using a Hungarian linker algorithm. To filter for more acceptable tracks, the maximum distance between linked particles was set to 2 mm.

Figure 3.14 Example of a particle projectile path being tracked while under the influence of muzzle gases.
Figure 3.15 The track corresponding to the still frames in Figure 3.14 identified by the tracking algorithm. Coordinate system is based on the camera sensor.

Once individual tracks were identified such as in Figure 3.15, a smoothing spline was used to provide estimates of the $x$ and $z$ position along with particle size. As an example, the $x$-position of an extracted trajectory is shown in Figure 3.16(a). The position in $x$ and $z$ were represented with a smoothing spline, and then 1st and 2nd derivatives were calculated to determine velocity and acceleration along the trajectory. The smoothing spline allowed for reduced noise in determining the derivative as it broke up the curve into multiple piece wise functions that follow the track closely compared to a polynomial which would overshoot/undershoot important features (Figure 3.16).
Figure 3.16 (a) Trajectory in a single direction (x for this example) is estimated with a smoothing spline. The derived (b) velocity $V(t)$ and (c) the acceleration $A(t)$ along the trajectory are estimated based on derivatives of the smoothing spline. The dashed lines represent the time interval surrounding the point of maximum acceleration, which was averaged and used for further calculations.

The time interval in Figure 3.16 represents the most significant muzzle gas interaction time. Tracks with significant muzzle gas influence were chosen for this analysis. Over a manually
chosen time interval of muzzle gas influence for each track, an average maximum acceleration was
determined for both $x$ and $z$-components ($a_x, a_z$). Drag force was then calculated:

$$F_{d,x} = -ma_x$$
$$F_{d,z} = mg - ma_z$$  \hspace{1cm} (3.8)$$

where $F_{d,x}$ and $F_{d,z}$ are the components of the drag force on the particle in N/m, $m$ is the mass of
the particle in kg, and $g$ is acceleration due to gravity in m/s$^2$. The drag force is expressed in terms
of the drag coefficient as

$$\vec{F}_d = \frac{\pi}{8} D^2 \rho_a C_d \left| \vec{V}_r \right| \vec{V}_r$$  \hspace{1cm} (3.9)$$

where $D$ is the droplet diameter in m, $\rho_a$ is the density of air in kg/m$^3$, $C_d$ is the coefficient of drag,
and $\vec{V}_r$ is the relative velocity of the droplet in reference to the muzzle gas velocity. The drop
velocity and muzzle gas velocity are then related by

$$\vec{V}_r = \vec{V}_d - \vec{V}_{mg}$$  \hspace{1cm} (3.10)$$

where $\vec{V}_d$ is the droplet velocity in m/s, and $\vec{V}_{mg}$ is the muzzle gas velocity in m/s. Due to the offset
distance of the muzzle during the shot the fully formed particles are already decelerating placing
most all of them under the threshold of $Re_d < 2 \times 10^5$. This provides the opportunity to use an
expression accurate within 6% of experimental data provided by Clift and Gauvin $^{40}$:

$$C_d = \left[ \frac{24}{Re_d} \left( 1 + 0.15 Re_d^{0.687} \right) \right] + \frac{0.42}{1 + \frac{42.500}{Re_d^{1.15}}}$$  \hspace{1cm} (3.11)$$

Here, $Re_d$ is the Reynolds number as a function of $V_r$ expressed as

$$Re_d = \frac{\rho_a \left| \vec{V}_r \right| D}{\mu_a}$$  \hspace{1cm} (3.12)$$

where $\mu_a$ is the dynamic viscosity of air in kg/m-s. This approach has been used successfully by
Attinger et al. to predict the origin of BPA patterns $^{37}$. 
The drag force can be related to the relative velocity by combining Equation (3.12) and Equation (3.11) into Equation (3.9). Now attempting to solve for \( \vec{V}_r \) becomes a non-linear relationship so a method to solve for \( \vec{V}_r \) would be using an objective function where variable \( \alpha \) is set equal to the scalar quantities. The non-linear relationship can be set equal to a residual vector \( \vec{R} \) defined as

\[
\alpha \left( \left| \vec{V}_r \right| \right) = \frac{\pi}{8} D^2 \rho_a C_d \left( \left| \vec{V}_r \right| \right) \left| \vec{V}_r \right|
\]

\[
\vec{R} = \vec{F}_d - \alpha \left( \left| \vec{V}_r \right| \right) \left| \vec{V}_r \right|
\]

\[
obj = \left| \vec{R} \right|
\]

(3.13)

Using ‘fminsearch’ in MATLAB, \( obj \) converged to zero as values for the relative velocity \( \vec{V}_r \) were scaled iteratively. This is the velocity relative to the muzzle gas field \( \vec{V}_{mg} \), which can then be determined through Equation (3.10).

Non-dimensional values such as Weber (\( We \)), Ohnesorge (\( Oh \)), and Reynolds number (Equation (3.12)) are important to characterizing secondary breakup and were then calculated by

\[
We = \frac{\rho_a \left| \vec{V}_r \right|^2 D}{\mu_b \sqrt{\sigma D \sigma}}
\]

\[
Oh = \frac{\mu_b}{\sqrt{\rho_a D \sigma}}
\]

(3.14)

where \( \rho_a \) is the density of air in kg/m\(^3\), \( \sigma \) is the surface tension of blood in N/m, \( \rho_b \) is the density of blood in kg/m\(^3\), and \( \mu_b \) is the viscosity of blood.

Next, separate droplet tracks were analyzed over a timeframe preceding the muzzle gases. These specific tracks were observed to breakup in the experimental data, so a particle velocity and size were extracted leading up to the muzzle gas stage. The relative velocity of this particle compared to the previously estimated muzzle gas velocity was determined using Equation (3.10). These droplets were then able to be compared with the droplets that did not breakup.
### 3.3.3.2 Error estimation

There were two main sources of quantifiable error throughout the process tracking particles from a high-speed shadowgraphy imaging system. First, the resolution of the images and how well a droplet edge could be localized. Ultimately, this resolution error impacted the initial diameter measurement of the droplets. Based on the calibration images taken with the system, an uncertainty of ±2 pixels was applied to the diameter measurement ($\delta D$). Since the magnification of the shadowgraphy setup was ~200 μm/pixel the uncertainty for droplet diameter was conservatively estimated as ±400 μm. Second, was the acceleration of the drops. As observed in Figure 3.16, the acceleration measurement was noisy due to position uncertainty, possibly originating from aliasing by sampling onto the discrete image sensor. Therefore, the uncertainty was estimated as the variance of acceleration within the time span manually chosen to average during the muzzle gas interaction event. These uncertainties changed on a per-track basis ($\delta a_x, \delta a_z$). These errors lead to uncertainty in the droplet mass, described by

$$
\delta m = |3| \left( \frac{\delta D}{|D|} \right) |m| \left( \frac{\pi \rho_b}{6} \right).
$$

(3.15)

In addition, the error in drag is given by

$$
\delta F_{dx} = \left| F_{dx} \right| \sqrt{\left( \frac{\delta m}{m} \right)^2 + \left( \frac{\delta a_x}{a_x} \right)^2},
$$

\[ \delta F_{dz} = \sqrt{(g - a_z) \delta m)^2 + (-m(\delta a_z))^2}. \]

(3.16)

To establish conservative bounds on the estimated velocities, four cases were considered as follows:
\[
\vec{V}_r \left( D, \vec{F}_d \right)
\]

\[
Case 1: \vec{V}_r(D + \delta D, \vec{F}_d) \\
Case 2: \vec{V}_r(D - \delta D, \vec{F}_d) \\
Case 3: \vec{V}_r(D, \vec{F}_d + \delta \vec{F}_d) \\
Case 4: \vec{V}_r(D, \vec{F}_d - \delta \vec{F}_d).
\]

Case 1-4 were calculated then the maximum and minimum were used as bounds for the uncertainty of relative velocity.

### 3.3.3.3 Results

For a case where the gun muzzle was discharged 125 cm away from the blood source, 10 particle tracks were chosen where significant deflection was evident. The muzzle offset distance allowed particles time to fully form before the muzzle gas front appeared in the shadowgraphy FOV. Back calculating relative velocity from particle position provides comparison to Weber number values (Figure 3.17). Even though all the particles tracked physically did not breakup, the majority of them are found in the bag breakup regime for particle atomization. As defined by Hsiang and Faeth\textsuperscript{25}, this is the region for \(11 < We < 50\), with \(Oh < 0.1\).

These estimates for the \(We\) for each droplet seem counter to the expected behavior with \(We\), but several possibilities exist for the deviation. First, drop deformation may be prevalent for drops of typical diameter of 1 mm or greater. The diameter used for calculations was a mean diameter as most of the larger particles were rotating ellipsoids during the effective time of the muzzle gases. If a droplet were to deform and rotate in such a fashion that increases the incident area visible to the muzzle gases, that would in turn increase the drag force and ultimately increase the relative velocity. Drag on deformed drops has been discussed in detail by Loth et. al.\textsuperscript{1}, and the drag coefficient has been shown to reduce by up to 20\%. Additionally, this is using a 2D projection of the true velocity, which may contribute to some velocity error and increased uncertainty in particle size estimation.
In addition, the bag breakup regime has been well established for cases with very well-defined velocity conditions (typically shock tube experiments). Here, the muzzle gas velocity gradients and variation during the drop impact may limit comparisons to canonical breakup experiments. Finally, these limits apply for Newtonian fluids. Blood is a well-known non-Newtonian fluid and breakup of these fluids has received far less attention, however work by Rocha and Sojka\textsuperscript{41} suggests that the Oh-\textit{We} space remains a good representation of the breakup regime.

Figure 3.17 Scatter plot of droplet velocity relative to the estimated muzzle gas flow field versus particle size. Two types of data are represented: 1) Tracks of droplets remaining unbroken through the influence of the muzzle gas, and 2) tracks of droplets before muzzle gas interactions that are observed breaking up when the muzzle gases arrive.

Muzzle gas velocity estimations are shown in Table 3.2 where the magnitude ranged from approximately 12-40 m/s based upon particle tracking and the peak acceleration due to muzzle gas interaction. This large variance could be due to the error previously mentioned, but muzzle gas
flow fields can vary even in the small field of view captured in this experiment. This means using one particle from a specific region of the field of view shouldn’t characterize the full flow field.

Table 3.2 Muzzle gas velocity approximations.

<table>
<thead>
<tr>
<th>$V_{mg}$ [m/s]</th>
<th>Min.</th>
<th>Avg.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12.27</td>
<td>29.5462</td>
<td>45.4</td>
</tr>
</tbody>
</table>

Table 3.3 presents the non-dimensional values of the 10 tracks that were observed changing trajectory due to the muzzle gas flow field. The Reynolds numbers indicates that these particles remain under the threshold of $Re_d < 2 \times 10^5$ where the drag correlation holds. The Weber number varies significantly across particle tracks, but this is a result of the relative velocity error as there is a squared velocity term when determining Weber number. Further characterization of muzzle gas fields may provide improved accuracy of in-flight Weber numbers.

Table 3.3 Minimum, maximum, and average values for non-dimensional values Reynolds, Weber, and Ohnesorge numbers from the 10 particle tracks effected by muzzle gases.

<table>
<thead>
<tr>
<th></th>
<th>Min.</th>
<th>Avg.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Re$</td>
<td>965.5</td>
<td>3572</td>
<td>5332</td>
</tr>
<tr>
<td>$We$</td>
<td>4.49</td>
<td>48.38</td>
<td>73.04</td>
</tr>
<tr>
<td>$Oh$</td>
<td>0.0153</td>
<td>0.0185</td>
<td>0.0223</td>
</tr>
</tbody>
</table>

Here, we also show the estimated Ohnesorge number. This is relevant due to the large variation of $Oh$ seen in many atomization processes (i.e. when drops approach the thermodynamic critical point, the surface tension drops significantly \(^{25}\)). For this experiment the $Oh < 0.1$ therefore the transitional breakup mode thresholds can be characterized using $We$ alone.\(^{26}\)

The use of droplet trajectories to assist in characterizing the muzzle gas flow showed that there are potentially significant effects which have not been accounted for to date in consideration of bloodstain pattern forensic analysis. The impact of muzzle gases by inducing secondary atomization and deflecting drops is obvious for cases where the muzzle is located within ~1 m of the target. The use of nearfield high-speed imaging provides a non-intrusive avenue to estimate
characteristics of the muzzle gas flow field, however a higher resolution system would be necessary to decrease the uncertainties experienced in this experiment. Furthermore, additional attention should be paid to the ability of muzzle gases to impact the formation and propagation of blood drops over longer distances and for a range of interaction scenarios.

3.4 Conclusion

This chapter demonstrated the importance of muzzle gas influence on droplet backspatter through both imaging and bloodstain pattern collection. First, the extent of muzzle gas expansion was observed in a free-field indication analyzed in order to compare real experimental data of gas expansion with different firearms to the self-similar vortex ring theory. This theory suggested that radial and leading-edge expansion of the vortex ring that the gases produce after being fired would expand with a $t^{1/4}$ dependence. After averaging 20 shots the radial and leading-edge expansion of the suppressed rifle both approached the power-law dependence after ~10 ms. Muzzle gas expansion from the pistol closely approached the expected power-law dependence at ~ 6 ms. The earlier approach of the pistol data to the self-similarity theory was attributed to the shorter blowdown time due to the shorter barrel length, more closely approaching the infinitesimal extent of the impulse considered by the self-similar turbulent vortex expansion theory.

Next, the distance at which the muzzle gases would influence the backspatter of droplets was determined for the suppressed rifle. The immediate influence on the backspatter ligaments was obvious at a muzzle standoff distance of 65cm from the blood source. After the ligaments have further developed into fully formed droplets, muzzle gas influence on these droplets occurred at a distance of 125cm. Additionally, droplet distributions and spatter patterns were showcased to show the spatter pattern and droplet distribution with the influence of muzzle gases. A comparison case without muzzle gas influence was shown for a 300 cm muzzle offset. For cases with significant muzzle gas influence, the maximum number of droplets decreased from 11,000 to 2,000
at a 60 cm offset and 7,000 at a 30 cm offset. The 60 cm case was observed to have a high number of large droplets under the target with a small angular distribution, while the increase in droplets for the 30 cm case was inherently the strong force of the muzzle gases atomizing all ligaments and droplets formed at such a close distance. Angular dispersion for the 30 cm case was very wide in comparison to both the 60 and 300 cm case. It can be attributed to the muzzle gas influence in some manner, with one scenario being the muzzle gases deflected from the target perpendicularly taking multiples of small drops along with it. Additionally, going from the 300 cm case to the 30 and 60 cm cases the horizontal displacement of droplets decreased from 400 cm to 100 cm.

Finally, particle tracking velocimetry was utilized with the shadowgraphy images taken to individually track larger particles influence by the oncoming gases. Obvious points of deceleration caused by the muzzle gases were identified and used to approximate the muzzle gas velocity through a drag force derivation. Droplets that were observed to not break up when influenced by muzzle gases were compared to droplets that did experience breakup under the influence of the muzzle gas field. Using the droplet trajectories in attempt to determine characteristics of the muzzle gas field resulted in a large range of estimates for the muzzle gas velocity. The results concluded with massive error, but the work did suggest that there may be affects unaccounted for in the current bloodstain pattern analysis field. Secondary atomization due to muzzle gas influence is obvious for muzzle offset cases of ~1m or less. High-speed imaging in the nearfield of blood backspatter does provide a non-intrusive route to analyzing characteristics of the muzzle gas flow field. To correctly do this however, a higher resolution experimental setup would be required to decrease the error experienced in the above work.
A set of over 2500 individual droplets were identified and tracked in three-dimensional space using holography. Holography as a technique does present an uncertainty in the depth reconstruction of droplets, so an error estimation was performed to showcase the accuracy of the tracks being analyzed. After applying a filter restricting the depth uncertainty measurement as well as the physical bound of the \( z \) velocity of particles, 2078 tracks remained provided a realistic distribution of droplets to be analyzed. The correlation between the forward projected holography tracks and the physical blood stains did show similarities in size distribution and projection angle, however the small holography FOV limited the drops observed so there was a distinct difference in stains farther from the blood source. Moving forward the axisymmetric nature of backspatter formation could potentially be used to better represent physical stain patterns. The data collected could be rotated about the bullet axis incrementally, which would inherently provide stains traveling farther as well as assist the count of stains to be closer to the magnitude of physical stains observed.

To better utilize the technique of analyzing individual drops in 3D space would be to increase the number of holography beams used. This would in turn decrease the error experienced above significantly and provide a more confident set of tracks. Additionally, the use of a phase conjugate system would allow the droplets to still be tracked even when the muzzle gases are in the holography FOV. Notice there were no cases where the holography was interfered by the muzzle gases, this is due to the fact that the density gradient of the gases completely blinded the holography image and didn’t allow for any data to be extracted when the muzzle gases were present.
Muzzle gas expansion was observed in a large FOV using retroreflective shadowgraphy to track the leading edge and radial expansion of various firearm’s muzzle gases. 20 shots were averaged to create an averaged trend to compare the expansion to the $t^{1/4}$ power-law dependence presented by Comiskey and Yarin 2019. It was observed for a pistol and suppressed rifle that the expansion trends approached the power-law dependence after ~6 ms and ~10 ms respectively.

Experimental visuals were then shown to depict the influence of muzzle gases on blood backspatter, specifically critical distance and difference in blood stain patterns for the suppressed rifle. Muzzle to blood source offset distances of importance were 65 cm for ligament interaction, and 125 cm for fully formed droplet interaction, while a case 300 cm away was presented to provide a control case of a normal backspatter formation.

Particle tracking velocimetry was applied to the shadowgraphy in order to observe large individual drops that were influence by the oncoming muzzle gas flow field. Droplets that both did and did not experience breakup were analyzed. For the droplets not experiencing breakup, a simple drag force model was applied to approximate the velocity of the muzzle gases using the deceleration of the droplet being tracked. This technique did present large errors that were documented, but also provided insight into an avenue of research for the future. The non-intrusive technique did provide information that secondary atomization is very apparent in gunshot cases less than ~1 m. To better the performance, a higher resolution high-speed imaging technique would be required. This also ties into the 3D particle tracking of the phase conjugate setup previously explained.

Overall, the data collected in this work can assist the advancement of BPA techniques moving forward. Experimental data to compare and verify numerical models is still a hole in the field of BPA and this data could be utilized in the future to assist better numerical modeling.
practices. More accurate modeling leads to law enforcement being able to perform their job much more efficiently and make accurate decisions in the court of law.
CHAPTER 5. BIBLIOGRAPHY


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