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Shot-to-shot variation in gunshot acoustics experiments

Robert C. Maher

Electrical & Computer Engineering, Montana State University, Bozeman, MT USA 59717-3780

Correspondence should be addressed to R.C. Maher (rob.maher@montana.edu)

ABSTRACT

Audio forensic examinations may involve recordings containing gunshot sounds. Forensic questions may include determining the number of shots, what firearms were involved, the position and orientation of the firearms, and similar queries of importance to the investigation. A common question is whether a sequence of shots are attributable to a single gun fired repeatedly, or if the sounds could possibly come from two or more different guns fired in succession. This paper describes a controlled experiment comparing ten repeated shots from several common handguns and rifles. Differences between shots are observed, apparently attributable to subtle differences between ammunition cartridges. The shot-to-shot differences are also compared at different azimuths, and between different firearms. Practical examples and applications are presented.

1 Introduction

In the United States and elsewhere around the world, audio forensic evidence may include the sound of gunfire. Interpretation of gunshot sounds in forensic recordings is increasingly common as more law enforcement organizations require officers to use body-worn and in-vehicle recording devices, and more private citizens utilize smartphones and home surveillance systems.

Forensic gunshot interpretation requests may include determining the number and order of shots in a sequence, the likely type of guns involved, and the position and orientation of the firearms [1].

Ordinary contemporary firearms use ammunition consisting of a cartridge. The cartridge has a bullet securely affixed to the open end of a small sealed cylindrical can, called the case or the casing, containing the propellant (gun powder) charge. The cartridge is mounted in the firing chamber at the breech end of the barrel. When triggered, the rapid combustion of the gunpowder inside the cartridge casing causes the bullet to separate from the cartridge and propels the bullet down the barrel of the gun. The sound of the gunshot, the *muzzle blast*, is due to the hot expanding gases emitted as the bullet leaves the muzzle [2].

Our interest in this particular study was to examine the consistency of audio recordings of a succession of shots from the same firearm using the same type of commercially-produced ammunition, same gun and microphone positions, and the same environmental conditions. The experimental question was to determine if there was a discernible shot-to-shot variation in the recordings for the "identical" shots, and if so, to assess the possible explanations for the differences [3].

Specifically, the focus is to understand what level of sonic difference would be foreseeable in a forensic gunshot recording that was attributable to repeated shots from a single firearm, versus a succession of shots from *different* firearms.

Competitive shooting sports enthusiasts assess the variability in such parameters as mass, power load, and muzzle velocity when using off-the-shelf commercial ammunition. Sports shooters interested in consistency often choose to load their own ammunition cartridges or use match round cartridges to reduce the shot-to-shot variability, regular users and law enforcement officers generally use commercial ammunition. In any case, the relationship between shot-to-shot variability in muzzle velocity and shot-to-shot variability in muzzle blast acoustical characteristics has not be widely studied.

2 Test conditions

As reported previously, a special gunshot acoustical test rig was designed and constructed, containing twelve omnidirectional instrumentation microphones [4]. Each microphone channel consists of a G.R.A.S. type 46DP microphone set (type 40DP 1/8" diaphragm 200 volt externally polarized condenser capsules and type 26TC ¼" preamplifiers), and G.R.A.S. type 12AA and 12AG power modules providing 200 volt polarization and 120V preamplifier power. The twelve microphones are placed on a semi-circular (180°) arc of 3 meter radius, with a microphone at 0°, 180°, and at 16.4° intervals (180° / 11) around the semi-circle, as depicted in Figure 1.

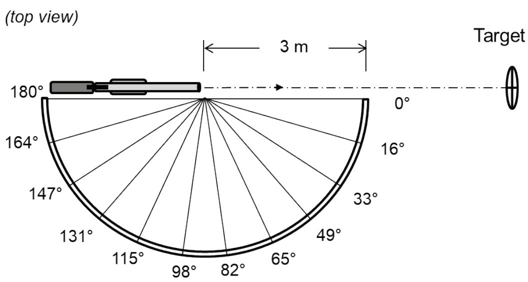

Figure 1: Microphone positions (plan view)

The signal from each microphone is sampled concurrently at 16-bit resolution and a 500 kHz sampling rate per channel.

Each firearm under test is fired from the center of the arc while the microphone system simultaneously and synchronously records the acoustical waveforms from each angular position.

The firearm shooting position and the microphone rig are both elevated 3 meters above the ground of the shooting range so that there is a time delay of approximately 10 ms between the arrival of the direct sound at the microphones and the arrival of the first reflected sound from the ground [4]. The delayed arrival of the first reflection ensures that the entire muzzle blast (typically no more than 5-6 ms in duration) is recorded anechoically [5]. The test configuration is shown in Figure 2.

Figure 2: Test configuration with microphones and firearm elevated for quasi-anechoic recording.

3 Firearms tested

For the purposes of this study, the recordings of three handguns and two rifles (five firearms total) were examined. The firearms tested included:

- Colt M1911A1 pistol (.45 ACP cartridge)
- Glock 19 pistol (9x19 ammunition)
- Ruger SP101 revolver (.357 Magnum ammunition)
- Custom rifle (.308 Winchester ammunition)
- Stag AR-15 rifle (5.56x45mm NATO ammunition)

Ten shots were recorded for each gun, and the results compared for waveform shape and peak pressure. The results were observed using the on-axis microphone, located 3 meters in front of the muzzle, ~0° azimuth. The findings are summarized next.

4 Ten successive shots Colt 1911 pistol

The Colt M1911A1 pistol (Figure 3), chambered in .45 ACP, was fired handheld by the expert shooter.

For each shot, the shooter aimed at the target, the recording system was started, the round was fired, and the recording system was stopped. The marksman checked the firearm and reloaded, if necessary. This process was repeated for the ten shots.

Figure 3: Colt M1911A1 Government pistol.

A muzzle blast recording obtained by the microphone at ~0° azimuth, 3 meters downrange, for one of the shots with the M1911A1 pistol is shown in Figure 4.

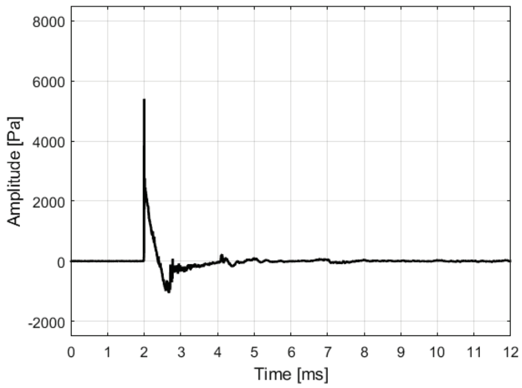

Figure 4: Single shot from Colt M1911A1 pistol (shot 2 from sequence of ten).

Note that the peak amplitude is dominated by the abrupt onset of the muzzle blast sound, and that this peak feature has a very brief duration.

The sequence of ten shots by the Colt M1911A1 pistol is shown in Figure 5, with a 14 ms offset so that all shots can be seen at once for visual comparison. As would be expected, the general characteristics of each recorded muzzle blast shown in Figure 5 is generally consistent, but the peak amplitude varies slightly for each shot. The average peak amplitude for the ten shots is 5123 Pa. The minimum peak of 4927 Pa (-3.8%) was observed for shot 10, and the maximum peak of 5407 Pa (+5.5%) for shot 2.

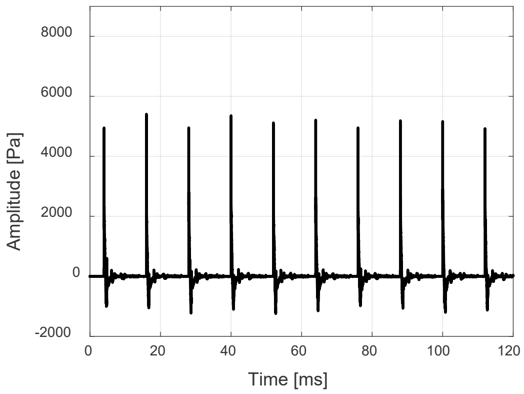

Figure 5: Overlapped plot of ten successive shots by Colt M1911A1 pistol.

The result is interesting: note that even with recordings obtained under carefully controlled conditions, there is a measurable difference between successive shots using commercial ammunition right out of the box.

It is possible to compute the sound strength, or relative "energy" of each shot, by integrating the square of the pressure waveform of the muzzle blast and dividing by the number of samples.

$$\text{"}Energy\text{"} = \frac{1}{N_2 - N_1} \sum_{n=N_1}^{N_2} x^2[n] \quad (1)$$

This calculation may be more indicative of the sound intensity variation than the very narrow peak overpressure. This result is shown in Figure 6.

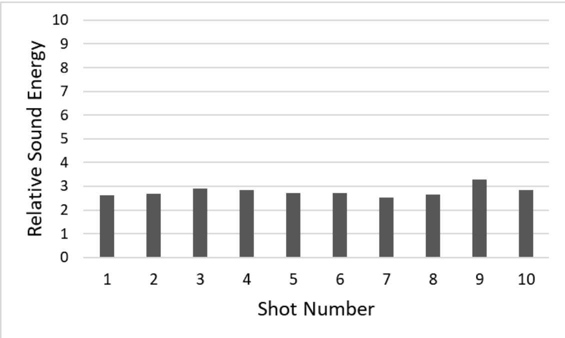

Figure 6: Relative sound strength for each shot of the Colt 1911 pistol.

Note that the relative energy calculation shown in Figure 6 and the peak amplitude observation shown in Figure 5 depict the shot-to-shot variation differently. The variation across the ten shots for the relative energy calculation is -9.6% to +18.6% compared to the average relative energy for the ten successive shots.

5 Ten successive shots Glock 19 9mm

The Glock 19 handgun (Figure 7) was fired ten times in succession. As with the Colt pistol, the recording procedure for the handheld Glock pistol started with the expert shooter aiming at the target, the recording system started, the shot fired, the recording system stopped, the marksman checked the firearm and reloaded (if necessary), and then the process repeated.

Figure 7: Glock 19 handgun.

A single shot from the Glock 19 is shown in Figure 8. As with the Colt 1911, the abrupt onset of the muzzle blast gives a very strong but narrow peak.

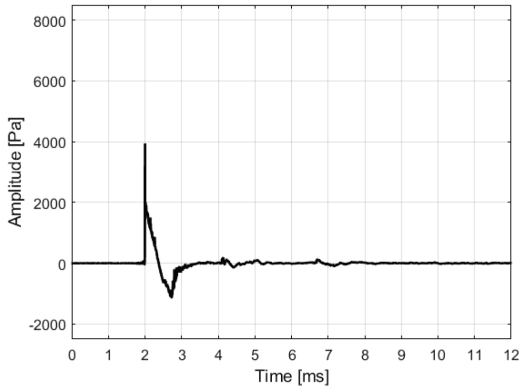

Figure 8: Single shot by the Glock 19 pistol (shot 1).

Ten successive shots from the Glock 19 are shown overlapped in Figure 9, with a 14 ms offset so that all shots can be seen at once for visual comparison.

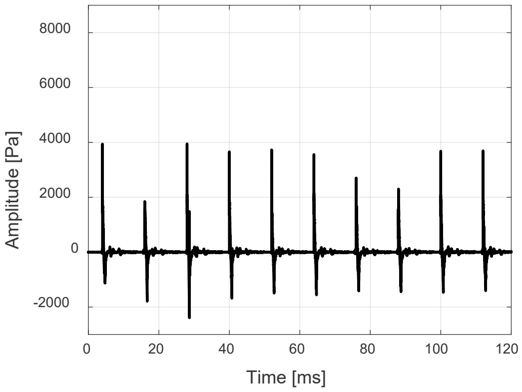

Figure 9: Overlapped plot of ten successive shots by the Glock 19 handgun.

The waveform general shape of each muzzle blast for the Glock 19 was consistent, but there was a significant difference in the peak amplitude of the ten shots. The average peak amplitude for the ten shots was 3307 Pa, the minimum peak of 1846 Pa (-44%) observed for shot 2, and the maximum peak of 3950 Pa (+19.5%) for shot 3.

Comparing the relative energy of each shot as was done for the Colt pistol, the variation shown in Figure

10 is observed. The variation across the ten shots for the relative energy calculation is -16% to +46% compared to the average relative energy.

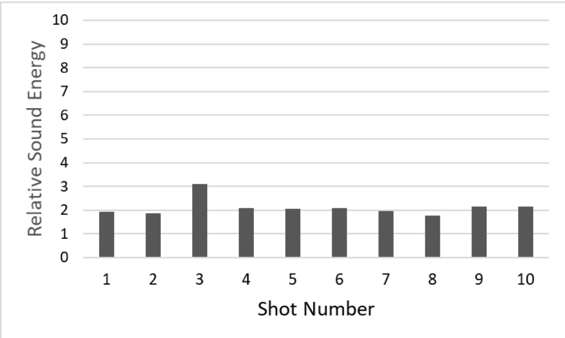

Figure 10: Relative sound strength for each shot with the Glock 19.

For forensic comparison, the substantial shot-to-shot variation observed for the Glock 19 could be challenging if a question was raised about how many different firearms might have been involved in a shooting incident. Comparing shot 2 and shot 3, the shot parameters are sufficiently different that they might be judged to come from two different firearms.

6 Ten successive shots Ruger SP101 revolver

The Ruger SP101 revolver (Figure 11) was fired ten times with 357 Magnum ammunition.

Figure 11: Ruger SP101 revolver handgun.

A single shot from the SP101 revolver is shown in Figure 12. The revolver produces a more complicated sonic response, due in part to the venting of combustion gas from the cylinder gap [6].

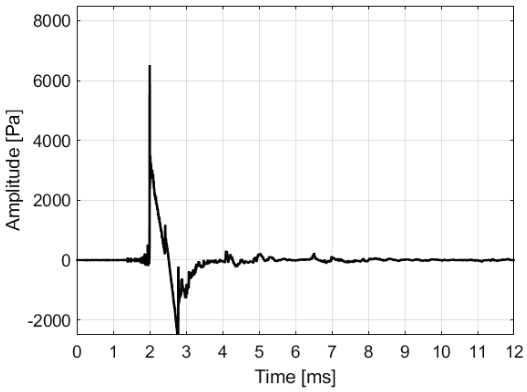

Figure 12: Single shot by the Ruger SP101 revolver (shot 5).

An overlapped plot of the ten shots by the SP101 is shown in Figure 13.

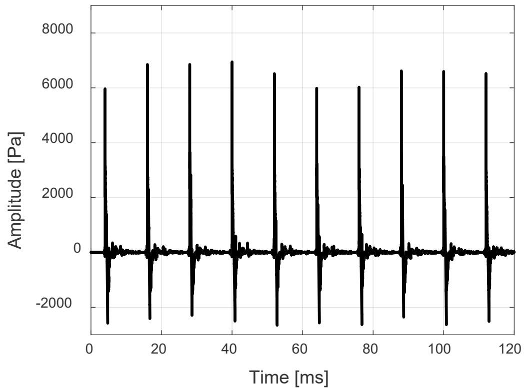

Figure 13: Overlapped plot of ten successive shots by Ruger SP101 revolver.

The average peak amplitude for the ten shots by the SP101 revolver was 6491 Pa, the minimum peak was 5968 Pa (-8%) observed for shot 1, and the maximum peak of 6948 Pa (+7%) for shot 4. The SP101 revolver produces a significantly greater acoustic peak amplitude compared to the Glock 19 pistol.

Again comparing the relative energy of each shot, the variation shown in Figure 14 is observed. The variation across the ten shots for the relative energy calculation is a narrower range than for the other handguns tested, -4.5% to +5.2% compared to the average relative energy.

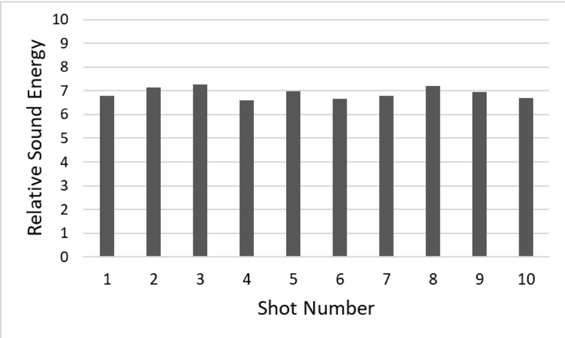

Figure 14: Relative sound strength for each shot with the Ruger SP101 revolver.

7 Ten successive shots 308 rifle

A custom rifle chambered in 308 Winchester was used (Figure 15).

Figure 15: 308 Winchester rifle.

A single shot from the 308 rifle is shown in Figure 16.

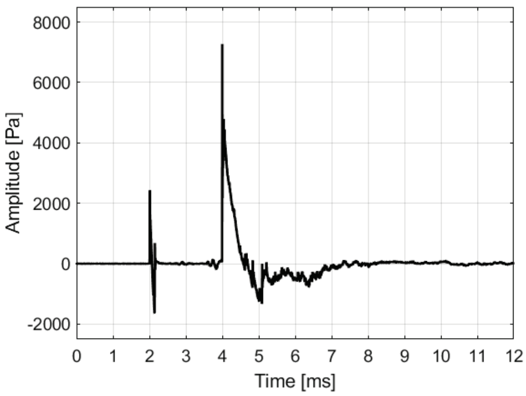

Figure 16: Single shot by the 308 Winchester rifle (shot 2). The ballistic shock wave of the supersonic bullet precedes the muzzle blast.

The bullet from the 308 rifle emerged from the muzzle at supersonic speed. Therefore, in Figure 16 the muzzle blast recording from 3 meters away at ~0° azimuth includes the ballistic shockwave of the bullet, preceding the arrival of the muzzle blast itself [4]. Ten successive shots with the 308 rifle are shown overlapped in Figure 17.

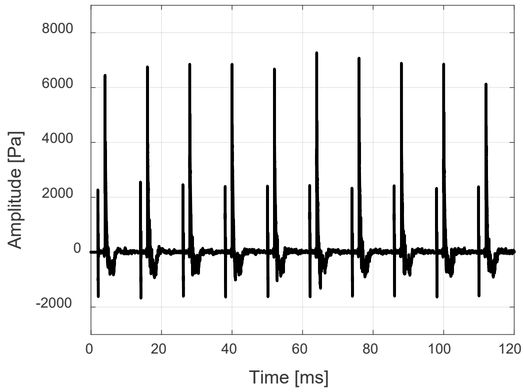

Figure 17: Overlapped plot of ten successive shots by the 308 rifle.

The average peak amplitude for the ten shots was 6780 Pa, the minimum peak of 6129 Pa (-9.6%) observed for shot 10, and the maximum peak of 7272 Pa (+7.2%) for shot 6.

Now comparing the relative energy of each shot, including the ballistic shockwave, reveals the variation shown in Figure 18.

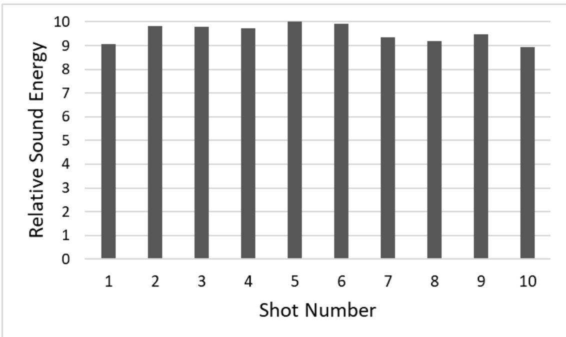

Figure 18: Relative sound strength for each shot with the 308 Winchester rifle.

Although the peak pressure amplitude for the 308 rifle is comparable to the Ruger SP101 handgun, the relative energy for the rifle shot is higher than for the handgun shots. The shot-to-shot relative energy variation ranged from -6.2% to +4.9% compared to the average relative energy of the 308.

8 Ten successive shots AR-15 rifle

The AR-15 rifle (Figure 19) was fired ten times with 5.56 NATO cartridges. As with the 308 Winchester rifle, the AR-15 produced supersonic projectiles. A single shot by the AR-15 is shown in Figure 20.

Figure 19: AR-15 rifle.

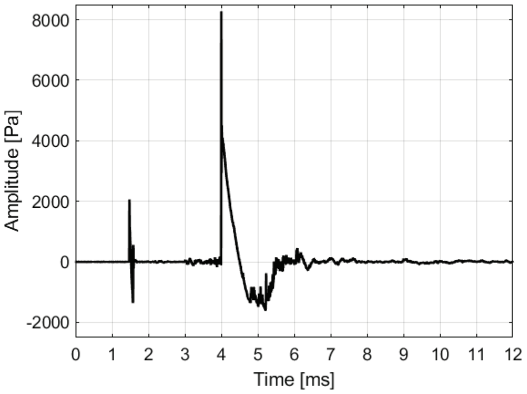

Figure 20: Single shot by the AR-15 rifle (shot 6). The ballistic shock wave of the supersonic bullet precedes the muzzle blast.

The ten successive AR-15 shots are overlapped in Figure 21.

The comparison of the relative energy of each shot, including the ballistic shockwave, is shown in Figure 22. The average peak amplitude for the ten shots was 8137 Pa, the minimum peak of 7512 Pa (-7.7%) observed for shot 3, and the maximum peak of 8594 Pa (+5.6%) for shot 2.

The shot-to-shot relative energy variation ranged from -7% to +5.6% compared to the average relative energy of the AR-15.

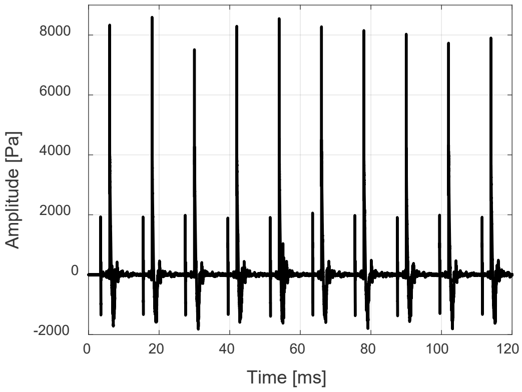

Figure 21: Overlapped plot of ten successive shots by the AR15 rifle.

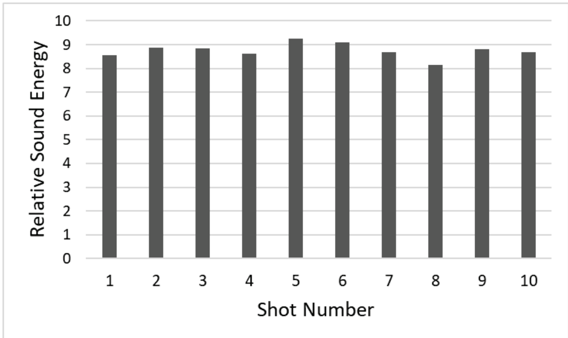

Figure 22: Relative sound strength for each shot with the AR-15 rifle.

9 Discussion and conclusions

The experiments were designed to keep constant the circumstances of each successive shot. Thus, the source of the shot-to-shot variation is attributable primarily to differences in the ammunition. Using commercially manufactured ammunition right out of the box, no attempt was made to match the individual parameters of each cartridge.

The ammunition temperature was similar for all of the test firings described in this paper. However, the efficiency of the cartridge is expected to vary with temperature: cold powder produces lower muzzle velocities than warmer powder [7]. The effect of cartridge temperature on muzzle blast *acoustics* does not appear to have been studied, so forensic examiners are also cautioned about assumptions regarding the acoustical consistency of the sound of a particular firearm and ammunition as a function of temperature.

Another potential source of shot-to-shot variation involves imprecise positioning of the firearm with respect to the recording microphones. The marksman hand-held the firearms during the testing, aiming at a target approximately 50 meters down range, and manually repositioned the firearm between shots. The guns were not mechanically restrained in any fashion, so there was undoubtedly some unintended small variation in aim and muzzle position from one shot to the next [8].

Based upon these results, a recommendation for audio forensic examiners is to use care before assuming that the recorded sound of a particular firearm is precisely repeatable in an investigation involving gunshot sounds. Moreover, as previously reported [4], the difference in muzzle blast waveform as a function of azimuth must also be considered if there is a chance that the relative orientation of the firearm changed with respect to the recording microphone between successive shots.

10 Acknowledgements

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