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Reconsidering the Ballistic Imaging of Crime Bullets in Gun Law Enforcement Operations

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Abstract *Automated ballistics imaging and analysis systems, such as the integrated ballistic identification system (IBIS), have advanced gun law enforcement operations by allowing images of gun crime evidence to be rapidly compared to a large inventory of evidence collected from other crime scenes. After firearm examiners confirm candidate matches, detectives can use the information generated by the links among gun crimes to help solve their cases. Links between recovered cartridge casings represent the vast majority of ballistic matches made through IBIS. Unfortunately, the two-dimensional grayscale digital photography used by the original IBIS equipment was often not refined enough to suggest potential matches between often highly damaged bullets from separate crime scenes. Through the acquisition of three-dimensional measurements, the BulletTrax-3-D image acquisition technology was specifically designed to improve the ability of law enforcement agencies to make bullet matches through automated ballistic imaging and analysis. This study examines the impact of 3-D imaging technology on the productivity of the Boston Police Department's Ballistics Unit in making bullet matches. When directly compared with 2-D imaging technology, we find that the 3-D imaging technology acquired larger amounts of crime bullet evidence and was associated with a nearly fivefold increase in the cold bullet matches by the Ballistics Unit. Interviews with Boston Police detectives confirmed the considerable investigative value of the cold bullet matches.*

Keywords evaluation, gun crime, ballistic, process improvement

Introduction

While gun violence has decreased since the early 1990s, many Americans still die by gunfire, and many more are still affected by non-fatal gun violence. In 2009, a total of 9,146 people were murdered with firearms (U.S. Dept. of Justice—Federal Bureau of Investigation 2009), and it is estimated that another 48,158 were treated in hospitals for gunshot wounds received in assaults (Centers for Disease Control and Prevention 2010). Research suggests that the bulk of urban gun violence is committed by a relatively small number of highly active criminals (e.g., see Braga et al. 2001). Crime guns are durable goods and, if not recovered by law enforcement, can be used in multiple violent incidents. This presents a challenge and an opportunity for strategic gun law enforcement operations.

When fired or ejected from firearms, bullets and cartridge casings pick up signature markings assumed to be unique to the gun (Bureau of Alcohol, Tobacco, Firearms, and Explosives [ATF] 2001; National Research Council 2008). Impact with the firing pin, breech face, and ejector cause signature marks on the cartridge casing, while the gun barrel leaves striations on the bullet as it passes through. Firearm examiners can link a gun to crimes by analyzing these signature markings. Automated ballistics imaging and analysis systems, such as Forensic Technology Inc.'s Integrated Ballistic Identification System (IBIS), have advanced gun law enforcement operations by allowing images of gun crime evidence to be rapidly compared to a large inventory of evidence collected from other crime

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scenes (ATF 2001; Braga and Pierce 2004). After firearm examiners confirm candidate matches, detectives can use the information generated by the links among gun crimes to move their investigations forward and, hopefully, hold offenders accountable for their crimes.

Links between cartridge casings represent the vast majority of ballistic matches made through IBIS (Inspector General 2005). Unfortunately, the two-dimensional grayscale digital photography used by the original IBIS is often not refined enough to suggest potential matches between crime bullets on a routine basis (National Research Council 2008). This is very problematic for gun law enforcement operations as investigative leads that could be generated from existing evidence are not being made. Forensic Technology Inc. has continued to improve the performance of its automated ballistic imaging and analysis systems and, in 2006, started to release a new family of IBIS products based on the acquisition of three-dimensional measurements from bullets and cartridge casings. The BulletTrax-3-D image acquisition technology was specifically designed to improve the ability of law enforcement agencies to make ballistic bullet matches through automated ballistic imaging and analysis.

In this paper, we assess the performance of the BulletTrax-3-D system in assisting law enforcement personnel in making "cold" ballistic matches, commonly called "hits" by investigators, of crime bullets where linkages are made between cases where previously there had been no known connection between the investigations. This study does not attempt to address the accuracy of computerized matching of 3-D ballistic bullet images, the value added by expanding ballistic imaging to include non-crime guns, or any other issues in the larger national debate on ballistics imaging technology. Rather, this research examines the impact of new 3-D ballistics imaging technology on the productivity of the Boston Police Department's (BPD) Ballistics Unit in making cold ballistic bullet hits across crime scenes.

The Emergence of the IBIS System and the Limits of 2-D Technology in Ballistic Imaging

In the past, the comparison of ballistics evidence was a very labor-intensive and time-consuming task as each piece of newly recovered evidence had to be manually compared to a potentially vast inventory of recovered or test-fired bullets and cartridge casings (ATF 2001). There was no means to automate the process and, given labor and time constraints, it was very difficult to make matches across crime scenes (ATF 2001). During the early 1990s, Forensic Technology Inc. developed the IBIS automated ballistics imaging and analysis system. The IBIS system maintains a computerized database of digital ballistic images of bullets and casings from crime guns. As new images are entered, IBIS compares the recovered evidence to existing images from prior crime scenes to identify possible matches. For cartridge casings, digital images are correlated based on characteristics such as breech face, firing pin, and ejector marks. For bullets, digital images of the lands (grooves from the rifling of the firearms barrel) are correlated. The IBIS technology quickly sorts through large volumes of ballistics evidence and suggests a small number of candidate cases that may match the evidence in question. Firearms examiners then manually look at the candidate matches and conduct a standard forensic comparison to confirm a match, if one actually exists.

In 1999, the Bureau of Alcohol, Tobacco, Firearms, and Explosives (ATF) and the Federal Bureau of Investigation (FBI) selected IBIS as the standard ballistics imaging technology for their then-proposed National Integrated Ballistics Information Network (NIBIN)(ATF 2001). Implemented in 2000, NIBIN seeks to unify and coordinate federal, state, and local law enforcement efforts to use ballistics technology to analyze and match recovered gun crime evidence within a jurisdiction and across different jurisdictions. NIBIN is intended to allow law enforcement to check digital images of recovered ballistic evidence against a nationwide file of many thousands of images of ballistics crime scene evidence. ATF has made a concerted effort to publicize the potential value of the technology in advancing its mission of apprehending violent gun criminals. As of March 2011, the NIBIN initiative had 155 participating agencies and 235 IBIS systems; since the program started, over 2 million pieces of crime scene evidence have been acquired and over 40,000 cold ballistic hits have been logged (ATF 2011).

As the IBIS technology developed, a number of firearms examiners and other researchers tested the system's performance. Some analysts scrutinized particular parts of the IBIS comparison process, such as the default comparison pass and 20 percent threshold for detailed image scoring and ranking (e.g., George 2004a, b). However, a bulk of the research focused on specific performance issues raised by the creation of large-scale reference ballistic image databases (e.g., Tulleners 2001; Thompson et al. 2002; DeKinder 2002). This research agenda was influenced by the passage of laws in Maryland and New York requiring ballistics "fingerprinting" of all handguns in their respective states and the calls of gun control advocates for a national reference database of ballistic images for the more than 250 million firearms in the United States (Brady 2002). Gun rights advocates countered that ballistic image databases were unreliable, expensive, and had little utility in solving crimes (Kopel and Burnett 2003). These critics also suggested that ballistics imaging technology was limited because determined criminals can alter markings on or replace barrels, slides, extractors, and firing pins.

These modifications would alter the telltale markings on ballistics evidence and prevent matches from being made.

Based on their review of the available scientific evidence, a panel of experts convened by the National Research Council (2008) concluded that a national reference ballistic image database of all new and imported guns was not advisable at that point in time. The panel observed, among other concerns, that the two-dimensional (2-D) grayscale images were useful for gross categorization and sorting of large quantities of evidence that represent routine law enforcement applications in a relatively modest pool of crime scene and test-fire images. However, the technology was much less reliable in distinguishing the extremely fine individual markings that would be necessary to make successful matches in enormous reference databases that would contain very large numbers of images with very similar gross class and subclass characteristics.

The National Research Council (2008) panel also concluded that the NIBIN program provided valuable crime-solving assistance to law enforcement agencies and that the program should be made more effective through technological and operational improvements. Among other technological recommendations, the National Research Council (2008) panel observed the potential promise of changing the ballistic imaging standard from 2-D grayscale photography to three-dimensional (3-D) surface measurement using noncontact microscopy. Briefly, 3-D imaging technology captures three-dimensional data on ridges and valleys from the striations on the surface of a fired bullet to create a digital map of its surface topography that can be mathematically processed. Experiments conducted for the panel by the National Institutes of Standards and Technology concluded that the 3-D imaging technology was superior in matching certain cartridge markings when compared to the existing 2-D technology (Vorburger et al. 2007). The panel cautiously concluded that further testing and development was necessary before full consideration could be given to adopting 3-D as the new standard in ballistic imaging.

The National Research Council (2008) report also suggested that the advancement of 3-D ballistic imaging technology could be helpful in improving match rates for crime bullets. The vast majority of NIBIN cold hits linked cartridge casings rather than bullets. Recovered bullets are often mushroomed and fragmented due to hitting intended and unintended targets. The IBIS 2-D technology is not very effective in detecting potentially identical markings among bullet images when compared to detecting potentially identical markings among less damaged and distorted cartridge casings recovered from crime scenes. The U.S. Department of Justice (DOJ) Inspector General's audit (2005) found that many NIBIN agencies were not entering bullet evidence into the system because firearms examiners believed that the IBIS equipment did not produce good quality images of the bullets.

A recent study found that 3-D ballistic imaging technology produced improved match correlations when directly compared to match correlations produced by 2-D technology. Beauchamp and Roberge (unpublished data) analyzed samples of bullets of known matched pairs of 9-mm Luger, .45 Auto, .38, and .22 Long Rifle calibers, and of two material compositions, copper jacketed and lead. They found that the 3-D data correlation yielded a 10 to 15 percent improvement over the 2-D data correlation. Interestingly, they also found that the correlation of the 3-D data combined with the 2-D data yielded a 25 percent improvement over the 2-D data correlation alone. Beauchamp and Roberge (unpublished data) concluded that 3-D data and 2-D data provided complementary information in the sense that a match not found by one algorithm may occasionally be found by the other. The 3-D matching performance was also noted to be better for copper jacketed bullets than for lead bullets.

Most of the National Research Council (2008) panel's operational recommendations involved practical steps to enhance the capacity of law enforcement agencies to collect, enter, and analyze gun crime evidence using the IBIS technology. Law enforcement agencies differ in the degree to which they use NIBIN resources and, as a result, differ markedly in the benefits they derive in establishing links between gun crimes and generating investigative leads. The DOJ Inspector General's audit (2005) found that, as more evidence was entered into NIBIN, law enforcement agencies greatly improved the likelihood that ballistic matches were identified. The DOJ audit reported that the 20 percent of NIBIN partner agencies that contributed 75 percent of the evidence to the NIBIN system also identified 72 percent of the cold hits.

Particular law enforcement agencies, such as the Boston Police Department (BPD), report considerable value added to their gun law enforcement operations by adopting and diligently using the IBIS ballistic imaging technology (Braga and Pierce 2004; Braga 2008). Since adopting the 2-D technology in March 1995, the BPD makes an aggressive effort to collect, image, and enter ballistic evidence from all incidents involving firearms, ranging from homicides to illegal possession cases to non-fatal gun assaults, into the IBIS database. The DOJ Inspector General (2005) audit report included the BPD as one of 12 agencies selected for a closer examination of hit rates. At the time the data were collected by DOJ, the BPD reported the highest number of total cartridge cases entered into the IBIS system (5,741) and the second highest number of total cold hits reported (431).

A recent assessment of the impact of ballistics imaging technology in Boston found that the adoption of IBIS was associated with a six-fold increase in the monthly number of cold hits made by the BPD Ballistics Unit (Braga and

Pierce 2004). Extended analyses of the cold hits reported that almost 39 percent generated significant investigative leads; IBIS cold hits were also associated with the arrest of very serious gun offenders and high conviction rates for their immediate gun offenses (Braga 2008). Cartridge casing matches generated most of these benefits, however. Bullet matches represented only 2 percent of the cold hits (8 of 396) made by the BPD during the 1995–2002 study period (Braga and Pierce 2004).

The Adoption of the BulletTrax-3-D Technology by the Boston Police Department

The BPD was selected as the site for an evaluation of the adoption of the BulletTrax-3-D technology based on the agency's reputation as engaging innovative gun violence reduction strategies and their commitment to the ballistic imaging of recovered gun crime evidence (e.g., see Braga et al. 2001; Braga and Pierce 2004). The BPD and FTI signed a memorandum of understanding to cooperate in an evaluative study to assess the value added by 3-D bullet imaging technology to their gun law enforcement operations in August 2008. Over the course of fall and early winter 2008, BPD acquired and tested the IBIS BulletTrax-3-D bullet imaging system and IBIS MatchPoint+, a comparative analysis system for 2-D and 3-D images. The 3-D system was fully operational as of January 1, 2009. The evaluation study period began at this time and continued until June 30, 2010.

Figure 1 presents the yearly counts of bullets and yearly counts of cartridge casings entered into ballistic imaging systems by the BPD Ballistics Unit between 1995 and 2010. Excluding the 1996, 1997, 2007, and 2008 years, the Ballistics Unit entered an average of 332 bullet images each year. According to Steven Faulkner, a long-time BPD IBIS technology operator, the low bullet image acquisition counts during those years was due to the directives of unit supervisors who believed that scarce resources should not be used to image all recovered crime bullet evidence. This directive was based on the supervisors' observations that the 2-D imaging technology was not very useful in generating cold bullet hits. After adopting BulletTrax-3-D, the BPD Ballistics Unit made 366 bullet entries in 2009 and 314 entries in 2010.

The yearly counts of cartridge casings entered into the IBIS 2-D imaging system (Figure 1) generally tracked yearly counts of gun homicide and gun assault incidents between 1995 and 2008 (Figure 2). Cartridge casing entries dropped off significantly during 2009 and 2010. According to Captain Detective Michael Broderick, then commander of all forensics operations for the BPD, the decrease in cartridge casing entries during these years was linked to the Ballistic Unit's participation in the evaluation study. As will be discussed further below, the impact evaluation required all bullet evidence to be imaged twice: once in the 2-D system and once in the 3-D system. This "double entry" procedure was necessary to make valid comparison in the performance of the two imaging systems. However, given limited resources, the Ballistic Unit's ability to keep up with cartridge casing acquisitions was diminished during the 18-month study time period. This should be considered an artificial condition necessary to complete a rigorous evaluation and not an indication that bullet entries somehow undermine cartridge casing entries.

Figure 3 presents the yearly number of cold ballistic bullet matches made by the BPD Ballistics Unit between March 1995, when the IBIS 2-D technology was first implemented in Boston, and December 2010. The Ballistics Unit averaged one bullet match per year between 1995 and 2003 and made zero bullet matches per year between 2004 and 2008. For the entire pre-test time period, the yearly average number of cold bullet hits was 0.64. The Ballistics Unit then adopted the BulletTrax-3-D technology and, in 2009 and 2010, averaged 4.5 bullet matches per year. All four hits reported in 2010 were made during the evaluation study period.

Impact Evaluation

To measure the impact of the BulletTrax-3-D technology on the productivity of the BPD Ballistics Unit, it is important to consider the nature of the technological innovation and its potential impact on BPD operations. The BulletTrax-3-D technology can cross-examine large volumes of crime bullet evidence and suggest a small number of candidate cases that may match the evidence in question. The firearms examiner then carefully looks at the candidate cases using standard procedures to determine whether a real match actually exists. The nature of a confirmed match and its utility to a criminal investigation does not change as a result of the 3-D technology. Forensic evidence, such as ballistics matches, is one part of an information chain (such as eyewitness testimony, circumstantial evidence, etc.) that leads to the ultimate arrest and prosecution of gun criminals. Arrest and prosecution is influenced by many factors beyond the forensic link of a particular gun to ballistics bullet evidence collected at separate crime scenes.

Since the value of a ballistics bullet match to the resolution of a crime is not meaningfully different before and after the adoption of 3-D technology, the outcome of interest is the number of bullet matches made by the Ballistics Unit, not the ultimate disposition of the resulting cases. While we do assess the investigative value of the bullet matches in a subsequent section, the central

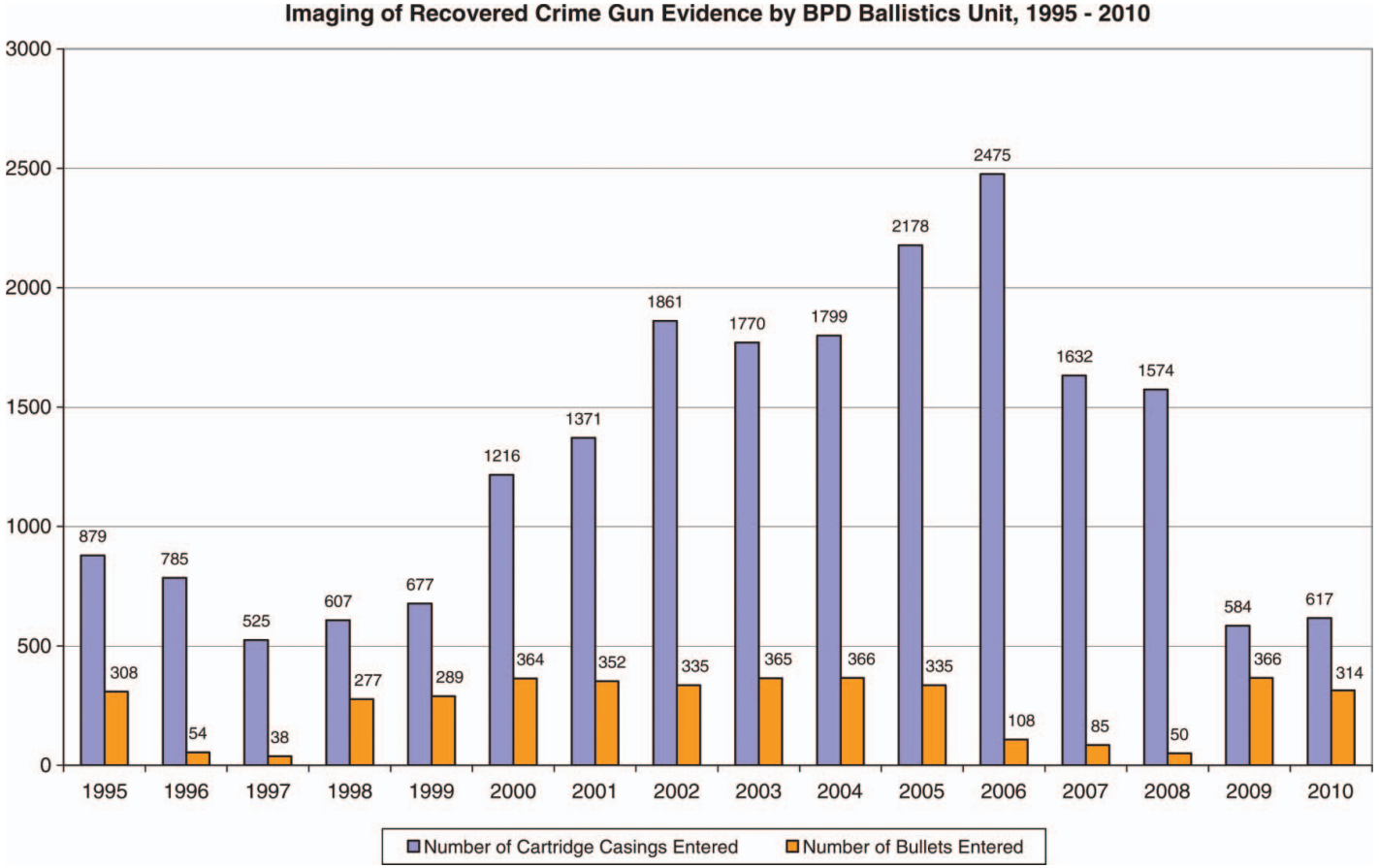

Figure 1. Imaging of recovered crime gun evidence by BPD Ballistics Unit, 1995–2010 (color figure available online).

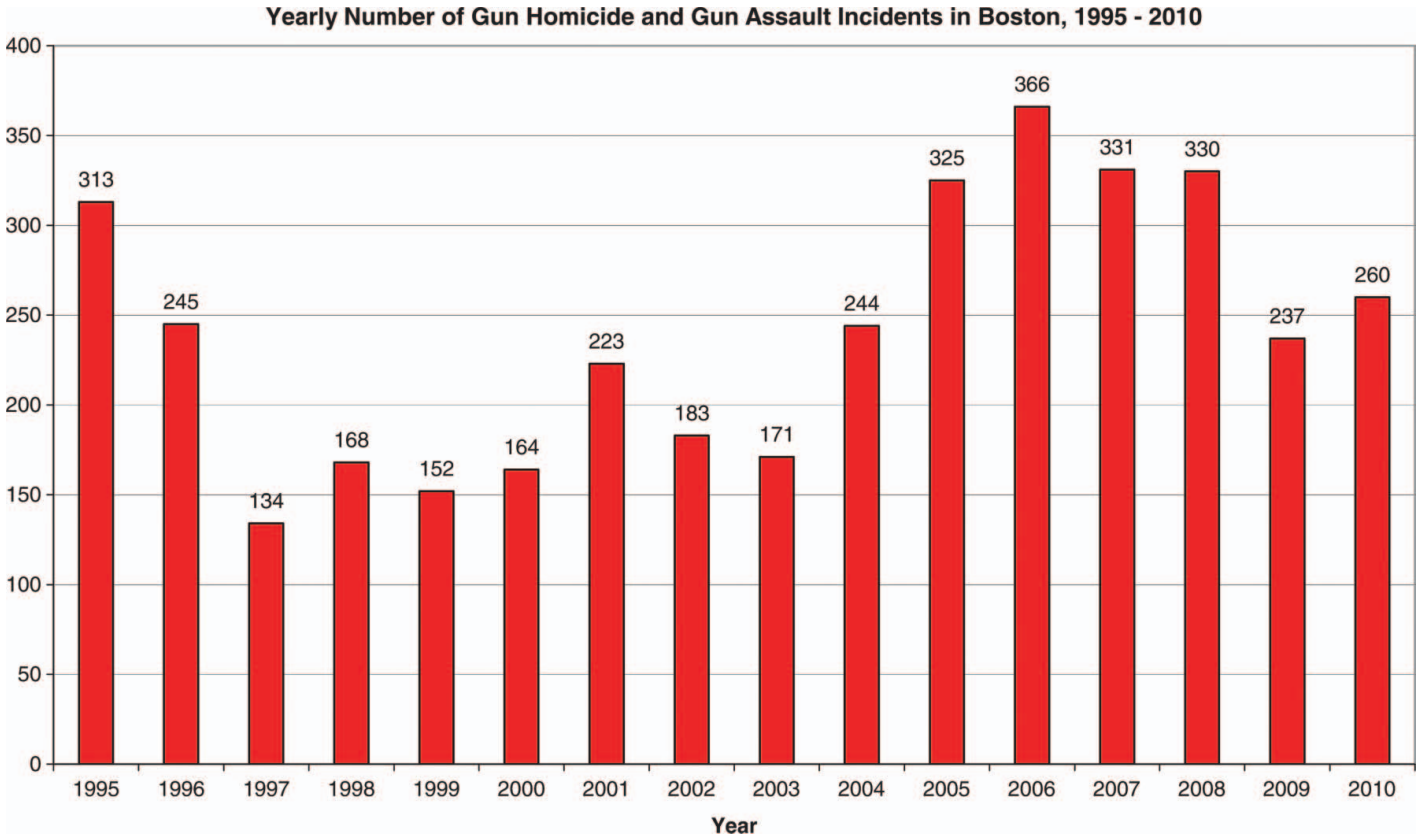

Figure 2. Yearly number of gun homicide and gun assault incidents in Boston, 1995–2010 (color figure available online).

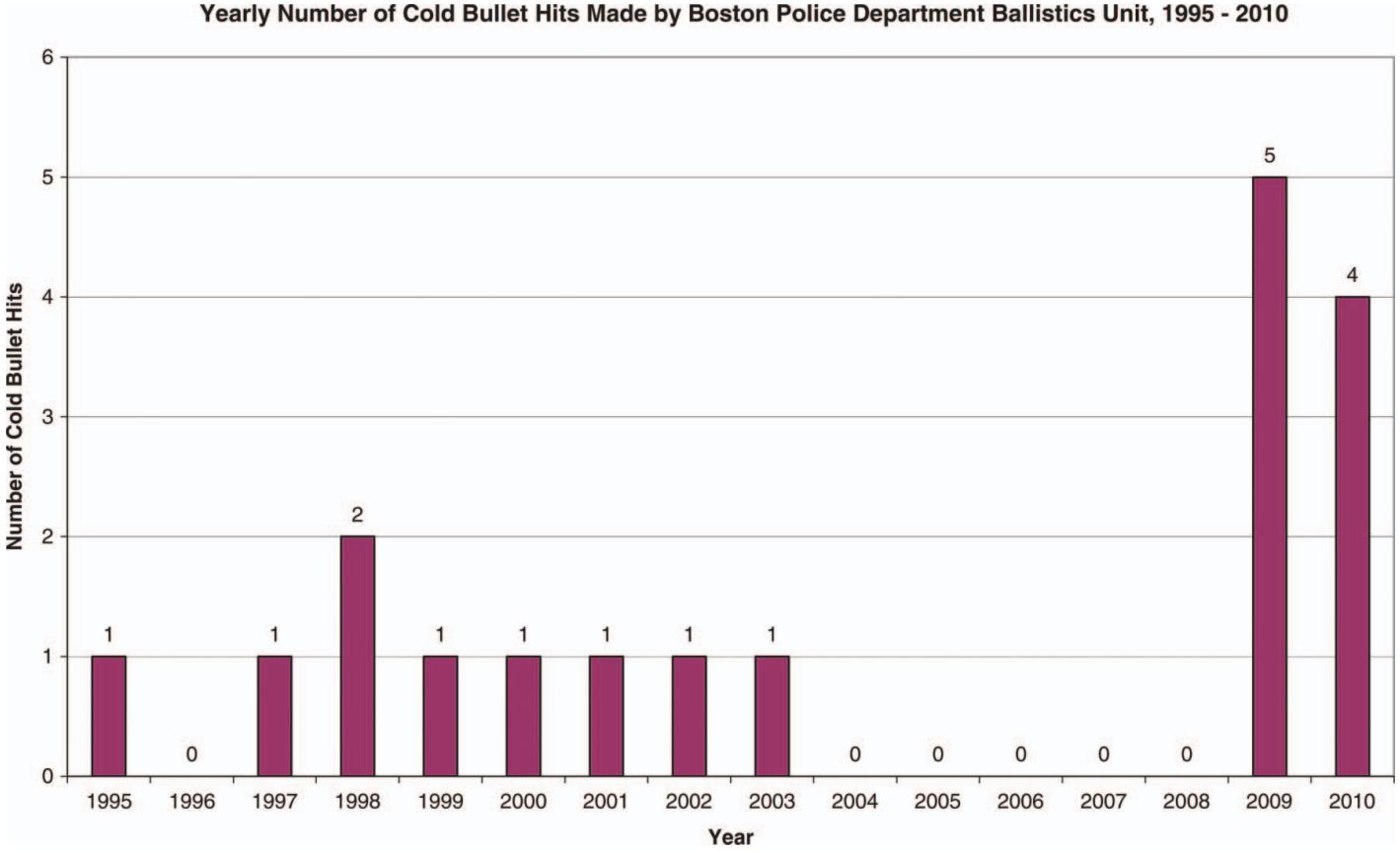

Figure 3. Yearly number of cold bullet hits made by Boston Police Department Ballistics Unit, 1995–2010 (color figure available online).

question considered by this study is whether the 3-D technology changes the ability of the BPD Ballistics Unit to link gun crimes by making crime bullet and bullet fragment matches. Stata /IC 11.0 statistical software was used to analyze the data presented below.

BulletTrax-3-D Imaging System v. Heritage 2-D Imaging System Comparison

During the January 1, 2009, through June 30, 2010, study time period, the BPD Ballistics Unit attempted to image and enter all recovered crime bullet evidence and bullets that were test-fired from recovered crime guns into both the BulletTrax-3-D system and the heritage IBIS 2-D system. The attempted double entry of all acquired crime gun evidence represents the most rigorous test of the ability of the new 3-D imaging technology to make cold hit bullet matches relative to the 2-D technology. Both technologies were used to analyze the same evidence, operated by the same support staff, and candidate bullet matches were analyzed under the microscope by the same firearm examiners.

The Ballistics Unit attempted to enter 650 pieces of crime bullet evidence into both systems over the course of the study. During the pilot study period, BPD BulletTrax-3-D and heritage 2-D system operators were instructed to spend up to two hours of effort on the image acquisition of each individual recovered crime bullet. Unfortunately, 63 recovered crime bullets (9.7% of 650) could not be entered into either the 3-D system or the 2-D system. The reasons that these crime bullets could not be entered included: 44.4 percent were .22 copper wash bullets that could not be acquired due to "slippage" (28 of 63), 34.9 percent were lead bullets that were too damaged (22 of 63), and 20.7 percent were bullets with poor markings that were fired from worn barrels or altered barrels that produced striations that ran together (13 of 68). The BulletTrax-3-D system acquired 587 crime bullet images, while the heritage 2-D system acquired only 520 crime bullet images. This represents a 12.9 percent improvement in the ability of the Ballistic Unit to image and analyze crime bullet evidence. The most common reasons for the differential entries were that the crime bullets were too damaged (40.3%, 27 of 67) or had poor markings because they were fired from worn or altered barrels (26.9%, 18 of 67).

Using the BulletTrax-3-D imaging technology, the Ballistics Unit made nine cold bullet hits from the acquired 587 crime bullet images. This represents a 1.53% hit rate (9/587*100). The Ballistic Unit did not make any cold bullet hits based on the 520 crime bullet images acquired by the heritage 2-D imaging technology (or a 0.0% hit rate, 0/520). We tested a null hypothesis that there is no difference in the proportion of cold bullet hits made by the 3-D system as compared to the proportion of cold bullet hits made by the heritage 2-D system. A simple difference of two sample proportions' z-score test was used to test the null hypothesis. Based on the size of the z-score that was generated by the test ($z = 2.83$) and associated p-value ($p < 0.0023$), we rejected the null hypothesis and concluded that the difference between these two proportions was so large that it was very unlikely to have happened by chance alone. This simple comparison suggested that the 3-D system generated a significantly higher proportion of cold bullet hits when compared to the proportion of cold bullet hits generated by the heritage 2-D system under the same conditions.

We also conducted a simple comparison of the cold bullet hit rates made by the Ballistics Unit over time. Between March 1, 1995, and December 31, 2008, the Ballistics Unit imaged 3,327 crime-related bullets in their heritage IBIS 2-D imaging system. During this 166-month pre-test period, only nine cold bullet hits were made by the heritage 2-D imaging system. The proportion of bullet evidence entries that resulted in a cold hit is 0.27% (9/3,327*100). Using a simple difference of two sample proportions' z-score test, we concluded that there was a statistically significant increase in the cold bullet hit rate when the Ballistics Unit adopted the BulletTrax-3-D technology ($z = 4.16$, $p < 0.000$). If the 3-D technology was available during the pre-test time period and the Ballistics Unit made matches at the same rate as during the post-test period, they would have made approximately 51 cold bullet hits during the pre-test time period (1.53% rate*3,327 = 50.9). This represents roughly 42 additional cold bullet hits or an estimated 467% increase over the performance of the heritage 2-D system.

In addition to the nine cold hits made during the 18-month pilot project time period, the Ballistics Unit also made eight "warm" hit matches using the BulletTrax-3-D technology. Warm hit ballistic matches occur when investigators have a priori knowledge that multiple gun crimes, or recovered firearms and incidents of gun violence, might be linked. In these eight warm hits, the suggested matches were initially examined via BulletTrax-3-D and, when potential matches were identified by the technology, a firearms examiner then confirmed the candidates using a microscope. It is important to note here that the BulletTrax-3-D equipment operators and the firearms examiners were blind to whether the matched crime bullets from separate cases were previously linked by existing investigative knowledge held by BPD detectives. The determination of warm and cold hits occurred after the match was confirmed and the information was forwarded to the appropriate case detectives for their consideration.

While warm hits do not generate previously unknown investigative links, the confirmed connections are still important to investigators as they develop cases against gun offenders. For instance, the BulletTrax-3-D system confirmed that the 9-mm handgun recovered from a

hollowed-out copy of Gray's Anatomy in the apartment of Philip Markoff, the so-called Craigslist killer, was indeed the same firearm that was used to kill 25-year-old Julissa Brisman in a Boston hotel. While there was plenty of other evidence to arrest Markoff, confirmation that Boston Police homicide detectives had recovered the murder weapon was an important investigative development. Summing the warm and cold hits, the total hit rate for the BulletTrax-3-D technology during the pilot period was 2.9% (17/587*100).

Multivariate Pre-Test v. Post-Test Comparison of the Productivity of the BPD Ballistics Unit

Our deeper analysis of the impact on the monthly number of cold bullet hits made by the BPD Ballistics Unit associated with the adoption of the BulletTrax-3-D technology follows a basic one-group interrupted time series design (Campbell and Stanley 1966; Cook and Campbell 1979). Unfortunately, we can only directly compare the performance of the BulletTrax-3-D technology to the heritage 2-D technology for the 18-month pilot project time period. We can, however, examine the impact of the technological change on the productivity of the Ballistics Unit over the entire 184-month time period between March 1995 and June 2010.

In absence of a separate comparison group, the key to a compelling one-group interrupted time series design is the degree to which forces not related to the intervention influence the outcome variable. If at the time the BulletTrax-3-D technology was introduced in Boston the staff of the Ballistics Unit also changed, this could pose a problem of a change in "instrumentation" (Cook and Campbell 1979, Shadish, Cook, and Campbell 2002). However, this was not the case in Boston. The unit had, on average, about five firearm examiners and 10 total personnel on staff between 1995 and 2008 (Table 1). The total personnel dropped by only one staff member between 2009 and 2010 as the unit lost two firearm examiners and hired an additional support staff member. The only substantive change in the dynamics of the Ballistics Unit was the addition of the BulletTrax-3-D technology.

Factors external to the Ballistics Unit that might potentially influence bullet matches were controlled for in our design though a time series analysis of the monthly counts of bullet matches before and after the introduction of BulletTrax-3-D technology. Monthly counts of cold bullet hits are distributed in the form of rare event counts. There are well-documented problems associated with treating event count variables, which are discrete, as continuous realizations of a normal data generating process (King 1989). As such, methods such as standard mean difference tests and ordinary least squares regression that assume population normality of the dependent variable should not be used to analyze count data (Gardner, Mulvey, and Shaw 1995). Rather, Poisson regression is generally used to estimate models of the event counts (Long 1997). The Poisson regression model has the defining characteristic that the conditional mean of the outcome is equal to the conditional variance. The outcome variable in this analysis, the monthly count of cold bullet matches, has a mean = 0.10 and variance = 0.11. A Komologorov-Smirnov goodness-of-fit test of the outcome variable distribution strongly indicated that it was generated by a Poisson process (KS = 0.087, $p < 0.999$).

Table 1. Staffing Levels of the BPD Ballistics Unit, 1995 – 2010

Year	Supervisors	Firearm Examiners	Support Staff	Total
1995	1	7	1	9
1996	2	7	1	10
1997	2	6	2	10
1998	2	5	3	10
1999	2	6	3	11
2000	2	5	3	10
2001	2	5	3	10
2002	1	4	4	9
2003	1	5	5	11
2004	2	4	4	10
2005	1	4	4	9
2006	1	5	4	10
2007	1	5	4	10
2008	2	5	3	10
2009	1	5	4	10
2010	1	3	5	9

The pre-BulletTrax-3-D time series was comprised of the monthly counts of cold bullet hits between March 1995 and December 2008; the post-BulletTrax-3-D time series was comprised of monthly counts of cold bullet hits between January 2009 and June 2010. A binary dummy variable indicating whether the BulletTrax 3-D technology was present or not was constructed to estimate the effects of the intervention on the monthly counts of cold bullet hits. It is important to recognize that the monthly number of cold bullet hits made by the BPD Ballistics Unit is influenced by the amount of evidence acquired by the unit every month. We included the monthly number of bullet images entered in our statistical models to control for the amount of evidence being entered into the ballistic imaging systems over time that may or may not lead to a bullet match. We also included the monthly number of cartridge casings entered into the IBIS ballistic imaging system in our statistical models as another measure of the workload experienced by the Ballistic Unit during the study time period. In order to account for seasonal variations in our model, we included dummy variables for each month. Finally, to control for the effects of assaultive gun violence levels on broader BPD enforcement operations, we included the aggregate monthly counts

of firearm homicide incidents and firearm aggravated assault incidents during the study time period.

The parameters for the independent variables were expressed as incidence rate ratios (i.e., exponentiated coefficients). Incidence rate ratios are interpreted as the rate at which things occur; for example, an incidence rate ratio of 0.90 would suggest that, controlling for other independent variables, the selected independent variable was associated with a 10% decrease in the rate at which the dependent variable occurs. To ensure that the coefficient variances were robust to violations of the homoskedastic errors assumption of linear regression models, Huber/White/sandwich robust variance estimators were used. Following social science convention, the two-tailed, .05 level of significance was selected as the benchmark to reject the null hypothesis of "no difference." The basic model was as follows:

$$\text{Monthly Count} = \text{Month} + \text{Monthly Count of Bullet Entries} + \text{Monthly Count of Cartridge Entries} + \text{Monthly Count of Bullet Matches Dummies of Gun Crimes} + \text{BulletTrax Dummy} + \text{Error}$$

Table 2 presents the results of the Poisson regression model. The monthly count of bullet and cartridge casing evidence being imaged and entered by the Ballistics Unit did not have a statistically significant relationship to the monthly counts of cold bullet matches over time when the other covariates were controlled in the model. However, controlling for the other covariates, an increase in the monthly counts of gun crimes in Boston was associated with a decrease in the number of monthly bullet hits made by the Ballistics Unit. Certain month dummy variables were also statistically significant, suggesting seasonal differences in cold bullet hits generated by the Ballistics Unit. Turning to the potential impact of BulletTrax-3-D, we find the adoption of the technology, controlling for the other independent variables, was associated with a statistically significant 4.69-fold increase in the monthly number of cold bullet hits generated by the BPD Ballistics Unit ($p < .01$).

Table 2. Results of Poisson Regression Model (N = 184)

Variable	I.R.R.	Robust Std. Error	Z	P > |Z|
BulletTrax-3-D	4.694	2.461	2.95	0.003
Bullets entered	1.017	0.011	1.54	0.124
Casings entered	0.989	0.009	−1.18	0.239
Gun violence	0.939	0.025	−2.29	0.022
February	1.555	1.177	0.58	0.559
March	1.099	0.981	0.11	0.915
April	0.336	0.430	−0.85	0.394
May	0.509	0.656	−0.52	0.601
June	1.077	0.877	0.09	0.927
July	1.128	1.055	0.13	0.897
August	0.001	0.008	−20.59	0.000
September	2.141	1.576	1.03	0.301
October	0.009	0.007	−21.00	0.000
November	0.363	0.305	−1.20	0.229
December	0.009	0.007	−21.39	0.000

Pseudo $R^2 = 0.3397$
Wald chi-square = 3063.54; degrees of freedom = 15; $p < 0.000$
Note: January was the reference category for the month dummy variables.

Investigative Value of Cold Bullet Hits

As described earlier, BulletTrax-3-D cold bullet hits do not change the inherent value of ballistics evidence in an investigation, as many other factors converge to determine whether an arrest is eventually made. A cold hit that links gun crimes, whether it involves bullets or cartridge casings, does not guarantee an immediate arrest. For instance, the linked incidents may not involve victims or witnesses that can or are willing to make a positive identification. Rather, cold hits better position law enforcement agents to identify gun criminals through strategic analyses of information and intelligence sharing. The Boston Police and their criminal justice partners use cold hit information as a tool to shed light on the dynamics at play in violent street social networks and to further their ability to apprehend violent gun criminals (Braga 2008). IBIS 2-D and BulletTrax-3-D systems provide Boston investigators with more opportunities to make links among individuals and locations through a particular gun.

We interviewed Boston Police detectives that were assigned to investigate the linked gun crimes for the nine cold bullet hits made by the BulletTrax-3-D technology to determine the investigative value of each hit. Table 3 presents the types of gun crimes that were linked in each cold hit, a brief synopsis of the gun crimes that were linked, and the interviewed detectives' assessment of the investigative value of the hits. These nine cold bullet hits linked three homicide incidents (including a triple homicide), seven gun assault incidents, four illegal gun possession incidents, and one found gun incident. All nine cold bullet hits were regarded as noteworthy investigative leads by the interviewed detectives, and the significance of each lead was determined by the investigative and intelligence information available from the linked gun crimes.

The detectives reported that two cold hits were directly associated with new arrests or the issuance of arrest warrants; in short, it would not have been possible to hold these offenders accountable for their violent crimes without the information linked by the cold bullet hit. For instance, in cold bullet hit number 4, a Taurus .40 Model PT 140 Pro semiautomatic pistol recovered from a non-fatal gun assault offender was linked to triple homicide incident that occurred four months earlier. A subsequent interview with the arrested gun assault offender

Table 3. Investigative Value of Cold Bullet Hits

Cold Bullet Hit Number	Linked Gun Crimes	Gun Crime Synopsis	Investigative Value
1	(1) Assault with deadly weapon–firearm (2) Illegal gun possession	The first incident involved the unsolved non-fatal shooting of four Hendry Street gangsters. Eight months later, the Boston Police chased three Bowdoin Street gangsters were in a stolen motor vehicle. A Norinco .45 Model 1911A1 semiautomatic pistol was recovered from one of the gangsters when Boston Police apprehended them.	There was not enough evidence to arrest the rival Bowdoin Street gangsters for the quadruple shooting. The cold bullet hit was considered value investigative information as it confirmed intelligence that the quadruple shooting was part on an ongoing dispute among these gangs. The arrested three suspects are in the process of being prosecuted for their immediate gun crime.
2	(1) Assault with deadly weapon–firearm (2) Illegal gun possession	The first incident involved the non-fatal shooting of a Cape Verdean Outlaw gangster. Six days later, BPD Youth Violence Strike Force officers observe a juvenile Olney/Norton gangster acting suspiciously. The juvenile was arrested after he admitted that he was illegally carrying a Hi-Point 9-mm Model C-9 semiautomatic pistol.	The cold bullet hit confirmed intelligence that the juvenile was the shooter. However, the Suffolk County District Attorney's Office declined prosecution of the gun assault incident and pursued the illegal gun possession charge. Juvenile was convicted and served 18 months in a secure juvenile facility.
3	(1) Homicide (2) Found gun	The first incident involved the homicide of a known street-level drug dealer. Ten days after the homicide, the Drug Control Unit and K-9 officers conducted a search of a nearby empty lot known for illegal drug activity. The officers recovered a Smith & Wesson .45 Model 645 semiautomatic pistol.	The cold bullet hit was considered a significant lead in the investigation as the homicide firearm was recovered. Despite the gun recovery, homicide investigators do not have enough evidence to arrest a suspect in the case. The investigation is ongoing.
4	(1) Assault with deadly weapon–firearm (2) Homicide (triple)	While patrolling a gun violence hot spot, BPD Youth Violence Strike Force witnessed a non-fatal gang shooting incident. The officers apprehend the shooter and recovered a Taurus .40 Model PT 140 Pro semiautomatic pistol. The gun was test-fired and the bullet matched recovered bullets from a triple homicide that occurred nearly four months earlier.	When the homicide detectives interviewed the gun possession suspect, they learned that their key suspect in the triple homicide had transferred the gun to the gun possession offender. This was viewed as a very significant lead in the triple homicide case and, coupled with other investigative information, led directly to the issuance of an arrest warrant for the homicide offender. After the recovered crime gun was traced, this murder investigation resulted in an ATF gun trafficking investigation.
5	(1) Assault with deadly weapon–firearm (2) Illegal gun possession	MIC gang member was shot in gymnasium at night during teen dance. About six weeks later, the Drug Control Unit served a warrant on the residence of a Greenwood Street gangster and recovered three guns, cocaine, and money. The guns were test-fired and a bullet fired from one of the recovered guns (Ruger .357 Magnum revolver) was linked to bullet evidence recovered at the earlier non-fatal shooting.	Boston Police detectives reported that this was a very important lead that confirmed a rival gang member perpetrated the non-fatal shooting. Combined with other evidence (such as phone records), the cold bullet hit was associated with the issuance of an arrest warrant.
6 & 7	(1) Assault with deadly weapon–firearm (2) Assault with deadly weapon–firearm (3) Assault with deadly weapon–firearm	After responding to a "shots fired" call for service, Boston police officers arrested two Homes Avenue gangsters for the non-fatal shooting a rival Wendover gang member. The officers recovered a Daewoo .40 Model D40 semiautomatic pistol. The gun was test-fired, and the bullet matched crime bullets recovered from two prior non-fatal shooting incidents.	The arrested suspects were prosecuted for their immediate gun crime. Both were convicted; one received a 5–7 year state prison sentence and the other received an 8–12 year state prison sentence. The cold bullet hit confirmed prior intelligence that the other non-fatal shootings were part of an ongoing gang dispute.

(Continued on next page)

Table 3. Investigative Value of Cold Bullet Hits *(Continued)*

Cold Bullet Hit Number	Linked Gun Crimes	Gun Crime Synopsis	Investigative Value
8	(1) Homicide (2) Illegal gun possession	The first incident involved the fatal shooting of a known street-level drug dealer. Three months later, the Drug Control Unit executed a search warrant on the apartment of another drug dealer and recovered crack cocaine, money, and a Hi-Point 9-mm Model C-9 semiautomatic pistol. The gun was test-fired and the bullet matched a crime bullet recovered from the prior homicide.	Homicide detectives regarded this cold bullet hit as a valuable lead in the investigation. While they acquired the homicide firearm, the detectives reported that additional evidence was necessary to connect a suspect to the homicide. There is no other information linking the suspect to the homicide victim. No arrest warrant was issued and the investigation is ongoing.
9	(1) Shots fired/Illegal gun possession (2) Homicide	Boston Police officers arrested a Peacevale gangster who was shooting at rival gang members (no victims found, property damage only). A Smith & Wesson 9-mm semiautomatic pistol was recovered and test-fired. The bullet matched a bullet recovered from a homicide of a street-level heroin dealer that occurred one month earlier.	Homicide detectives regarded this cold bullet hit as a valuable lead in the investigation. Coupled with prior intelligence, the cold bullet hit confirmed that two suspects of interest committed the homicide. At the time of the interview, the investigation was very active and an arrest warrant was believed to be forthcoming.

revealed that the lead suspect in the triple homicide incident had provided Taurus .40 semiautomatic pistol to him. Sergeant Detective Marc Sullivan, the lead investigator on the triple homicide case, commented, "The bullet match was a significant lead in the Boston Police Department's investigation of a triple homicide. Through further investigation, we were able to link the recovered firearm to the homicide offender and obtain an arrest warrant." A gun trafficking investigation also developed from this case as a subsequent ATF trace of the recovered firearm revealed that a third party had recently purchased the Taurus .40 semiautomatic pistol at a licensed dealer in an Interstate-95 highway southern state with lax gun control laws when compared to Massachusetts tighter gun control laws.

Conclusion

The results of this research study suggest that the BulletTrax-3-D imaging technology significantly improved the ability of the BPD Ballistic Unit to make cold hit bullet matches during the pilot study time period. When directly compared with the performance of the 2-D imaging system that analyzed the same bullet evidence, our impact evaluation found:

- The BulletTrax-3-D technology was associated with a 13% increase in the capacity of the Ballistic Unit to image submitted crime bullet evidence.
- The BulletTrax-3-D made nine cold bullet hits from 587 crime bullet images acquired during the pilot test period (1.53% hit rate), while the heritage 2-D system made zero cold hits from 520 crime bullet images acquired during the pilot period (0.0% hit rate).
- If the 3-D technology was available during the pre-test time period and the Ballistics Unit made matches at the same rate as during the post-test period, they would have made 42 additional cold bullet hits or an estimated 467% increase over the performance of the heritage 2-D system.
- When examining the March 1995 through June 2010 time period, multivariate Poisson regression models estimate that the BulletTrax-3-D technology was associated with a 4.69-fold increase in the ability of the Ballistic Unit to make cold bullet hits.
- The BulletTrax-3-D technology was associated with the generation of noteworthy investigative leads in the cases linked by the nine cold bullet hits, including the issuance of arrest warrants in two sets of linked cases that would not have been possible without the cold hit.

Clearly, the enhanced capacity of the BulletTrax-3-D imaging technology represents a significant improvement over the heritage 2-D system in ballistic imaging and analysis. While nine cold bullet hits over an 18-month period may seem like a very modest number, it is important to recognize that Boston is a relatively safe city that experiences lower levels of gun violence. In 2010, Boston had a population of 617,594 residents and experienced 60 gun homicides and 200 non-fatal shootings (Figure 2). In comparison, Baltimore, a city of 620,961 residents, experienced 170 gun homicides and 420 non-fatal shootings in 2010. Jurisdictions with larger numbers of fatal and

non-fatal gun incidents seem likely to generate larger numbers of cold bullet hits.

Of course, it is important to note that the 3-D technology alone is not enough to improve gun law enforcement operations. As suggested by the DOJ Inspector General's audit (2005), the technology needs to be accompanied by an organizational commitment to image and analyze all recovered crime gun evidence in a comprehensive manner (see also Gagliardi 2010). Law enforcement agencies also need to ensure that linked information gets to the appropriate criminal investigators and that these investigators follow up on all investigative leads. Only then will repeat gun criminals face an increased risk of being apprehended for their crimes.

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