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Diagnostic and therapeutic considerations in cases of civilian intravascular ballistic embolism: a review of case reports

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ABSTRACT

Background Ballistic embolism (BE) is a rare complication of firearm injuries notoriously associated with a vexing clinical picture in the trauma bay. Unless considered early, the associated confusion can lead to needless delay in the management of the patient with a gunshot wound. Despite this known entity, there is a relative paucity of high-grade evidence regarding complications, management, and follow-up in these patients.

Methods An electronic database literature search was conducted to identify cases of acute intravascular BE in pediatric and adult civilians occurring during index hospitalization, filtered to publications during the past 10 years. Exclusion criteria included non-vascular embolization, injuries occurring in the military setting, and delayed migration defined as occurring after discharge from the index hospitalization.

Results A total of 136 cases were analyzed. Nearly all cases of BE occurred within 48 hours of presentation. Compared with venous emboli, arterial emboli were significantly more likely to be symptomatic (71% vs. 7%, p<0.001), and 43% of patients developed symptoms attributable to BE in the trauma bay. In addition, arterial emboli were significantly less likely to be managed non-invasively (19% vs. 49%, p<0.001). Open retrieval was significantly more likely to be successful compared with endovascular attempts (91% vs. 29%, p<0.001). Patients with arterial emboli were more likely to receive follow-up (52% vs. 39%) and any attempt at retrieval during the hospitalization was significantly associated with outpatient follow-up (p=0.034). All but one patient remained stable or had clinically improved symptoms after discharge.

Conclusion Consideration for BE is reasonable in any patient with new or persistent unexplained signs or symptoms, especially during the first 48 hours after a penetrating firearm injury. Although venous BE can often be safely observed, arterial BE generally necessitates urgent retrieval. Patients who are managed non-invasively may benefit from follow-up in the first year after injury.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Intravascular ballistic embolism (BE) is a rare complication of firearm and blast injuries that has been reported hundreds of times in the literature since the 1970s and warrants clinical consideration in the civilian setting.

⇒ The literature on BE is composed of case reports and reviews, but there is an absence of high-grade evidence regarding complications, management, and follow-up in these patients.

WHAT THIS STUDY ADDS

⇒ We include more than 60 new cases since the last systematic review in 2019 and limited our review to include only cases of acute intravascular BE occurring during the index hospitalization. We also narrowed the review to cases published in the past 10 years due to modern advancements and increased utilization of endovascular interventions.

⇒ Although previous reviews have focused heavily on interventional management of BE, this review is uniquely geared toward trauma and surgical intensive care teams.

⇒ We provide a new perspective on the diagnostic challenges of BE and to our knowledge, we are the first to describe limitations of three commonly cited clinical associations with BE.

⇒ To our knowledge, this is the first systematic review describing information regarding follow-up in patients with BE.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ This review will raise clinical awareness of BE among trauma clinicians and accentuate aspects of BE that warrant clinical consideration in the acute setting.

⇒ We hope our work encourages further research to address optimal management and follow-up in these patients.

⇒ There are three regularly discussed observations associated with BE. We highlight some limitations in applying these principles and provide a list of considerations for authors of future case reports regarding BE.

BACKGROUND

Ballistic embolism (BE) is a rare and potentially life-threatening complication of penetrating ballistic injuries that was initially studied in the military setting, with incidence rates reported as low as 0.04%.[1] Although certainly rare, this phenomenon is not limited to the military setting or to the use of military weapons.

The penetrating and injury potential of projectiles is influenced by the amount of kinetic energy (KE=½ MV²) transferred to the tissues, the rate at which this

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occurs, and the local response of the affected tissue zone.[2 3] Compared with the military setting, civilian firearm injuries are more often due to lower-energy firearms, such as handguns. Since the penetrating potential of a projectile is influenced by the amount of kinetic energy transferred, it is thought that these low-energy firearms may have a heightened propensity for intravascular migration due to their capacity for partial penetration through one vessel wall without a complete through-and-through injury.[3]

In 1979, Mattox *et al* were among the first to bring attention to the diagnostic and therapeutic challenges of BE in the trauma bay.[4] BE may create a confusing clinical picture for two main reasons: projectiles can enter the circulation from nearly any point of injury and the presenting signs and symptoms rarely correlate with those expected from the anticipated tract of the projectile.[4 5] The clinical picture in the trauma bay is complicated further when patients present with penetrating wounds in multiple regions of the body, all with incompletely appreciated trajectories and paths of destruction.

Arterial emboli often present with signs of distal ischemia or claudication, frequently necessitating emergent removal.[4 5] In contrast, patients with venous BE are often asymptomatic and there remains controversy regarding optimal management.[6] This dilemma has been complicated in the past 10 years by the advances and increased utilization of catheter-directed interventions.

Kuo *et al*, in a review published in 2019, looked at intravascular BE primarily from a vascular and interventional perspective. However, there was no distinction made between acute BE during the index hospitalization and delayed BE occurring up to years after the initial injury.[6] We aim to provide an updated review focused on the diagnostic and therapeutic challenges that may arise in the trauma bay and/or surgical trauma intensive care unit.

METHODS

Data sources and search strategy

The Preferred Reporting Items for Systematic Review and Meta-analyses guidelines were used to perform this systematic review.[7] As this was a systematic review of case reports, it was not registered. An electronic database literature search strategy was performed using the keywords "embolism," "embolization," "emboli," "embolus," "migration," and "intravascular" cross-searched with the keywords "bullet," "pellet," "missile," and "projectile." The results were filtered to publication date from 2013 to 2023, English-language results, and human studies. All database records were downloaded to EndNote V.x9 (The EndNote Team, 2021) and uploaded to Covidence software (Veritas Health Innovation, https://www.covidence.org, 2023) for de-duplication, screening, and full-text evaluation.

Study selection

Inclusion criteria were English-language case reports and case series describing acute intravascular bullet embolisms in pediatric or adult civilians during the index hospitalization. Abstracts without full text were included if a sufficient description of the case was available. Exclusion criteria included non-vascular embolization, ballistic injuries occurring in the military setting, and delayed migration defined as occurring outside the index hospitalization.

Data extraction and management

Abstracts and full-text articles were reviewed by two independent reviewers to include publications containing cases of actual intravascular BE. Data from each article selected for inclusion were extracted independently by two reviewers using a survey in Qualtrics (Qualtrics, Seattle, WA) which was then exported for statistical analysis. Conflicts between two reviewers were adjudicated by a third reviewer. When there was insufficient information to reasonably infer, the information was considered unknown. Data retrieved included information relating to age, sex, wound location(s), injury type (single gunshot, multiple gunshot, shotgun, or air gun, BB gun injury), entry and terminating vessels, complications, management, and follow-up. Non-invasive management was defined as observation of BE.

BE was classified as belonging to the arterial (left cardiac chambers, systemic arteries, and pulmonary veins) or venous (right cardiac chambers, systemic veins, and pulmonary arteries) determined by the ballistic destination. They were further classified as antegrade (following the direction of normal blood flow), retrograde (against the direction of blood flow), mixed (involving both antegrade and retrograde migration), or paradoxical (crossing into the contralateral circulation).

Quality assessment

Because the literature concerning BE primarily consists of uncontrolled clinical observations published in the form of case reports which are traditionally excluded from systematic reviews, we were unable to perform a more structured quality and bias assessment. Rather, we used the Joanna Briggs Institute (JBI) Critical Appraisal Checklist for case reports to appraise the methodological quality of the studies.[8] Using this checklist, we only included case reports that met the following criteria: (1) clearly described cases of intravascular BE with proposed entry and terminating sites, and (2) clearly described the relevant clinical history. We collected data regarding demographics, adverse events, and takeaway lessons when provided, although we did not require this information for inclusion.

Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics Premium GradPack V.29. We assessed categorical variables with Pearson χ^2 statistic or Fisher's exact test when appropriate. P value of <0.05 was considered significant. Categorical data are reported as count and percentage (%). Continuous data were reported as median and IQR for non-normally distributed data.

RESULTS

Available reports

A flow chart illustrating the available data source is shown in figure 1. A preliminary literature search from PubMed and Embase (Elsevier) databases literature search resulted in 1146 publications of which 115 were included in the review. From the 115 publications, a total of 136 unique BEs were included. The included reports are listed in online supplemental table 1.

Patient demographics and injury characteristics

A total of 125 unique patients were included in the review. Among these patients, 105 (84%) were identified as male. The median age was 27.8 years (IQR 19.5–34 years). Patients were under the age of 18 years in 21 (17%) cases. 10 of these patients had multiple embolisms. The majority of BE resulted from a single gunshot (n=92, 74%), followed by multiple gunshots (n=27, 22%), and minority resulting from blast injuries (n=2, 2%) and unknown mechanisms (n=2, 2%). At least 24 (19%) cases occurred in the context of shotgun injuries, and non-powdered firearm injuries (airsoft, BB, and pellet guns) attributed to 15 (12%) cases.

Wound localization is depicted in figure 2. Most BEs occurred in the context of penetrating wounds to a single region. Among patients with wounds localized to a single anatomical region, projectiles entering the anterior thorax (n=30, 35%) and lower

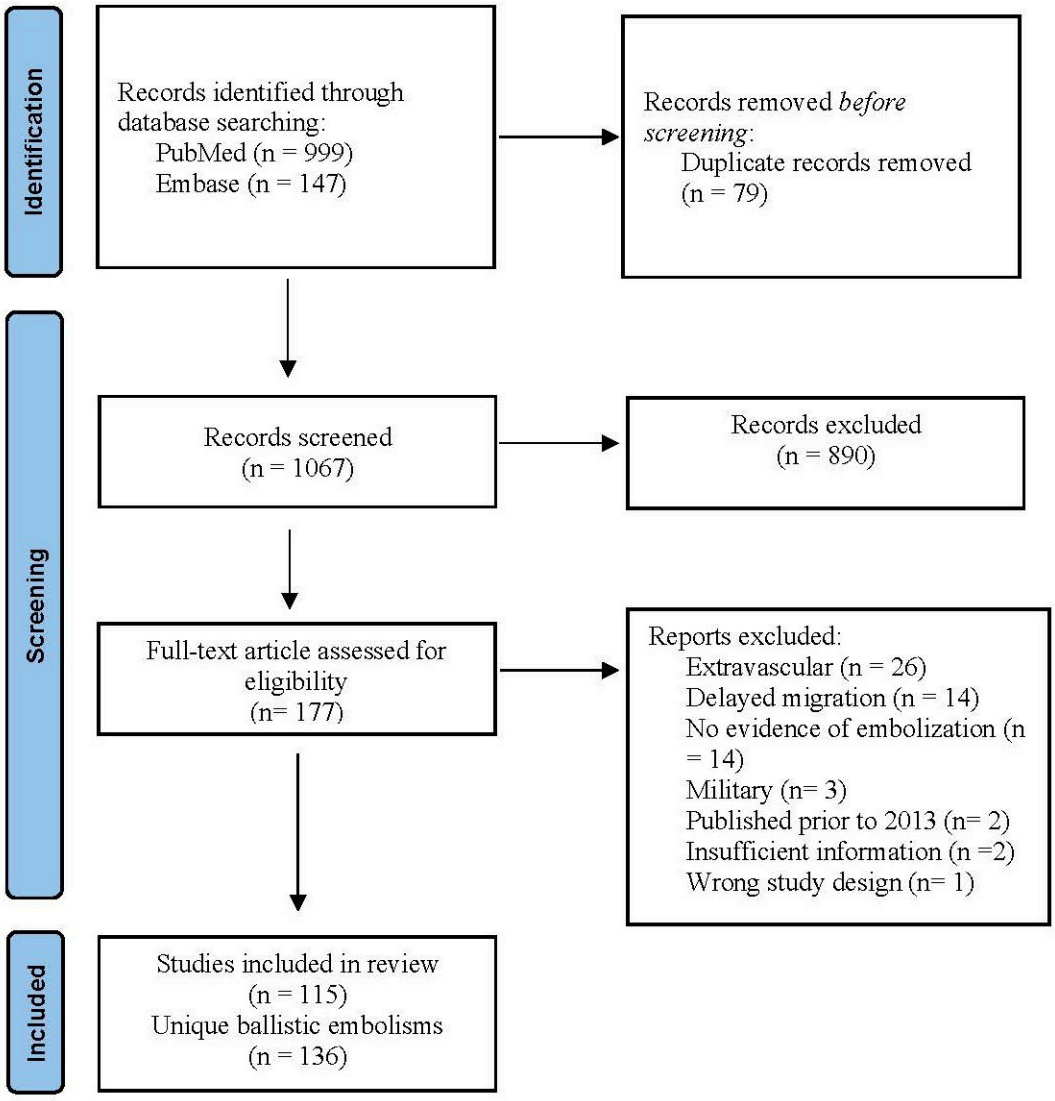

Figure 1 Preferred Reporting Items for Systematic Review and Meta-analyses flow diagram.

extremity/gluteal region (n=11, 13%) accounted for nearly half of all cases. BEs were less commonly the result of neck (n=8, 9%), lateral thorax and axilla (n=8, 9%), posterior thorax (n=8, 9%), flank and abdomen (n=8, 9%), head and face (n=7, 8%), and upper extremity and shoulder (n=6, 5%) injuries.

Vascular injury and entry vessels

BE was more often the result of injury to right circulatory structures compared with left circulatory structures (54% vs. 32%). The vast majority of BEs originating from injury to left circulatory structures involved the left ventricle (n=10, 23%), pulmonary vein (n=10, 23%), abdominal or thoracic aorta (n=6, 14%), or carotid arteries (n=5, 11%). The most frequently injured right circulatory structures included the inferior vena cava (n=11, 15%), iliac vein (n=10, 14%), right atrium or cavoatrial junction (n=10, 14%), right ventricle (n=8, 11%), femoral vein (n=7, 9%), and subclavian vein (n=7, 9%). Portal venous entry was rare, seen in only two cases.

BE appeared to embolize from direct cardiac injury or involvement of the cavoatrial junction in 30 (22%) cases. Regarding cardiac involvement, BE mostly migrated from the left ventricle (n=10, 33%) and right atrium or cavoatrial junction (n=10, 33%), followed by the right ventricle (n=8, 27%) and less commonly, the left atrium (n=2, 7%).

Patterns of migration and terminating vessels

BE more frequently terminated in the right circulation compared with the left (60% vs. 40%). More than half of venous BEs terminated in the pulmonary artery (n=31, 38%) or a right-sided cardiac chamber (n=30, 37%). In contrast, arterial BE tended to lodge more peripherally with more than half terminating in either femoral (n=16, 30%), cerebral (n=10, 19%), or iliac (n=7, 13%) arteries.

Overall, BE tended to originate from injury to a right circulatory structure, migrate in antegrade fashion (n=96, 71%), and terminate in a right circulatory structure. Retrograde migration was significantly more likely to occur in venous rather than arterial system (OR 7.35, 95% CI=0.91, 58.8, p=0.030). Mixed and paradoxical emboli each accounted for 3% of cases.

Symptoms and clinical presentation

Most cases of embolization occurred within the first 48 hours (97%). Among all symptomatic patients, 17 (43%) had clinical

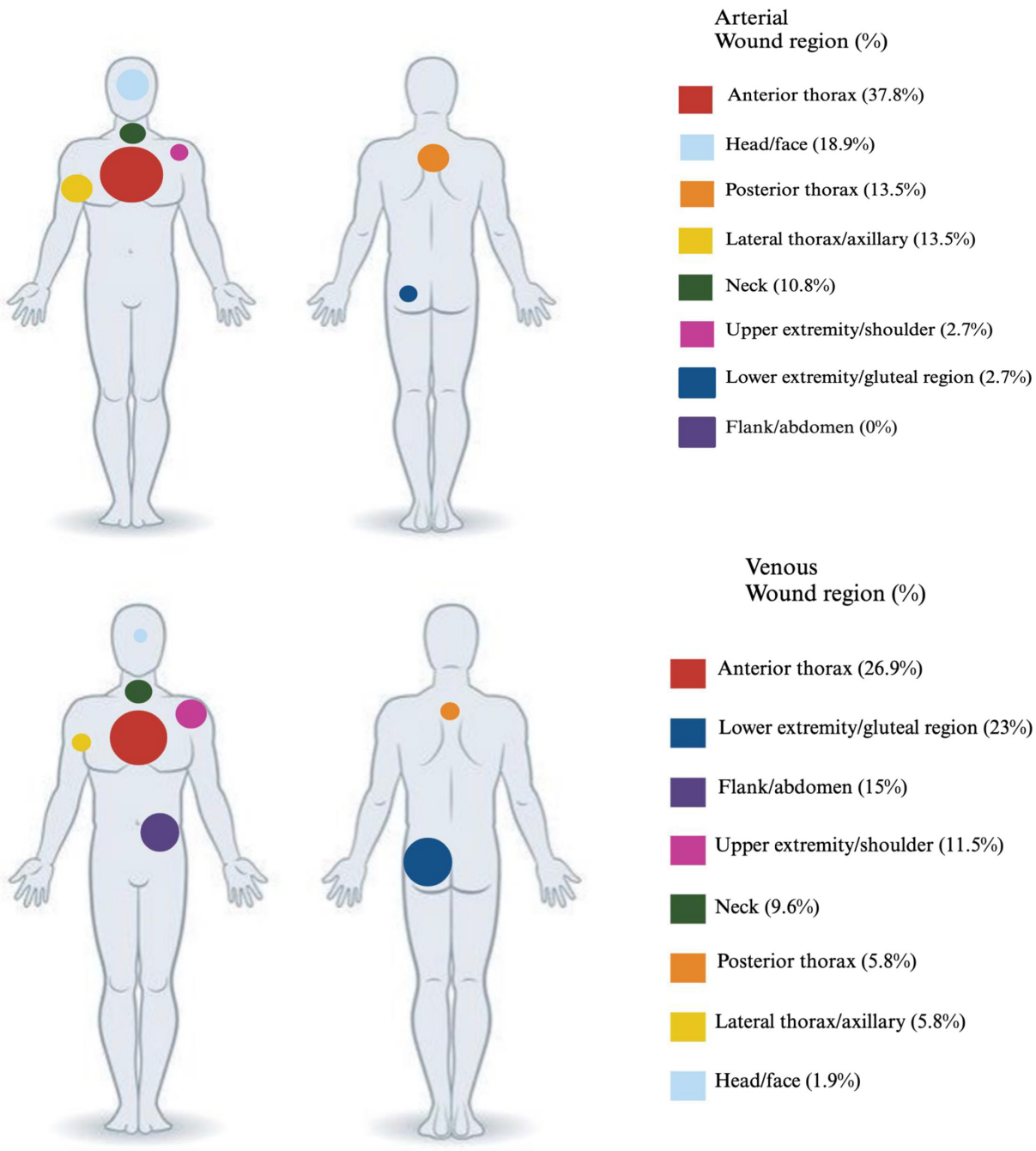

Figure 2 Proportional depiction of the localization of wounds among patients with ballistic embolism occurring in the context of wounds localized to a single region, separated by whether the projectile entered right (right heart chamber, pulmonary arteries, systemic veins) or left circulation (left heart chamber, pulmonary veins, systemic arteries). Created with BioRender®.

signs or symptoms attributable to the BE in the trauma bay. Arterial BEs were significantly more likely to be symptomatic (71% vs. 7%, OR 32.54, 95% CI=10.82, 97.90, p<0.001). Symptomatology associated with arterial BE was mostly from limb ischemia (n=25, 52%), and focal neurological deficits (n=7, 15%) from BE in a cervical or cerebral artery. One patient had signs of intestinal ischemia due to ballistic emboli in branches of the superior mesenteric artery. Another patient had subacute hemodynamic instability attributed to BE in the proximal ascending thoracic aorta. A high percentage of arterial BEs were lodged in cervical or cerebral arteries (n=13, 24%). Among these, the middle cerebral artery was most commonly involved (46%), followed by the carotid artery (23%). The basilar and posterior cerebral artery each accounted for 15% of cervical/cerebral BE.

Venous BEs were more likely to be asymptomatic and only those in a pulmonary artery led to complications. Overall, however, only a minority of BEs lodged in a pulmonary artery developed complications (n=5, 19%). Four out of five of these patients developed signs of pulmonary ischemia or infarction on imaging, which appeared within 48 hours of injury in all but one case. All cases involved BE in segmental branches of the pulmonary artery. One patient developed new-onset atrial fibrillation in the context of a pulmonary artery BE.

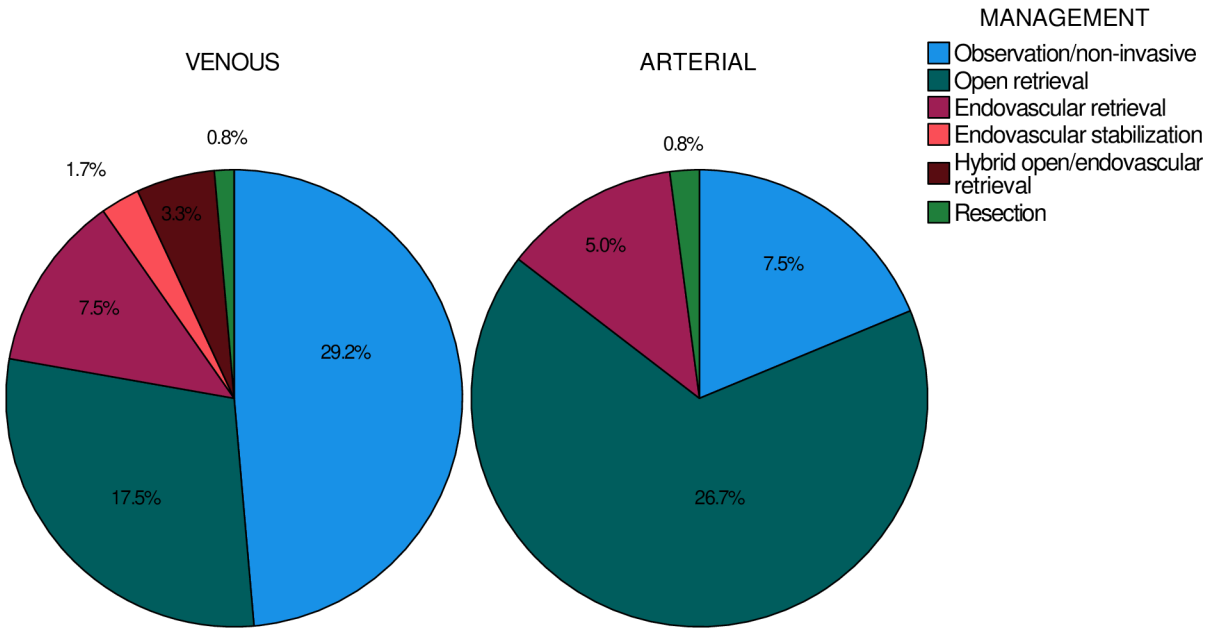

Figure 3 Pie chart depicting trends in management of arterial and venous ballistic embolisms. This is only representative of the final approach to management in these patients and does not reflect initial attempts at retrieval.

Management

Differences in approach to management of venous and arterial BEs are depicted in figure 3. When compared with patients with venous embolisms, arterial embolisms were significantly less likely to be managed non-invasively (19% vs. 49%, OR .24, 95% CI=0.10, 0.58, p<0.001). However, among patients with venous BE, there was no significant difference observed between conservative and interventional management which were both reported with equal frequency (n=35, 48%). Open operative retrievals contributed to more successful retrievals of both arterial and venous BEs when compared with endovascular or percutaneous retrievals (76% vs. 24%).

Out of 123 patients, 25 (20%) underwent an initial retrieval attempt that failed. When looking at initial retrieval attempts, open or hybrid retrieval attempts were significantly more likely to be successful compared with endovascular alone (91% vs. 29%, OR 25.0, 95% CI=6.88, 90.84, p<0.001). Among all patients who were initially managed non-invasively, approximately 30% ultimately required an intervention for retrieval during the index hospitalization.

Follow-up

Out of 112 patients who survived hospitalization, 50 (45%) had reported outpatient follow-up. Patients with arterial BE were more likely to receive follow-up compared those with venous BE (53% vs. 39%, OR 1.8, 95% CI=0.84, 3.89, p=0.13). Furthermore, patients who underwent any attempt at bullet retrieval during their hospital stay were significantly more likely to receive follow-up when compared with BEs that were simply observed (OR 2.41, 95% CI=1.06, 5.50, p=0.034). Among all patients, the median duration of the longest follow-up was 3 months (IQR 1.5–9 months).

In total, only one patient developed new or worsening clinical signs or symptoms after discharge that were attributable to BE. This patient had a pulmonary artery BE that was managed non-invasively. He developed shortness of breath 2 months post-discharge and had a computed tomorgraphy angiogram (CTA) which showed stable positioning of the bullet without any evidence of pulmonary infarction, pulmonary artery thrombosis, or other complications. No intervention was performed.

DISCUSSION

The diagnostic challenge

Projectiles can gain entry into the circulation from nearly any point of entry and can travel antegrade, retrograde, or paradoxically to a distant region in the body remote from the expected trajectory of the bullet.[4 6] Patients may develop signs or symptoms inconsistent with what would be expected based on the pattern of wounds and the anticipated trajectory of the projectile.[4 6] Additionally, many patients with venous emboli may be completely asymptomatic with respect to BE.[6] In this review, nearly 30% of patients with arterial BE and 93% of patients with venous BE were not reported to have any clinical signs or symptoms attributable to BE. Given the seemingly boundless array of manifestations, the clinical presentation of BE can be confusing, even to teams at some of the leading trauma centers.[4 9]

Nearly all cases of BE in this review were identified within the first 24–48 hours of injury. However, 57% of symptomatic patients did not not actually develop symptoms until after completion of the primary and secondary surveys and initial imaging studies. Based on these observations, BE should remain on the differential for any unexplained clinical signs or symptoms throughout the hospital stay, especially within the first 48 hours. Rarely, delayed BE has been reported up to 26 years after injury.[10–16]

We also observed variability in aspects of clinical history. First, there are reports of BE in civilian patients occurring from a variety of firearms, each with unique ballistic phenomenon.[6] BE has also been observed in the context of injuries from non-ballistic penetrating projectiles such as pins, needles, wood, and foreign bodies dislodged from lawn mowers.[4 17]

Second, BE has been observed in patients with a variety of wound patterns.[6] We observed that single gunshot wounds accounted for more cases of BE than multiple gunshot wounds (74% vs. 22%), which is consistent with findings from a previous

review.[6] This may be explained by single gunshot wounds being more common overall.[6 18 19] It has been thought that the probability of BE may increase with each additional penetrating wound.[6] Though this may be statistically true, it is misleading. The penetrating potential of a projectile, and thus, the propensity for intravascular migration is confounded by the energy potential of the projectile at the time of impact, which is dependent on the trajectory stability, distance traveled, entrance profile of the projectile, and the amount of yaw (the angle of deviation from the projectile's long axis).[20 21] Embolization potential of the projectile is additionally dependent on patient characteristics such as body mass index, position, and the effect of gravity.[2 20 21] Because of these nuances and the lack of any randomized controlled trials, we caution against surmising any clinical features that may influence the likelihood of BE.

Lastly, we observed that 15 (12%) cases were due to non-powdered firearm injuries (ie, airsoft, BB, and pellet guns). We bring attention to this due to literature suggesting non-powdered firearms are often perceived as benign, leading to an underestimation of the penetrating and injury potential of these weapons.[22–27] Furthermore, 21 (17%) cases occurred in patients less than 18 years of age. Based on these observations, both pediatric and adult trauma providers should be aware of this phenomenon.

Clinical associations

During this review, we identified three frequently discussed observations that have been associated with clinical suspicion for BE. First, there may be an odd number of penetrating wounds without intraoperative or radiographic visualization of the bullet within the expected cavity.[2 3] Second, imaging may demonstrate a ballistic body in a location inconsistent with the anticipated trajectory of the projectile.[2 3] Finally, serial imaging may reveal a migratory foreign body in different positions.[2 3] Due to the frequency with which these observations are referenced, we describe some potential pitfalls in the application of these principles as they relate to the cases in this review.

The first observation that has been linked to BE is known as the 'bullet rule,' and was referenced by more than one-third of the cases in our review. It states that the sum of the number of bullet wounds and bullets visualized on imaging should always be an even number.[28 29] Accordingly, bullets can either traverse the body and leave both entrance and exit wounds, or they can enter and remain in the body. We identified several cases in the literature that deviate from the bullet rule and highlight limitations in its applicability to BE.[30–34]

When there is apparent discordance with the bullet rule, alternative explanations should be explored. The first of these include re-examination of the patient to ensure there were no missed wounds on the initial survey. Second would be to determine if there is a history of gunshot wounds with a retained bullet. If neither of these are the case, other etiologies of deviation from the bullet rule should be explored, including the possibility of BE.

One common reason for this deviation is secondary to the nature of the different firearms and projectiles. For example, shotgun injuries can be hard to distinguish due to number of pellets, scattering of pellets, and those that caused damage to skin but did not penetrate leading to injury patterns being unpredictable.[35–38] Although rare, tandem bullets, defined as two or more bullets entering the body through the same entrance wound, can also lead to deviation from the bullet rule.[30]

Another reason there may be deviation from the bullet rule is secondary to projectiles fragmenting.[6 39] This may be evidenced by visualization of an even number of wounds on examination and a projectile identified on imaging. This can result when the projectile is only a fragment of the initial bullet that exited the body.[6] Additionally, a bullet may fragment into more than two pieces, and any or all of these fragments have the potential to independently embolize.[38] Because of the vast array of possibilities, we are concerned that the strong association of the bullet rule with BE is misleading.

Moreover, successful application of this principle is dependent on accurate discovery and labeling of wounds in the trauma bay, which has proved to be challenging. Previous studies have demonstrated that emergency physicians and trauma surgeons make erroneous identification of entrance and exit wounds more than half the time, and frequently make errors in determining the total number of penetrating wounds.[40 41] With respect to these limitations and medicolegal implications, it is recommended that non-forensic physicians describe wound(s) in objective detail and refrain from documenting the interpretation of wounds as 'entrance' or 'exit.'[42–44] Keeping with best practices both in the clinical setting and in the literature, we refrained from categorizing wounds as entry or exit and we recommend that future reports on BE describe the wounds with this in mind.

The second observation that has been associated with BE is radiographic evidence of a bullet in a location inconsistent with the anticipated trajectory.[45–57] Many patients in the trauma bay may be asymptomatic with respect to BE or present with concomitant injuries confounding symptomatology. Thus, a high degree of clinical suspicion may be required to prompt search for a projectile outside the anticipated trajectory. Delaying investigation and/or intervention until the onset of signs of critical ischemia may result in irreversible injury necessitating amputation of the affected limbs, resection of ischemic bowel, or result in permanent neurological deficits.[49 58–61] Based on these observations, it may be reasonable to consider additional imaging in search of an embolized projectile in any susceptible patient who develops any new or persistent unexplained signs or symptoms, even if mild.

This concept is not limited to the immediate presentation in the trauma bay. Migration of a projectile on sequential imaging may raise clinical suspicion for BE.[4 11 50 51 62–64] It has been hypothesized that bullets are most likely to migrate during the immediate postinjury period due to the rapid changes in hemodynamic status and changes in patient position.[2] In this series, 132 (97%) cases of embolization occurred within 48 hours of presentation, supporting this hypothesis. This is particularly relevant when patients are taken to the operating room within this time frame. We identified multiple reports in the literature of projectile remigration attributed to repositioning of a patient in preparation for a procedure or during interventional manipulation within this time period.[65–67] There are two implications of this. First, if a patient is repositioned to undergo an attempt at bullet retrieval, this may have the inadvertent consequence of causing remigration of the bullet and lead to failure of the initial operative approach.[66 67]

The therapeutic challenge

In the acute phase of traumatic injuries, repair of internal damage along the projectile's path often takes precedence over removal of the projectile itself.[5] Additionally, clinical management should be made in the context of a complete clinical picture. With this in mind, we provide a brief overview of previously proposed management strategies.

Table 1 Overview of initial management failures and management complications

Case	Signs and symptoms	Circulation	Terminating vessel	Initial management	Final management	Management complications
Naidoo *et al*[82]	Asymptomatic	Arterial	Lesser curvature AA->descending TA	Open failure	Open retrieval	Migration
Green *et al*[83]	Limb ischemia	Arterial	Subclavian artery	Endovascular failure	Open retrieval	—
Helán *et al*[60]	Stroke/TIA	Arterial	Internal carotid artery->distal migration	Endovascular failure	Open retrieval	Migration
Gomez *et al*[84]	Stroke/TIA	Arterial	Internal carotid artery	Endovascular failure	Conservative	—
Greenlees *et al*[85]	Asymptomatic	Arterial	Left ventricle	Open failure	Open retrieval	—
Ahmed *et al*[86]	Asymptomatic	Arterial	Basilar artery->distal migration	Endovascular failure	Endovascular retrieval	Migration
Yu *et al*[87]	Asymptomatic	Arterial	Right ventricle	Endovascular failure	Conservative	—
Castater *et al*[51]	Asymptomatic	Venous	Pulmonary artery	Endovascular failure	Open retrieval	—
Bakan *et al*[88]	Asymptomatic	Venous	Interventricular septum facing right ventricle	Endovascular failure	Conservative	Arrhythmia
Gross *et al*[56]	Pulmonary infarction	Venous	Pulmonary artery->right pulmonary artery	Conservative	Lobectomy	Migration
Castater *et al*[51]	Asymptomatic	Venous	Internal iliac vein	Endovascular failure	Stabilization with stent	—
Mussie *et al*[69]	Asymptomatic	Venous	Right ventricle	Open retrieval	Open retrieval	Infectious*
Echeverria *et al*[65]	Asymptomatic	Venous	Pulmonary artery, inferior branch	Endovascular failure	Open retrieval	—
Naeim *et al*[89]	Asymptomatic	Venous	Right ventricle	Endovascular success	Endovascular retrieval	—
Halicek *et al*[67]	Asymptomatic	Venous	Right atrium->coronary sinus>RA/IVC junction	Open failure	Endovascular retrieval	Migration
Mojtahedi *et al*[71]	Asymptomatic	Venous	Right ventricle->pulmonary artery	Endovascular failure	Hybrid retrieval	Migration
de Sousa Arantes Ferreira *et al*[90]	Asymptomatic	Venous	Right ventricle	Endovascular failure	Open retrieval	—
Hazen *et al*[91]	Asymptomatic	Venous	Pulmonary artery, hilum	Endovascular failure	Open retrieval	—
Kovalev *et al*[92]	Asymptomatic	Venous	Pulmonary artery	Endovascular failure	Open retrieval	—
Lu *et al*[93]	Asymptomatic	Venous	Right ventricle	Endovascular failure	Open retrieval	Pericardial effusion
Yamanari *et al*[68]	Pulmonary infarction	Venous	Pulmonary artery, lingular	Endovascular failure	Conservative	—
Winkler *et al*[66]	Asymptomatic	Venous	Right atrium->coronary sinus	Endovascular retrieval	Endovascular retrieval	Migration
Sparkman and Batson[11]	Asymptomatic	Venous	Renal vein (hilum right kidney)	Endovascular failure	Conservative	—
Chew *et al*[94]	Asymptomatic	Venous	Renal vein->IVC->iliac vein->superior gluteal vein	Endovascular failure	Endovascular retrieval	Migration
Hatchimonji *et al*[95]	Asymptomatic	Venous	External iliac vein	Endovascular failure	Open retrieval	—
Sabour *et al*[45]	Asymptomatic	Venous	Pulmonary artery->left pulmonary artery	Endovascular failure	Stabilization with coil embolization	Migration
Salahuddin *et al*[96]	Asymptomatic	Venous	RA/IVC junction->external iliac vein	Endovascular failure	Endovascular retrieval	Migration
Daskalaki *et al*[97]	Asymptomatic	Venous	Right ventricle	Open failure	Conservative	—

*Pericarditis, mediastinitis, retrosternal abscess.
AA, abdominal aorta; IVC, inferior vena cava; RA, right atrium; TA, thoracic aorta; TIA, transient ischemic attack.

In 2019, Kuo *et al* proposed a management algorithm that takes into consideration three key factors: right versus left circulation, symptomatology, and the presence of a cross-circulation shunt.[6] First, with respect to circulation, arterial BEs generally warrant urgent retrieval, irrespective of symptomatology given the risk of delayed complications such as ischemia.[6] In contrast, in the presence of BE in right circulatory structures, the first step is to obtain imaging to evaluate for the presence of a septal defect or perforation. If present, this supports retrieval due to risk of a paradoxical embolism into the arterial circulation.[6] Additional factors that may warrant retrieval of right circulation BE are those in the pulmonary artery resulting in pulmonary infarction, abscess, or erosion in the bronchus.[4 5]

In this review, we identified 32 cases of pulmonary artery BE. Among 29 patients who survived their acute injuries, 18 (62%) were managed non-invasively. We identified four patients who developed signs of impaired pulmonary perfusion or ischemia.[55 56 68 69] Two patients ultimately underwent successful retrieval. One patient required a lobectomy after several failed retrieval attempts. The fourth patient only had decreased perfusion to segmental branches of the lower lobe and without any apparent parenchymal ischemia and did not undergo any further retrieval attempts. We did not identify any cases of pulmonary BE in the past 10 years resulting in an infectious process or erosion into the bronchus. This is somewhat in contrast to the reports of Kortbeek *et al*, who

HISTORY

- Description of all identified wounds (i.e. number and location)
- Description of firearm and projectile type (e.g. shotgun pellet, pellet from air gun, BB from BB air gun)
- Size of projectile
- Description of whether the projectile is fragmented or intact

MANAGEMENT

- Description of any successful or unsuccessful attempts at retrieval
- Medical decision making for non-interventional management vs. retrieval
- Antibiotics? Antiplatelet or anticoagulant therapy?
    - If yes, describe primary purpose for initiation (e.g. concomitant thrombosis, open fracture)

FOLLOW-UP

- Was a follow-up plan established? With surgery?
- Was elective outpatient retrieval offered?
- Screening for psychological sequelae?
- Screening for lead toxicity?
- Retained pulmonary artery BE -> right heart function? Infarction? Arrhythmia? Erosion?
- Long-term follow-up data (> 12 months)

Figure 4 Considerations for future reports on ballistic embolism (BE). Created with BioRender®.

in 1992 reviewed 32 cases of pulmonary artery BE that were observed without complication and subsequently advocated for conservative management of pulmonary artery BE.[70] In 2011, Miller *et al* proposed a management algorithm that gave special consideration to the management of pulmonary artery BE compared with venous BE in any other location.[5] Due to modern advancements in endovascular techniques and acknowledged risk of delayed complications from retained BE, Miller recommended retrieval of all symptomatic pulmonary artery BEs and asymptomatic pulmonary artery BEs, if endovascularly accessible.[5] In contrast to the algorithm proposed by Kuo in 2019, Miller also proposed retrieval of all non-pulmonary artery, venous BEs, irrespective of symptomatology.

Both Miller and Kuo recommend endovascular rather than open retrieval, but this comes with a substantial risk of retrieval failure.[6] Kuo *et al* reported an endovascular retrieval success rate of only 63%.[6] However, it is not clear if multiple endovascular attempts were required to achieve this success rate. In our series, nearly 70% of initial attempts at endovascular retrieval failed or required replanning of the intervention and/or additional attempts through different access points. Endovascular retrieval was additionally complicated by remigration during manipulation or poor access to the bullet (table 1). Options to prevent remigration include clamping of the distal vessel or the use of a distal occlusion balloon or embolic protection device when endovascular retrieval is attempted.[6] In contrast, we observed an open operative success rate of 92%.

In summary, arterial BEs generally necessitate retrieval. The management of venous BE remains controversial. If endovascular retrieval is pursued, utilization of a hybrid interventional radiology suite may be beneficial due to reported risk of remigration during manipulation, potentially requiring a new approach.[45 70 71] When there is a treatment delay, updated imaging may be beneficial to confirm the absence of any interval migrations.[66 67] Shared decision-making with these patients may be especially important, discussing the relative risks and benefits of retrieval versus observation, with an understanding that there is no high-grade evidence to help guide management.

Follow-up

At most institutions, these patients will be admitted and discharged by the trauma service. Despite best efforts, many trauma patients, especially those with firearm injuries, will be lost to follow-up.[72 73] This, in combination with the relative rarity of intravascular BE, makes it challenging to assess long-term outcomes and optimal follow-up in this patient population.

In this review, less than half of published case reports documented information regarding outpatient follow-up. In most cases, the setting of follow-up was not specified (ie,

outpatient office or emergency department) and it was not clear what percentage of these follow-ups was dedicated primarily to the monitoring of BE. In this review, we observed some complications attributable to lodged BE during the index hospitalization, described previously. By comparison, there were no reports of patients developing any new or worsening clinical signs of symptoms attributable to BE after discharge; however, our follow-up data are limited.

Considerations during follow-up include long-term monitoring for lead toxicity and psychological sequelae.[72 74–79] Most of the relevant literature concerning lead toxicity is in the context of retained extravascular bullet fragments, rather than intravascular.[75–77] Hypermetabolic and hyperinflammatory states, such as trauma, result in an increase in vascular permeability, blood flow, and bone turnover.[76] These physiologic changes may contribute to a favorable environment for systemic absorption of lead from retained bullet fragments.[75 76] Diagnosing lead toxicity in this context may require a high degree of clinical suspicion as the clinical presentation is often insidious and non-specific.[76] Common clinical signs and symptoms suggestive of chronic lead toxicity include persistent, unexplained neuropsychiatric and/or vague gastrointestinal symptoms with microcytic anemia.[75 76]

Urgent removal is generally recommended in symptomatic patients, although this decision should be tailored to the individual and the broader clinical context.[75] Asymptomatic patients should have blood lead levels monitored in 3-month intervals for 1 year.[75 76] Patients who develop blood lead levels above 5 µg/dL may be good candidates for removal if there is minimal risk in doing so.[75] However, more research is needed to assess indications for retrieval in patients with retained intravascular bullet fragments.

In addition to potentially placing patients at risk of long-term physiological sequelae, retained ballistic fragments may serve as a reminder of the traumatic event and increase the risk of post-traumatic stress disorder, anxiety, major depressive disorder, feelings of shame, and social isolation.[79 80] There are currently no standard tools or guidelines to monitor the long-term psychological impact on trauma patients. As such, we propose utilization of the Revised Impact of Event Scale, a short self-report measure designed to assess subjective distress caused by traumatic events.[81]

Despite a clear need for follow-up, a survey distributed in 2016 to surgeon members of the Eastern Association for the Surgery of Trauma found that only 14.5% of respondents reported having institutional policies for bullet removal.[80] Importantly, having the opportunity to follow up with patients to discuss removal was significantly predictive of removal (OR 2.25, 95% CI=1.05, 4.85, p=0.04). Additionally, routinely asking about retained bullets during follow-up appointments was predictive of psychological illness screening (OR=1.94, 95% CI=1.19, 3.16, p=0.01). Thus, encouraging follow-up and a shared decision-making approach with patients in whom retrieval would be reasonably safe may prove to be beneficial.

Limitations

Our study has some recognized limitations. First, as this was a systematic review of published case reports, the overall quality of the available data is low, and our findings are likely influenced by selection bias. We aimed to mitigate any potential selection bias by using the JBI Critical Appraisal Checklist and predetermined exclusion/inclusion criteria. Second, we observed variability across cases with respect to what information was included and in how it was reported. This commonly arose in the description of wound locations. Few cases reported the wounds in objective, observable detail without assigning any interpretation. To minimize speculation regarding originating wound location, when describing wounds, we only included cases of patients with wounds in a single region. We also noted inconsistent and interchangeable use of terms to describe emboli type such as pellet, air gun, BB gun, bullet, and bullet fragment both within and across case reports, limiting our ability to reliably use these data in our review. We opted to exclude this information from our results out of caution to avoid any false presumptions. Finally, due to the nature of BE and the limitations of case studies, cases that are not confirmed intraoperatively or forensically inherently involve some degree of conjecture by physicians. Therefore, our data are limited by the hypotheses provided by authors. Given the limitations we observed, the rarity of BE and reliance on anecdotal evidence, we provide a list of considerations for future reports on BE in figure 4.

CONCLUSION

Trauma surgeons should consider the possibility of BE in all patients with penetrating firearm or blast injuries, especially within the first 48 hours. Arterial emboli are more frequently symptomatic and tend to present with signs and symptoms of ischemia, generally necessitating urgent retrieval. Most patients with venous emboli may be asymptomatic with respect to BE and more research is needed to determine optimal management in these patients. Despite low long-term complications in patients with retained BE, there may be benefit in close follow-up for the first year after injury.

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