Complications, outcomes, and management strategies of non-missile penetrating head injuries

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OBJECTIVE While high-velocity missile injury (gunshot) is associated with kinetic and thermal injuries, non-missile penetrating head injury (NMPHI) results in primary damage along the tract of the piercing object that can be associated with significant secondary complications. Despite the unique physical properties of NMPHI, factors associated with complications, expected outcomes, and optimal management have not been defined. In this study, the authors attempted to define those factors.

METHODS Consecutive adult patients with NMPHI who presented to Tygerberg Academic Hospital (Cape Town, South Africa) in the period from August 1, 2011, through July 31, 2018, were enrolled in a prospective study using a defined treatment algorithm. Clinical, imaging, and laboratory data were analyzed.

RESULTS One hundred ninety-two patients (185 males [96%], 7 females [4%]) with 192 NMPHIs were included in this analysis. The mean age at injury was 26.2 ± 1.1 years (range 18–58 years). Thirty-four patients (18%) presented with the weapon in situ. Seventy-one patients (37%) presented with a Glasgow Coma Scale (GCS) score of 15. Weapons included a knife (156 patients [81%]), screwdriver (18 [9%]), nail gun (1 [0.5%]), garden fork (1 [0.5%]), barbeque fork (1 [0.5%]), and unknown (15 [8%]). The most common wound locations were temporal (74 [39%]), frontal (65 [34%]), and parietal (30 [16%]). The most common secondary complications were vascular injury (37 patients [19%]) and infection (27 patients [14%]). Vascular injury was significantly associated with imaging evidence of deep subarachnoid hemorrhage and an injury tract crossing vascular territory ($p \leq 0.05$). Infection was associated with delayed referral (> 24 hours), lack of prophylactic antibiotic administration, and weapon in situ ($p \leq 0.05$). A poorer outcome was associated with a stab depth > 50 mm, a weapon removed by the assailant, vascular injury, and eloquent brain involvement ($p \leq 0.05$). Nineteen patients (10%) died from their injuries. The Glasgow Outcome Scale (GOS) score was linearly related to the admission GCS score ($p < 0.001$). One hundred forty patients (73%) had a GOS score of 4 or better at discharge.

CONCLUSIONS The most common NMPHI secondary complications are vascular injury and infection, which are associated with specific NMPHI imaging and clinical features. Identifying these features and using a systematic management paradigm can effectively treat the primary injury, as well as diagnose and manage NMPHI-related complications, leading to a good outcome in the majority of patients.

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KEYWORDS non-missile penetrating head injury; outcome; surgery; treatment; traumatic brain injury

NON-MISSILE penetrating head injuries (NMPHIs), an important subset of penetrating head injuries, involve a sharp object being driven through the skull into the brain, causing a focal injury along the tract of the object that is not associated with the thermal and kinetic components found in high-velocity penetrating injuries,

such as gunshot wounds.¹ Stab injuries also differ from machete or axe injuries,^{2–4} which typically cause a crushing injury associated with significant driven-in intraparenchymal debris and large dural defects. While accidents are the predominant cause of NMPHI around the world, interpersonal violence using a knife is the most common cause

ABBREVIATIONS dSAH = deep SAH; GCS = Glasgow Coma Scale; GOS = Glasgow Outcome Scale; ICH = intracerebral hematoma; NMPHI = non-missile penetrating head injury; SAH = subarachnoid hemorrhage.

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FIG. 1. Tygerberg Academic Hospital management algorithm for NMPHI. angio = angiography.

of NMPHI in South Africa.^{5–7} Because NMPHIs have different kinetic and physical properties, there are unique features associated with this type of brain injury and outcome. Specifically, NMPHIs can cause neurological deficits and death from the primary injury and/or secondary complications, including associated vascular lesions and infection.^{5,8–12}

Despite the morbidity and mortality associated with NMPHI, the expected outcomes, factors associated with complications, and optimal management have not been defined. To establish those factors associated with complications, outcomes, and optimal management, we analyzed patients with NMPHIs treated using a defined management algorithm at a single institution.

Methods

Patients

General

Consecutive adult patients (age ≥ 18 years) with NMPHI who presented to Tygerberg Academic Hospital, Cape Town, South Africa, in the period from August 1, 2011, through July 31, 2018, were enrolled in an institutional review board–approved protocol (University of Stellenbosch Health Research Ethics Committee approval). Inclusion criteria consisted of a history of NMPHI confirmed on CT imaging.

Clinical Evaluation

Patients underwent detailed neurological examination on admission, immediately before and after surgery (if

performed), during hospitalization, at discharge, and at distant follow-up. Time from injury to assessment and serial Glasgow Coma Scale (GCS) and Glasgow Outcome Scale (GOS) scores were recorded.^{25,26} After discharge, the distant follow-up occurred at secondary hospitals, and patients were referred back to Tygerberg Academic Hospital for any complications, including all infectious and vascular complications.

Management Paradigm

General

All patients with NMPHI received care via a defined management protocol (Fig. 1). A single dose of cefazolin (2 g intravenously) was given for prophylaxis at admission, unless contraindicated. Noncontrast CT (0.6- to 1-mm slice thickness) was performed for all patients at the initial assessment. Laboratory evaluation on admission, during hospitalization, and after discharge was defined by clinical need.

Patients at High Risk for Vascular Injury

Those patients at risk for vascular injury—defined by deep subarachnoid hemorrhage (dSAH), intracranial depth of weapon penetration > 40 mm, tract near major vascular structures, intracerebral hematoma (ICH) larger than the weapon tract, or transorbital weapon entrance—underwent CTA if the weapon had already been removed or DSA under general anesthesia if the weapon was retained. Retained weapons in patients at high risk for weapon-associated vascular injury were removed us-

ing the “knockout” technique or craniotomy (see *Surgical Technique*). DSA was performed immediately after weapon removal. A post-weapon removal CT scan was performed to exclude intracranial hemorrhage. If a vascular lesion was present, it was treated using endovascular or open techniques.

Patients at Low Risk for Vascular Injury

Patients with a GCS score < 15 and at low risk for vascular injury with the weapon in situ underwent DSA under general anesthesia. The retained weapon was removed via the knockout technique or craniotomy (see *Surgical Technique*), and DSA was performed immediately after weapon removal. Post-weapon removal CT was performed to exclude intracranial hemorrhage. If a vascular lesion was present, it was treated using endovascular or open techniques. Patients with a GCS score of 15, a low risk for vascular injury, and the weapon in situ underwent weapon removal via the knockout technique under local anesthesia. Post-weapon removal CT and CTA were performed to exclude intracranial hemorrhage and vascular lesion. Finally, patients at low risk for vascular injury without a retained weapon underwent clinical management after wound debridement and closure. These patients underwent CTA if the weapon tract depth was ≥ 10 mm or any risk factors for vascular injury were present.

Surgical Technique

Knockout Removal

This procedure can be performed in the angiography suite (under general anesthesia) or operating theater (local scalp anesthetic or general anesthesia). A vise grip is attached perpendicular to the protruding weapon (Fig. 2). A mallet is used to tap the retained weapon from the cranium (Video 1).

VIDEO 1. Removal of a retained blade in an angiography theater using the knockout technique. Copyright Bradley M. Harrington. Published with permission. [Click here to view.](#)

The mallet strikes are made parallel to the weapon tract to remove the weapon in-line to the tract. Alternatively, the vise grip can be attached in-line and an orthopedic slap hammer used to remove it. The wound is closed in layers after weapon removal.

Craniotomy

If it is not possible to attach a vise grip to the weapon, the weapon cannot be removed without significant manipulation, or there is an associated intraparenchymal mass lesion that requires removal, a craniotomy is performed. The craniotomy is made circumferentially around the retained weapon and designed to be large enough to accommodate removal of a mass lesion, if present. To eliminate any additional tissue injury, the weapon is removed en bloc with careful attention to remove the weapon in-line with the tract. The dura mater is closed in a water-tight manner, and the scalp is closed in layers.

Statistical Analysis

Statistical analysis was conducted to evaluate the factors predictive of a vascular injury or an infectious com-

FIG. 2. A patient with a GCS score of 15 and a left frontal penetrating knife wound undergoing the knockout technique for removal of the retained weapon while awake. A vise grip is attached perpendicular to the retained blade and then is gently tapped to remove the blade. The patient is observed after removal.

plication and those affecting outcome. The variables assessed were not independent of each other and thus both univariate and multivariate analyses were conducted with significance defined as $p \leq 0.05$. For each category, cross-tabulations with categorical variables were performed and evaluated using the chi-square test. Odds ratios and 95% confidence intervals were estimated. Lowess nonparametric smoothers were used to analyze nonlinear features. Data were analyzed using Stata Statistical Software, Release 15 (StataCorp LP).

Results

Patient Characteristics

Two hundred fifty-two NMPHI patients were enrolled

TABLE 1. Patient and clinical characteristics in 192 NMPHIs

Characteristic	No. (%)
Sex	
Male	185 (96)
Female	7 (4)
Side of injury	
Lt	134 (70)
Rt	58 (30)
Admission GCS score	
15	71 (37)
12–14	66 (34)
9–11	27 (14)
7–8	15 (8)
4–6	11 (6)
3	2 (1)
Time to referral/arrival at hospital	
<24 hrs	144 (75)
>24 hrs	48 (25)
Cause of injury	
Interpersonal violence	192 (100)
Other	0 (0)
Weapon	
Knife	156 (81)
Screwdriver	18 (9)
Nail gun	1 (0.5)
Garden fork	1 (0.5)
Barbeque fork	1 (0.5)
Unknown	15 (8)
Location of wound	
Temporal	74 (39)
Frontal	65 (34)
Parietal	30 (16)
Transorbital	10 (5)
Nasal	6 (3)
Occipital	4 (2)
Cerebellar	3 (2)
Wound location associated w/ vascular complication*	
Temporal	17 (23)
Frontal	11 (17)
Parietal	4 (13)
Transorbital	5 (50)
Prophylactic antibiotics	
<24 hrs†	99 (52)
>24 hrs†	29 (15)
None	64 (33)
Weapon in situ	
Yes	34 (18)
No	158 (82)
Method for removal of weapon in situ	
Knockout technique	27 (79)
Craniotomy	7 (21)

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TABLE 1. Patient and clinical characteristics in 192 NMPHIs

Characteristic	No. (%)
Risk of vascular injury at admission	
High	156 (81)
Low	36 (19)
Mass lesion requiring surgery	
Yes	55 (29)
No	137 (71)
Vascular complication	
Yes	37 (19)
No	155 (81)
Infectious complication	
Yes	27 (14)
No	165 (86)
Mortality	
Yes	19 (10)
No	173 (90)
GOS score at discharge	
4 or 5	140 (73)
3	32 (17)
2	1 (0.5)
1	19 (10)

* Percentages expressed as percent of total number of wounds at specific location.

† Time from injury to antibiotic administration.

and treated during the study period. One hundred ninety-two patients (185 males [96%], 7 females [4%]) with 192 NMPHIs were included in our analysis (i.e., all the patients with complete data sets; Table 1). The mean age at injury was 26.2 ± 1.1 years (range 18–58 years). The weapons used most often included knives (156 [81%]) and screwdrivers (18 [9%]). All injuries were the result of interpersonal violence. Thirty-four patients (18%) presented with the weapon in situ. One hundred thirty-four injuries (70%) were left-sided and 58 (30%) were right-sided. The most common sites of injury were temporal (74 wounds [39%]) and frontal (65 [34%]). One hundred fifty-six patients (81%) were categorized as high risk for vascular injury. Seventy-one patients (37%) presented with a GCS score of 15.

Imaging Findings

All 192 patients underwent CT scanning upon presentation. Ninety-six patients (50%) underwent CTA, 29 (15%) DSA, and 15 (8%) both. All patients at high risk for vascular injury (156 patients [81%]) underwent CTA and/or DSA, which demonstrated a vascular lesion in 37 (24% of high-risk patients; Table 2). Eight of the 36 patients (22%) with a low risk for vascular injury (those with a tract depth of 10–40 mm) underwent CTA, and none had a vascular lesion. The mean stab depth was 52 ± 3.6 mm (range 2–131 mm). Intracranial pathology included 105 ICHs (55%), including 74 (39%) that were larger than the

TABLE 2. Vascular injury among 192 patients with NMPHIs

Vascular Injury	No. of Patients (%)	No. of Deaths (%)
Traumatic pseudoaneurysm	17 (46)	1 (6)
Vessel cutoff	12 (32)	6 (50)
Vasospasm	5 (14)	0 (0)
Carotid cavernous fistula	2 (5)	1 (50)
Sagittal sinus thrombosis	1 (3)	0 (0)
Total	37 (19)	8 (22)

stab tract. There were 69 cases (36%) of SAH, including 56 (29%) that were dSAHs. There were 19 cases (10%) of intraventricular hemorrhage, 15 (8%) of subdural hematoma, 5 (3%) of infarct, and 3 (2%) of epidural hematoma.

Surgical Management

The 34 weapons in situ were removed via the knock-out technique (27 cases [79%]) or craniotomy (7 [21%]; Table 1). Surgery for mass lesions was required in 55 cases (29%), including 39 (71% of surgical mass lesions) ICHs, 8 subdural hematomas (15%), 3 empyemas (5%), 3 abscesses (5%), and 2 epidural hematomas (4%). Six of the cases (11%) requiring mass lesion removal also involved a retained weapon that was removed in the operating room contemporaneously with evacuation of the lesion.

Complications

Vascular

Vascular complications occurred in 37 patients (19%), all high-risk vascular patients (Table 1). The most common complications included aneurysms (17 patients [46%]) and vessel cutoffs (12 [32%]; Table 2). Eight patients, 22% of those with vascular complications, died from vascular-associated complications. Univariate analysis revealed dSAH, a stab wound across vascular territories, transorbital penetration, ICH larger than the tract, and a stab depth > 40 mm as significantly associated with vascular injury (Table 3). Multiple logistic regression revealed that dSAH and a tract crossing a vascular territory are significantly

associated with vascular injury. No low-risk vascular patients had vascular complications.

Infectious

Infection occurred in 27 patients (14%; Table 1) and included abscess in 11 (41% of infectious cases), meningitis in 8 (30%), empyema in 4 (15%), wound infection in 2 (7%), abscess/empyema in 1 (4%), and ventriculitis in 1 (4%). The mean time from stab to referral for patients with infection was 4.1 ± 6.2 days (median 2.7 days, range 0.1–30 days). No patients died as a result of infectious complications. Univariate analysis revealed that time to referral (> 24 hours) and the lack of prophylactic antibiotics administration were significantly associated with an increased rate of infectious complications (Table 4). Multinomial regression revealed that the time from stab to referral, the lack of prophylactic antibiotics, and a weapon in situ were significantly associated with infectious complications.

Outcomes

Nineteen patients (10%) died from their injuries, and the mean time to death was 10.2 ± 19.2 days (median 4 days, range 1–87 days). Eight patients (42% of all mortalities) died from vascular-associated complications. Eleven patients (58%) had severe primary injuries associated with low admission GCS scores, mass lesions, and/or injury to eloquent areas of the brain, including 3 basal ganglia (16%), 3 brainstem (16%), and 2 motor area (11%) injuries. Two patients (11%) had subdural hematomas, and 1 patient (5%) died from increased intracranial pressure from multiple rapidly enlarging intraparenchymal hematomas.

One hundred forty patients (73%) had a GOS score of 4 or better at discharge (Table 1). Univariate analysis revealed that patients with a lower admission GCS score, a vascular injury, and eloquent brain involvement had significantly worse outcomes (Table 5). Ordinal logistic regression revealed that a vascular complication or eloquent brain involvement was associated with significantly worse outcomes. A weapon in situ was associated with a more favorable outcome in both models. When presenting GCS score was included in the ordinal logistic regression, only admission GCS score, involvement of eloquent brain,

TABLE 3. Factors associated with vascular injury

Risk Factor	Univariate Analysis		Multiple Logistic Regression		
	Vascular Injury	p Value	OR	95% CI	p Value
Depth of stab (<40 or >40 mm)	10% vs 24%	0.047	1.7	0.5, 5.6	0.404
Stab location					
Frontal	17%	0.6	2.2	0.5, 9.0	0.3
Temporal	23%	0.3	0.9	0.3, 4.9	0.7
Transorbital	50%	0.01	5.6	0.8, 39.4	0.08
Weapon in situ on admission	12% vs 21%	0.2	1.1	0.2, 4.6	0.9
Presence of dSAH	45% vs 9%	0.0001	3.6	1.4, 9.5	0.01
Stab trajectory crossing vascular territories	24% vs 3%	0.0001	5.6	1.3, 22.9	0.02
ICH larger than tract	28% vs 14%	0.03	1.5	0.6, 3.8	0.5

Boldface type indicates statistical significance.

TABLE 4. Factors associated with infectious complication

Risk Factor	Univariate Analysis		Multiple Multinomial Regression		
	Infectious Complication	p Value	OR	95% CI	p Value
Delayed time to referral (>24 hrs)	21% vs 8%	0.0001	3.6	1.1, 12.1	0.04
Antibiotic prophylaxis	8% vs 26%	0.002	0.3	0.1, 0.8	0.02
Involvement of mucosal surface	24% vs 13%	0.3	2.0	0.6, 7.3	0.3
Weapon in situ	21% vs 13%	0.5	5.5	1.5, 21.1	0.01
Surgery for mass lesion	19% vs 12%	0.09	1.4	0.5, 4.1	0.5

Boldface type indicates statistical significance.

and time to referral were associated with outcome. Lower GCS score at admission was linearly associated with lower GOS score ($p < 0.001$, ordered logistic regression).

Discussion

Previous Studies

Previous studies have described complications, detailed surgical techniques, and/or communicated outcomes associated with NMPHI managed using diverse treatment paradigms. In 1975 de Villiers⁹ reported a 17% rate of infection (associated with transorbital stabs), a 50% rate of vascular complications, and an overall 17% mortality rate in 93 NMPHI patients. In 1984 Kieck and de Villiers¹⁰ described a 20% vascular complication rate in NMPHI patients and advised using delayed angiography at the 2nd week postinjury to exclude pseudoaneurysms. In 1991, however, du Treu and colleagues¹³ did not demonstrate a higher yield of aneurysms with delayed angiography in NMPHI patients. In 1997 Taylor and Peter⁷ found that retained blades were associated with an increased risk of early and late vascular complications and that stab wounds traversing mucosal surfaces were associated with infective

complications (prophylactic antibiotics were not administered). In 2016 de Holanda and colleagues⁸ found that the admission GCS score was associated with outcome in 11 patients. Various methods of blade removal have been described.^{5–7,14–16}

Because of the lack of consistent management paradigms, retrospective data collection, conflicting management strategies, and/or the rarity of the injury, factors associated with complications, outcome, and optimal management of NMPHI have not been defined. Here, we report the findings in consecutive NMPHI patients prospectively managed using a defined algorithm at a single institution.

Current Study

Based on the biomechanics of injury, optimal NMPHI management requires consistent and timely treatment of the primary injury and identification of potential secondary complications. Findings from the current study provide direct insight into the factors associated with outcome related to primary injury, features linked to secondary complications, and the effectiveness of a defined management strategy in NMPHI.

TABLE 5. Factors affecting outcomes after NMPHI

Risk Factor	Univariate Analysis		Ordinal Logistic Regression			Ordinal Logistic Regression (including presenting GCS score)		
	Effect on Outcome	p Value	OR	95% CI	p Value	OR	95% CI	p Value
Lower admission GCS score	Poorer	<0.001	NA	NA	NA	1.4	1.3, 1.6	<0.001
Stab depth >50 mm	Poorer	0.01	0.5	0.3, 1.1	0.07	0.8	0.4, 1.7	0.5
Weapon in situ	Favorable	0.002	3.9	1.4, 11.4	0.01	2.1	0.7, 6.0	0.2
Vascular injury	Poorer	<0.001	0.3	0.2, 0.8	0.004	0.5	0.2, 1.2	0.1
Eloquent brain involved	Poorer	<0.001	0.1	0.07, 0.3	<0.001	0.2	0.1, 0.4	<0.001
Stab location	*	0.3						
Temporal	—	—	1.5	0.5, 4.5	0.5	1.9	0.6, 5.9	0.3
Parietal	—	—	1.4	0.4, 4.8	0.6	1.5	0.4, 5.4	0.6
Frontal	—	—	2.4	0.8, 7.2	0.1	2.5	0.8, 8.0	0.1
Side of stab (lt or rt)	Poorer	0.6	1.4	0.7, 2.7	0.3	0.9	0.5, 1.9	0.9
Shorter time to referral	Poorer	0.086	1.2	1.1, 10.2	0.006	1.1	1.0, 1.3	0.02

NA = not applicable.

Boldface type indicates statistical significance.

* Comparison between locations showed no significant difference.

FIG. 3. Axial noncontrast CT images of a right-sided parietal knife wound. The images reveal intraparenchymal hemorrhage, dSAH, and injury to the brainstem.

Management Algorithm

To effectively and consistently manage NMPHI, a systematic protocol for patients at Tygerberg Academic Hospital was developed. This protocol was designed to provide accurate and rapid assessment of time-sensitive neurosurgical issues in patients with NMPHI. Specifically, it was developed to identify intracranial mass lesions and the potential for vascular injury at the time of initial evaluation (Fig. 1). The effectiveness of this diagnostic and treatment paradigm was underscored by its utility in rapidly identifying critical primary injury–associated mass lesions and directing patients at high risk for vascular injury immediately into specific vascular imaging protocols. Alternatively, among the 36 patients with a low risk for vascular complications, no vascular lesions were found in the 8 who underwent imaging (i.e., 22% of the low-risk patients were imaged).

While prior studies have described weapon removal principally via craniotomy,^{5–7,14–16} we employed a knock-out technique in all cases (79% of weapon removal cases; Video 1) except in those in which the weapon could not be removed without significant out-of-tract manipulation (e.g., weapon with barb lodged below inner table of calvaria) or a mass lesion that required surgical removal at the time of weapon retrieval. Movement of the blade is exaggerated at the tip and has the potential to cause injury to deep vessels and sensitive structures. This is seen after an assailant manipulates the blade to remove it (Fig. 3), and the removal technique should aim to avoid this. Further, we used the knockout technique in awake patients (GCS score 15) under local anesthesia, as this provided direct clinical assessment after removal and permitted immediate imaging and/or tract exploration if necessary. The thin profile of a knife (and other weapons) permits healing of the dura without direct closure and explains the lack of cerebrospinal fluid leakage encountered.

Primary Injury

Consistent with other forms of traumatic brain injury,¹⁷ NMPHI overwhelmingly occurred in young male patients (96% of cases; mean age at injury 26 years). Moreover, this injury was the result of interpersonal violence in all cases

in this study. Consistent with a frontal attack by a right-handed assailant, 70% of wounds were left-sided and in the frontotemporal region. As in previous studies,^{5,7–9} the most common weapon used in NMPHI in South Africa was a knife. Consistent with vascular damage at the primary injury, 55% of patients had ICH and 36% had SAH (including 29% with dSAH) on admission CT. Most patients (82%) presented without the weapon in situ, with the attacker having removed the weapon for repeated and/or later use. Surgical evacuation of a mass lesion was required in 29% of the patients because of the primary injury. The most frequent indication for surgery immediately after the primary injury was mass effect due to intracranial hemorrhage, including ICH (71% of surgical cases) and subdural hematoma (13%).

Vascular Complications

Vascular injuries were the most common secondary complication of NMPHI^{9,10,13,18,19} and occurred in 19% of patients. Specifically, pseudoaneurysms (46%) and vessel cutoff (32%) represented the most common secondary vascular complications (Table 2).^{13,20} Left untreated, these lesions can lead to significant morbidity and death.^{7,13,21–23} Twenty-two percent of patients with secondary vascular injuries died, underscoring the critical impact and need for effective management of these lesions. The presence of dSAH, a tract crossing a vascular territory, an ICH larger than the tract, and a stab depth > 40 mm were associated with vascular injury (Table 3), and these findings support immediate further diagnostic investigation (i.e., CTA and/or DSA).

As in prior studies,^{7,9} transorbital stab wounds were associated with a higher risk of vascular injury (50% of injuries). Assessment of the intracranial weapon trajectory is critical in defining the risk of vascular injury after transorbital stab wounds. Wound tracts directed superiorly through the orbital roof frequently do not cross a major vascular territory. Alternatively, weapon tracts directed down and/or medially through the orbit can transect the internal carotid or middle cerebral artery. Consistent with this anatomical feature, a transorbital medio-inferior trajectory and dSAH were associated with major vascular injury (Table 3). CT evidence of these features support

immediate further diagnostic investigation (i.e., CTA and/or DSA).

Infectious Complications

As in prior reports (15%–20% rate of infection),^{8,9,24} infection was a common secondary complication in NMPHI (14% of patients; Table 1). Consistent with direct weapon inoculation and an open wound, the most common infectious complications were brain abscesses (41%) and meningitis (30%). Infection was managed with appropriate antibiotics and surgery when needed. The mean time from stab to referral for patients developing infection was 4 days. Twenty-two patients (81%) with infectious complications presented within 6 days of injury. No patients died of related complications. Risk of infection was associated with a prolonged time to referral (over 24 hours), lack of antibiotic prophylaxis, and weapon in situ. (Note that the nature of the multinomial regression model that took subgroups [including death] into account led to the difference in significance regarding a weapon in situ.) Patients presenting 24 hours after injury (25%) without effective primary wound care and prophylactic antibiotics had significantly higher rates of infection (26% vs 8%). Inconsistent prophylactic antibiotic administration was attributable to differences in referring center policies regarding antibiotic prophylaxis.

Contrary to authors of previous publications,^{6,7} we did not find an increased rate of infectious complications after transection of a mucosal surface after NMPHI. This may be the result of the use of prophylactic antibiotics in the majority of our patients, whereas prior series have not used routine prophylaxis. Further, while differing outcomes associated with retained weapons have been reported in the literature, patients with retained weapons had a higher incidence of infection in the current series. Twenty-two (81%) infectious processes were clinically evident within 6 days of injury, underscoring the importance of early clinical surveillance and a reduced likelihood of infection beyond 1 week. While a single dose of prophylactic antibiotics within 24 hours of injury significantly reduced infectious complications, further study will be necessary to determine if additional antibiotic dosing can provide additional protection in certain circumstances.

Outcomes

Consistent with other traumatic brain injury studies,^{8,25} we found an association (linear relationship) between admission GCS score and GOS score on discharge. Patients who presented with a low GCS score tended to have poorer functional outcomes than those presenting with a good GCS score. Higher mortality rates due to primary injury were found in patients with direct trauma to eloquent regions, including the basal ganglia, motor area, and brainstem. Patients who did not have primary injury to eloquent areas or major vessels had a good prognosis. These features of NMPHI are in contrast to high-velocity missile injuries, in which the kinetic and coagulative forces create significant primary injury away from the tract.¹ These properties of NMPHI and the current study findings underscore the importance of the successful management of secondary complications to avoid exacerbation of the

impact of the direct injury, which is principally limited to (and not beyond) the wound tract.

Study Limitations

Limitations of the current study include the fact that follow-up care for some patients was conducted through distant hospitals local to the patient, limiting some details related to long-term outcomes. Subsequently, we were unable to precisely assess the time of the onset of infection in all cases or assess the optimal timing of repeat angiography to identify delayed development of traumatic pseudoaneurysms. These are the focus of future study.

Conclusions

The most common NMPHI secondary complications are vascular injury and infection, which are associated with specific NMPHI imaging and clinical features. Identifying these features and using a systematic management paradigm can effectively treat the primary injury, as well as diagnose and manage NMPHI-related complications, leading to a good outcome in the majority of patients.

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Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions

Conception and design: Vlok, Harrington, Gretscher, Lombard. Acquisition of data: Vlok, Harrington, Gretscher. Analysis and interpretation of data: all authors. Drafting the article: all authors. Critically revising the article: Vlok, Harrington, Lonser. Reviewed submitted version of manuscript: Vlok, Harrington, Gretscher, Lonser. Approved the final version of the manuscript on behalf of all authors: Vlok. Statistical analysis: Lombard. Study supervision: Vlok.

Supplemental Information

Videos

Video 1. <https://vimeo.com/409757188>.

Previous Presentations

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