Introduction and Methodology

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In 1995, the American Association of Neurological Surgeons and the Brain Trauma Foundation collaborated on the development of evidence-based *Guidelines for the Management of Severe Head Injury*[1] and in the subsequent enlarged and revised *Guidelines for the Management of Severe Traumatic Brain Injury*.[2] These Guidelines undertook to assess the scientific basis for the acute management of patients who had suffered blunt trauma to the brain. They did not address the management of patients injured by missiles or other penetrating objects. In the spring of 1998, the International Brain Injury Association, the Brain Injury Association, USA, and members of the American Association of Neurological Surgeons and the Congress of Neurological Surgeons began work on this task. The approach taken in this document involves developing treatment recommendations on the basis of medical evidence as reflected in the published literature. The purpose of this document is to delineate the known science regarding treatment of penetrating brain injury (PBI) and to formulate guidelines from this science. In addition, the literature was evaluated for conclusions regarding prognosis and prognostic factors in the patient's clinical status.

PBI occurs through accidents with firearms and other implements but more often results from intentional injury caused by singular acts of self-destruction or armed conflict in civilian or military arenas. These two latter circumstances differ from each other in significant ways. The principal differences are in mechanism of injury and outcome, especially death. These will be discussed in detail below. These differences are related in part to the nature of the weapons involved, so an understanding of the nature and role of ballistics in determining injury is relevant.

INFLUENCE OF BALLISTICS ON PBI

Ballistics is the study of the dynamics of projectiles; wound ballistics is the study of the projectile's action in tissue. Penetrating head wounds generally result from bullets, shrapnel, and lower velocity sharp objects, such as arrows and knives. The ability to penetrate the intracranial space is determined by the energy and shape of the object, the angle of approach, and the characteristics of intervening tissues (skull, muscle, mucosa, etc.). The primary injury to the brain is related to the ballistic properties (kinetic energy, mass, velocity, shape, etc.) of the projectile and any secondary projectiles, such as bone or metallic fragments.

Lower velocity sharp projectiles, such as arrows (120–250 ft/s [36–76 m/s]), wooden sticks, knives, and pencils create a track of primary tissue damage without substantial bruising or blunt tearing of surrounding tissue. In contrast, higher velocity projectiles result in a more complex wounding pattern. An impact shock wave precedes the projectile. This sonic wave is very brief (2 μs) and does not contribute substantially to tissue destruction. As the projectile penetrates brain tissue, it crushes tissue in its path, creating a permanent track of tissue injury. Higher velocity projectiles will impart an additional temporary cavitation effect in their wake, which is a velocity-related phenomenon. This results from the transmission of the kinetic energy of the projectile to the surrounding tissue, thus rapidly compressing it tangentially from the primary track. After the cavity expands to its maximum size, it starts to collapse under negative pressure and can suck in external debris. This cavity will then often undergo smaller expansions and contractions of diminishing amplitude. In relatively inelastic tissue, such as the brain, this results in a track of injury often 10 to 20 times the size of the offending projectile.

The size of this temporary cavity is related to the velocity, mass, and shape of the projectile. The velocity and mass are proportional to the kinetic energy as defined by the equation $KE = 1/2\ mv^2$. The shape of the projectile influences its velocity. Every projectile has a ballistic coefficient that expresses its ability to overcome air resistance and thus maintain velocity. A form factor in the equation for the ballistic coefficient relates to the shape. The sharper the nose of a bullet, the less the velocity will be decreased by air resistance. The rounder the nose of a bullet or more irregular the shape (as in shrapnel), the quicker the velocity slows and kinetic energy decreases. Projectiles traveling at higher velocities carry more kinetic energy and will create larger temporary cavities.

The shape of the projectile also affects the size of the temporary cavity through its influence on yaw. Yaw describes the rotation of a projectile around its long axis. Although small amounts of circular motion (precession and nutation) occur during flight, projectiles will often tumble when striking tissue. As the projectile rotates 90 degrees to its long axis, the primary track of tissue destruction increases. The entire length of a projectile contributes to this permanent track when the yaw is maximized at 90 degrees. This imparts more kinetic energy to the tissue, and the size of the temporary cavity increases. This also explains why the exit wound is generally larger than the entrance wound in perforating injuries. For these reasons, a .45 automatic pistol (muzzle velocity of 869 ft/s [265 m/s] and a short round-nosed projectile with little yaw) will create a very small temporary cavity. Conversely, a 7.62-mm rifle (muzzle velocity 2,830 ft/s [863 m/s] and a long, sharp nose with maximum yaw) will create a very large temporary cavity.

The caliber of a weapon is defined as the internal diameter of the barrel and thus represents the widest diameter of the bullet. This may be expressed in millimeters, as in a 9-mm handgun, or in inches, as in a .44 magnum. Magnum refers to a load with extra powder, thereby imparting more velocity to the projectile. In general, handguns (710–1,610 ft/s [216–491 m/s]) will be lower velocity weapons than rifles (2,690–3,150 ft/s [820–960 m/s]). The velocity also will be degraded over distance secondary to the ballistic coefficient discussed above. For example, the U.S. military M16A1 rifle has a muzzle velocity of 3,150 ft/s (960 m/s), which drops to 2,186 ft/s (666 m/s) at 300 yards (274 m) and 835 ft/s (255 m/s) at 1,000 yards (914 m).

One projectile characteristic deserving mention is fragmentation potential. In addition to yaw, projectiles can also deform or fragment on striking tissue. Copper jacketing of lead bullets, as mandated for military rounds by The Hague Peace Conference (1899), helps limit the fragmentation potential. Irregularities made by scoring the surface of the bullet (dum-dums) lead to increased fragmentation. Fragmenting rounds can create multiple injury tracks, as each fragment becomes an irregular, tumbling projectile. The Glaser round is filled with small pellets that disperse on impact. Hollow point rounds, often seen in civilian shootings, expand their diameter on impact, thus creating a larger primary wound track and more destructive temporary cavitation effects. Explosive bullets are designed to detonate on impact and will thus produce extensive tissue injury with additional kinetic energy transfer.

Shotguns simultaneously deliver multiple pellets with a large collective mass. At close range, the pellets all remain in a compact arrangement and are delivered to the target as if a single fragmenting round. This contributes to massive tissue destruction with the use of these weapons at close range. All the kinetic energy is transmitted to the tissue, with exit wounds rarely occurring. At greater distances they disperse, depending on choke, barrel length, and type of ammunition. The kinetic energy is distributed to these pellets, and their shape and light weight contribute to a rapid loss of energy. By 80 yards (73 m), most lightweight pellets will not penetrate the skin, and by 200 yards (183 m) the majority lose all their energy. This same rapid energy loss also occurs in tissue.

Shotguns are designated by gauge instead of caliber. Gauge is defined as the number of balls of a diameter that will fit in the barrel that can be made from 1 lb of lead. In other words, the lead ball that would fit into a 12-gauge barrel weighs $\frac{1}{12}$ lb. Therefore, a 12-gauge shotgun has a larger barrel than a 20-gauge. There are many types of shells, ranging from 9 pellets per shell (No. OO) to 2,385 pellets per shell (No. 12). Shotguns can also deliver a single projectile with a single-slug shell.

It is hoped that this brief ballistic overview will impart a general appreciation of the terminology used with some of the weapons that cause PBI. By understanding the wounding mechanism, we can enhance our evaluation and management of each individual injury.

METHODOLOGY OF GUIDELINE DEVELOPMENT

Guidelines can be developed using two different, but overlapping, methods: consensus based or evidence based. Consensus-based guidelines are developed with the input of experts in a given field who make recommendations on the basis of a literature review and their personal experience. Evidence-based guidelines use a strict process of literature review, ranking the published articles by strength of study design. The recommendations, therefore, are linked to the comparative scientific rigor of the studies used. The advantage of evidence-based guidelines over consensus-based guidelines is that the former are less prone to influence by personal or professional bias and are more objective, following a methodology spelled out in advance. The methodology chosen for this Guideline is evidence based and follows the recommendations of the Institute of Medicine Committee to Advise the Public Health Service on Clinical Practice Guidelines (1) outlined below:

1. There should be a link between the available evidence and the recommendations.
2. Empiric evidence should take precedence over expert judgment in the development of guidelines.
3. The available scientific literature should be searched using appropriate and comprehensive search terminology.
4. A thorough review of the scientific literature should precede guideline development.
5. The evidence should be evaluated and weighted, depending on the scientific validity of the methodology used to generate the evidence.
6. The strength of the evidence should be reflected in the strength of the recommendations, reflecting scientific certainty (or lack thereof).
7. Expert judgment should be used to evaluate the quality of the literature and to formulate guidelines when the evidence is weak or nonexistent.
8. Guideline development should be a multidisciplinary process, involving key groups affected by the recommendations.

These key components of evidence-based guidelines have been further formalized by the American Medical Association and many specialty societies, including the American Association of Neurological Surgeons and the American Academy of Neurology.[3,4] This formalization has involved the designation of specific, unambiguous relationships between the strength of evidence and the strength of recommendations. In this paradigm, evidence is classified into that derived from the strongest clinical studies of therapeutic interventions (randomized, controlled trials), and called Class I evidence. Class I evidence is used to support treatment

Table 1 Classification of Evidence on Therapeutic Effectiveness

Class I	Evidence from one or more well-designed, randomized controlled clinical trials, including overviews of such trials.
Class II	Evidence from one or more well-designed comparative clinical studies, such as nonrandomized cohort studies, case-control studies, and other comparable studies.
Class III	Evidence from case series, comparative studies with historical controls, case reports, and expert opinion.

recommendations of the strongest type, called practice Standards, reflecting a *high degree of clinical certainty*. Nonrandomized cohort studies, randomized controlled trials with significant design flaws, and case-control studies (comparative studies with less strength) are designated Class II evidence and are used to support recommendations called Guidelines, reflecting *a moderate degree of clinical certainty*. Other sources of information, including observational studies such as case series and expert opinion (Class III evidence), support practice Options reflecting *unclear clinical certainty*. These categories of evidence are summarized in Table 1.

The general term for all of the recommendations is Practice Parameters. Because so few practice Standards exist, the term more commonly used to describe the whole body of recommendations is practice Guidelines. Thus, we have named this document *Guidelines for the Management of Penetrating Brain Injury*.

One of the practical difficulties encountered in implementing this methodology is that a poorly designed randomized controlled trial might take precedence over a well-designed case-control or nonrandomized cohort study. The authors of this document have attempted to avoid this pitfall by carefully evaluating the quality of the study as well as its type. All of these criteria apply to practice Guidelines (parameters) for **treatment**. To assess literature pertaining to **prognosis**, **diagnosis**, and **clinical assessment**, completely different criteria must be used. These are described in Part 2 of this Guideline, *Prognosis in Penetrating Brain Injury*.

For diagnosis, articles are evaluated differently. The issues addressed by articles on diagnosis are related to the ability of the diagnostic test to successfully distinguish between patients who have and do not have a disease or pertinent finding.

GUIDELINES DEVELOPMENT PROCESS

A group of individuals with interest and expertise in the treatment of PBI patients and/or Guideline practice parameter development was assembled. The group reflected expertise in neurosurgery, neurology, neuropsychology, and clinical epidemiology. The issues chosen for inclusion in the document were those considered pertinent to PBI (e.g., surgical treatment, antibiotic prophylaxis, vascular injury, intracranial pressure, and antiseizure prophylaxis).

A MEDLINE search from January 1966 to January 2000 was carried out using the following search terms: *wounds*, *gunshot*, and *brain injuries* or *head injuries*. The search was limited to human subjects and included English language literature only. Additional articles were found through the reference lists in the articles found, as well as from other sources known to the author group. Two independent reviewers read the abstracts of the articles found. Articles were rejected on the basis of lack of appropriateness to the topic (e.g., pediatric population only, non-English language, case reports, irrelevance to the project, atypical mechanisms of injury, and fewer than 25 subjects). Individuals then brought additional articles of relevance from other sources. Some of these included literature written in other languages, including Russian, with translations. Because there were only translations, the entire group could not review each article separately, and a formal evidence-based analysis was not possible. However, because this large series reflected a wealth of experience in PBI, it was thought appropriate to include these in the scientific foundation of the appropriate sections. All articles were then evaluated according to the scheme outlined above. For therapy, recommendations were derived; for prognosis, conclusions were reached. The drafts were revised and authors different from the primary authors rewrote the drafts, and the final product was agreed on by consensus.

A major goal in the evidence-based medicine process is the development of treatment parameters. During the process of analyzing the literature on PBI, it readily became apparent that there is a distinct paucity of research into the efficacy of individual treatment methods, outside of debridement and the management of cerebrospinal fluid leaks, to influence outcome. This prohibited the development of treatment recommendations specific to PBI in some other areas. Therefore, a thorough discussion of this issue by the document's author group concluded that, until the time that data specific to the efficacy of specific treatment protocols in PBI becomes available, the clinician should default to the conclusions included in the *Guidelines for the Management of Severe Brain Injury* for any treatment issues not covered by this document.

Unlike therapy and diagnosis, recommendations are not possible for prognosis. The purpose of reviewing the literature on prognostic indicators was to define which features correlate with poor outcome for purposes of planning future research, prognostication, and for communicating with families of victims of PBI. *No attempt should be made to use the prognosis literature review to determine treatment*. In addition, interactions between prognostic factors cannot be determined from this review. The data derived from the studies examined in this review cannot be excised, pooled, or combined to determine interaction. To determine such interactions, a carefully designed prospective observational study with a standard protocol for collecting the desired data is necessary. In addition, the data need to be examined using multivariate analysis and tests of association of factors.

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