Trepanation Procedures/Outcomes: Comparison of Prehistoric Peru with Other Ancient, Medieval, and American Civil War Cranial Surgery

David S. Kushner¹, John W. Verano², Anne R. Titelbaum³

¹Department of Physical Medicine & Rehabilitation University of Miami Miller School of Medicine, Miami, Florida

²Department of Anthropology, Tulane University, New Orleans, Louisiana

³Department of Basic Medical Sciences, University of Arizona College of Medicine, Phoenix, Arizona, USA

To whom correspondence should be addressed: David S. Kushner, M.D. [E-mail: dkushner@med.miami.edu]

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Abbreviations and Acronyms: AD: Anno Domini, BC: Before Christ, ca.: Circa

ABSTRACT

More prehistoric trepanned crania have been found in Peru than any other location worldwide. We examine trepanation practices and outcomes in Peru over nearly 2000 years from 400 BC to provide a perspective on the procedure with comparison with procedures/outcomes of other ancient, medieval, and American Civil War cranial surgery. Data on trepanation demographics, techniques, and survival rates were collected through the scientific analysis of more than 800 trepanned crania discovered in Peru, through field studies and the courtesy of museums and private collections in the United States and Peru, over nearly 3 decades. Data on procedures and outcomes of cranial surgery ancient, medieval, and during 19th-century through the American Civil war were obtained via a literature review. Successful trepanations from prehistoric times through the American Civil War likely involved shallow surgeries that did not pierce the dura mater. Although there are regional and temporal variations in ancient Peru, overall long-term survival rates for the study series were about 40% in the earliest period (400-200 BC), with improvement to a high of 91% in samples from AD 1000-1400, to an average of 75%-83% during the Inca Period (AD 1400s-1500). In comparison, the average cranial surgery mortality rate during the American Civil war was 46%-56%, and short- and long-term survival rates are unknown. The contrast in outcomes highlights the astonishing success of ancient cranial surgery in Peru in the treatment of living patients

INTRODUCTION

Trepanation, or trephination, the scraping, cutting, or drilling of an opening into the cranium, was practiced in various parts of the world in prehistoric times, dating back 5000 years ago in Europe and to around 2500 years ago in the New World.¹ Interestingly, more prehistoric trepanned crania have been found in Peru than any other location in the world.¹ And even more interesting, the survival rates for the ancient procedure in Peru rival those for trepanation done during other ancient and medieval times and through the American Civil War in the 19th century, which is impressive, considering the many potential risks of cranial surgery, including direct or indirect perioperative complications such as infection and bloodloss.²

Treatment of head trauma was the main reason for the evolution of cranial surgery in ancient times through the start of the modern surgical era in the 19th century. Similarly, there is an association of trepanation in prehistoric Peru with evidence of cranial trauma, making it plausible that head injury was probably the main reason that this procedure was developed. However, just as modern neurosurgery is performed for many reasons other than brain injury, prehistoric trepanation was done on crania that have no clear evidence of trauma, suggesting that the procedure also was performed for other reasons.

Neurosurgery evolved into a distinct profession by the end of World War I,³ and since then, neurosurgical research developments have continued to hone the understanding of brain anatomy, physiology, and pathology while improving outcomes through better surgical tools, techniques, pharmacology, and perioperative management. Likewise, in Peru, from 400 before Christ [BC] through the time of the Inca Empire (circa [ca.] anno Domini [AD] 1400-1500), advances in trepanation techniques led to improvements in long-term survival. This article will compare the evolution of trepanation procedures and outcomes in prehistoric Peru with other cranial surgery in ancient times through the time of the American Civil War to provide a perspective on the development and outcomes of these practices while underscoring the remarkable success of the ancient surgery in Peru.

DESIGN/METHODS

Ancient Trepanation in Peru

Data on trepanation survival rates, types of injury, techniques, and demographic information including age and sex were collected through the scientific analysis of more than 800 trepanned crania and artifacts discovered in coastal regions and the Andean Highlands of Peru, dating from ca.400 BC through the time of the Inca (ca. AD 1400-1500). Data were acquired from the analysis of the trepanned crania and artifacts through the courtesy of museums and private collections in the United States and Peru and through field studies over nearly 3decades by biological anthropologist Dr. John W. Verano and colleagues (Table 1).^{1,4-6} Although precise dating is not available for all crania described in this article, most sites with trepanned crania have been dated by associated artifacts and/or radiocarbon dates.^{1,6} Ancient trepanation survival rates(short- and long-term) were gauged by evidence of healing, which manifests as bone remodeling along the perimeter of the trepanation opening. Degree of healing (survival time) was assessed by visual examination of trepanation openings, and classified into 1 of 3 categories:

1. None, where no evidence of bone reaction is visible, suggesting that the patient died during or within days of the surgical procedure (Figures 1 and 2).
2. Short term, where there is evidence of necrotic bone and osteoclastic activity surrounding the trepanation opening but no visible remodeling of the margins of the trepanation opening (Figure 3). In these cases, the survival time is probably less than 2 weeks, based on comparison with documented cases of skull fracture and gunshot wounds from U.S. Civil War medical specimens.⁷
3. Long-term, where the margins of the trepanation opening are extensively remodeled, with no remaining exposure of the diploe and no visible cut marks or necrotic bone (Figures 4 and 5). If the margins of a trepanation opening are fully healed, the operation is considered to have been successful.

For the purposes of this paper, we score categories 1 and 2 as unsuccessful, and category 3 as a successful surgical outcome. Thus, our estimates of successful outcomes are calculated as the percentage of trepanations with a score of 3 relative to those with scores of 1 or 2. Our sample is composed of all crania with trepanations collected from a given archaeological site or region. Although more individuals may have been trepanned at other sites or time periods (successfully or

unsuccessfully), we cannot estimate this number in the absence of evidence. However, we are confident that the trepanations we recorded can be confidently classified into 1 of the 3 categories described previously, making our estimates of survival accurate for the available skeletal data.

A variety of procedures for prehistoric trepanation are identified by tool marks and the shape of cranial openings and in some cases by possible tools found at archeological sites with trepanned crania. Methods for trepanation in prehistoric Peru included scraping, circular grooving, linear cutting, and boring and cutting (Table 1). Whereas scraping led to the progressive removal of the outer and inner tables of the cranium (Figure 1), circular grooving and linear cutting involved scoring an outline (circular, rectangular, or triangular), with the goal of removing the central plug of bone. The boring and cutting technique involved drilling a series of holes through the cranium and then cutting through the residual bone to remove the central plug. With the exception of a single known example, the removed plug of bone was not replaced after the operation.¹

The tools that were used for trepanation is still a matter of speculation, as specifically identified surgical tool kits have not been found archaeologically. Bifacially flaked obsidian and chert knives, some still hafted to wooden handles, were found in association with trepanned crania discovery sites for the earliest time period. It is likely that sharpened stone tools continued to be employed in later time periods, although it is likely that metal tools (copper and bronze) were experimented with as well. Yet, which metal tools are unclear; in two modern experiments that used actual Inca metal knives called *tumis* (tools with semilunar blades) to perform trepanations, it was found that these tools were able to cut through the skin and pericranium but not through bone.¹

A related matter of speculation is how infection was prevented. At present, consideration of the use of antiseptic agents is conjecture. It is likely that extradural pathology would have had the best outcomes after prehistoric trepanation due to the shallower location of the lesions beneath the cranium and due to the fact that the protective dura mater would have maintained its integrity without compromise limiting the likelihood of infection.

Many of the trepanations are on crania with visible fractures resulting from blunt force trauma (e.g., from clubs and sling stones) and occasional perforating injuries from pointed mace heads. Sling stones, stone mace heads, and stone projectile points have been recovered from some of the trepanned crania discovery sites for the AD 1000-1400 time period.¹

The locations of the trepanations on the cranium vary by geographical region and time period (Table 1). In the earliest sample from the South Coast, trepanation was most commonly found on the frontal and occipital bones. During the later time periods, there was a low frequency of surgeries involving the temporal fossa and the nuchal region of the occipital bone, possibly due to an awareness of bleeding risks.¹ Interestingly, as many trepanations are associated with traumatic injury, differences in position probably reflects points of injury on the cranium. A consideration with trauma is that the timing of surgery would have affected survival, particularly if initiated too late. Thus, patient selection factors may have had a role in outcomes as well as the execution of surgery, and ultimately, where it was positioned on the cranium.

Most trepanations were singular events, but there are numerous crania with more than 1 surgery, including 2 Inca examples with seven successful operations (Table 1).^{1,5} The greatest frequency of crania with multiple trepanations was found at Inca sites (Figures 4 and 5).¹ Although some of the crania demonstrate that multiple openings were done at roughly the same time, others have openings with different stages of remodeling, indicating that the surgeries were done at different times during the individual's life.

The motivation for the numerous holes is unclear; in some cases, the surgery appears to have treated multiple injuries related to trauma; in other cases, however, there is no evidence of fracture. In still other cases, the number and position of the surgeries appears to reflect the trepanner's understanding of anatomy; for instance, there are several examples in which there are trepanations on both sides of the sagittal suture, but not on it, which suggests the surgeon may have wanted to avoid the superior sagittal sinus (Figure 6).¹ Also, a few crania have been found (circa AD 1000) with evidence of postmortem trepanations that were likely performed for the purpose of understanding cranial anatomy and improving techniques.^{1,8}

Regarding patient demographics, across time and space, adult men were more likely to be trepanned than adult women, and children rarely were trepanned (Table 1). An exception to this distribution was found at the Inca site Ollantaytambo, where the sex ratio was nearly 1:1.¹ This latter site is unusual in that there was a low frequency of cranial trauma associated with trepanation, suggesting that the surgery was done for reasons other than acute injury.¹

Other Ancient Trepanations Through the American Civil War

Data on other ancient cranial surgery through the time of the American Civil War, including survival rates, motivations, techniques, and demographic information, were obtained through a literature review. Trepanned crania have been discovered around the world from ancient times possibly dating back as far as 10,000 BC.⁹⁻¹²

Similar to the case in Peru, prehistoric surgeons in other parts of the world used 4 basic techniques in trepanation, including scraping, grooving, boring and cutting, and rectangular intersecting incisions.^{1,10,11,13,14} Sharpened stone, flint, obsidian, or bone instruments were used in the Neolithic period (10,000-2000 BC), with an increase in metal tools during the Bronze Age (2000-600 BC) and the Iron Age (600-200 BC), particularly in Europe and Asia.¹⁰⁻¹²

Motivations for the ancient surgeries apparently included therapeutic (trauma, infection), and therapeutic magic (no clear evidence of trauma or infection and therefore possibly other problem such as headaches, seizures, or mental illness). For example, a trepanned skull from 3000 BC in China had a right parietal defect (31 x 25 mm) with evidence of long-term survival but no signs of trauma^{10,11} whereas another skull from 2000 BC had a biparietal opening (42 x 33 mm) with evidence for depressed skull fractures also with signs of healing.¹¹ Multiple trepanations also were done on some trepanning subjects during ancient times. For example, in a series of 13 skulls discovered in China dating as far back as 1000 BC, nearly all had evidence of trauma, whereas several had up to 5 trepanations and one had 7 openings, and all had evidence of healing.¹¹ Evidence suggests that in some cases with multiple surgeries that the trepanations were performed at different times.¹¹ Interestingly, 3 trepanned skulls, (2 male, 1 female), two with signs of trauma were discovered in the Altai Mountains, which were operated on by nomadic Pazryk surgeons of Scythian Siberia (500-300 BC), most likely with bronze tools via the scraping method.¹⁴ It is hypothesized that copper shavings from the surgical instruments discovered on the skulls may have had an antiseptic effect (2 of the 3 skulls have signs of long-term healing).^{13,14}

Ancient literature documents the practice of trepanation in China and Europe. A Chinese text from 2697 BC called "Huang Ti Nei Jing" mentions a physician, "Yu Fu," who practiced trepanation.¹¹ There is also Chinese literary evidence of trepanation with anesthesia by surgeon Hua Tuo (AD 108-208).¹¹

Guidelines for therapeutic trepanation were codified in classical Greece in the fifth century BC by Hippocrates (460-377 BC).^{1,12} Hippocrates' book on the topic may have been a revision of earlier texts, and some of the tenets were accepted in Western medicine for approximately 2000 years afterward into the time of the Middle Ages.¹² One of Hippocrates many observations was that seizures caused by head trauma often appear on the opposite side of the body and require prompt trepanation, possibly the

origin of trepanation as a treatment for epilepsy.¹ Hippocrates also advocated prompt surgery, within 3 days of trauma, and advised that care be taken not to perforate the meninges and that any fracture fragments be removed.¹² Interestingly, Hippocrates recommended against trepanation in the case of depressed fractures, possibly because he considered the procedure would be dangerous.¹ In contrast, Celsus (25 BC-AD 50) wrote a medical text advocating a conservative approach for head trauma, recommending trepanation mainly if there were clinical signs of deterioration but recommending trepanation for depressed skull fractures.^{1,12} Celsus described the evaluation of head wounds and intracranial bleeding and made important contributions regarding trepanation drilling tools and drilling procedures.^{1,12} Galen (AD 129-210), a Roman physician whose clinical work included treatment of gladiators, favored prompt trepanation for head trauma, studied neuroanatomy, and described safe techniques for trepanation.^{1,12}

Trepanations became less common, and technologic advances in the procedure ceased, after the classical Greco-Roman era.^{1,12} The procedure was rarely performed in the Middle Ages by European, Byzantine, Arab, and Eastern surgeons partly because the action of the air on the brain was considered harmful.¹² A rare example of trepanation during the Middle Ages was discovered in Tuscany on a 13th-century male skull having evidence of trauma from a bladed weapon but without signs of healing after the surgery.¹⁵ A 13th-century surgeon, Rolando de Parma, who taught at the medical school of Salerno, wrote about trepanation as a treatment for mental illness, including mania and melancholy, which may have laid the foundation for later psychosurgeries.^{1,16}

Interest in trepanation was rekindled during the Renaissance, particularly with the increase in head trauma from warfare and firearms.¹² Celsus' medical text *De re Medicina* was published in Europe in 1478 after it was rediscovered during the late Middle Ages and early Renaissance.¹ In the 16th through 17th centuries, trepanation was widely used for trauma, septic, and vascular disorders to remove bone fragments, to decompress, and to drain blood, clots, and purulent material but with efforts not to puncture the dura; these procedures and tools were described in illustrated books.¹² By the end of the 18th century in Europe, there was a significant decrease in the performance of trepanations due to the increasing incidence of infections in the hospitals where these surgeries were performed.¹²

At the time of the American Civil War (1861-1865), head trauma was classified as puncture wounds, blunt injuries, and gun-shot wounds, with or without signs of compression or concussion, but there was no stratification by severity.^{17,18} Military surgical manuals described head trauma including various types of fractures, epidural and sub-dural hematomas, and delayed complications such as blood clots and infection.^{17,18} Military surgeons had a variety of opinions ranging from a conservative/expectant approach to an aggressive surgical approach, particularly when there were depressed fractures, foreign bodies/bone fragments, epilepsy, or collections of pus or blood.^{17,18} An effort was made not to puncture the dura during surgeries and to avoid cranial surgery over the middle meningeal artery. Surgical technique included many unhygienic practices, such as using unsterilized medical tools and the use of bare fingers to probe open cranial wounds or to break up epidural hematomas.^{17,18} Nearly 100% of soldiers having gunshot wounds subsequently suffered from infections.⁷ Shortly after the American Civil War and through the end of the 19th century, improved understanding of cerebral localization, antiseptic and aseptic techniques, anesthesia, and technological advances paved the way for cranial surgery to gradually evolve into the profession of neurosurgery.

RESULTS

Ancient Trepanation in Peru

There were regional differences within Peru, but overall long-term survival rates for the series described in this study were nearly 40% in the earliest examples (400-200 BC) (n = 59), with improvement to a high of 91% (range 53%-91%) in samples dating between AD 1000-1400 (n = 430) to an average of 75%-83%

during the Inca Period (AD 1400-1500, n = 160) (Table 1). Crania having multiple trepanations discovered at Inca burial sites had an average long-term survival rate of 79.5% (Figures 4 and 5).¹

Trepanations were more common in men, but examples were found in women and children. Of the various trepanation methods, scraping and circular grooving were the most commonly seen over time and space (Table 1). Conversely, linear cutting and boring techniques were the least common and resulted in some of the lowest success rates, possibly due to the increased risk of perforating the dura mater (Figure 2).^{1,6,8} Interestingly, a variety of methods were found among the earliest examples of trepanation, but by the time of the Inca, the circular grooving technique was most frequently observed (Figures 4 and 5), with only a few infrequent, unsuccessful attempts at incising and drilling.¹

The size of trepanations varied in ancient Peru, from small and focal (10 mm diameter) to ones that were surprisingly large (90 x 57 mm) and comparable in size with some modern craniectomies.⁴ Although the larger trepanations were not the norm, they occurred more frequently, and less successfully, during the earliest time period (Figure 1); however, by the time of the Inca, even large trepanations demonstrated long term healing.¹

Trauma often was found in association with trepanations, particularly during the AD 1000-1400 time period (Table 1). Given the frequent association of trepanation and fractures, it is likely that head trauma was the primary reason that cranial surgery was developed in prehistoric Peru (Figure 3).^{1,2,5} However, although many trepanations are associated with traumatic injury, there are many that are not. Indeed, the Inca had the lowest rate of trepanations associated with trauma, with nearly 90% of the surgeries apparently done for other reasons. The Inca had the greatest frequency of crania with multiple successful surgeries. A comparison of trepanations in prehistoric Peru by time period, region of discovery, demographics, surgical techniques and outcomes is given in the Table 1.

Other Ancient Trepanations Through the American Civil War

There is no large series of trepanned crania discovered from any of the other prehistoric through medieval time periods documented in the literature for comparison with the outcomes in the sample series from ancient Peru. However, a series of 13 trepanned crania reportedly having signs of healing were discovered in China in 2000 tombs dating to approximately 1000 BC.¹¹ Cranial surgical mortality rates were documented from the American Civil War in several series as follows: in 1 series (n = 122), the average mortality was 48%.¹⁷ In another cranial surgical series (n = 911), the mortality rate was 46%, whereas the mortality rate specifically for removal of bone splinters or elevation of depressed bone was 39% (n = 454).¹⁷ In yet another series (n = 196), the average mortality was 56%.¹⁷ Finally, taking all modes of treatment into account, conservative versus surgical, the Union Army had an 82% mortality rate for “penetrating headwounds.”¹⁸ Short- and long-term survival rates during the American Civil War were not recorded. There were acknowledged problems in the collection of Civil War time data on cranial surgeries, including the outcomes, which may not be fully representative.¹⁷

DISCUSSION

There are striking similarities in the evolution of trepanation in ancient Peru with that of other ancient civilizations. Evidence shows that the surgical techniques from all the civilizations and time periods were initially the same but were refined through trial and error. Written texts beginning from the time of Hippocrates document the gradual refinement of trepanation tools and procedures in Western medicine to the time of the Middle Ages and through the Renaissance. There are no written records from ancient Peru through the time of the Inca Empire; however, there is physical evidence of a similar refinement of the trepanation process. The skills used in trepanation in prehistoric Peru were likely passed from one generation to the next via oral tradition and apprenticeship in the absence of a written language.

Trauma as a motivation for trepanation is common to all the civilizations and time periods. The motivations for the trepanations on crania without evidence of trauma remain a matter of speculation without written records or osteological evidence. Interestingly, Paul Broca, who introduced cranial cerebral topography in 1868, and 19th-century cranial surgeon Sir Victor Horsley were both aware of ancient trepanned crania showing that the operation was performed on living patients, and both speculated that the procedure was done for neurologic reasons.¹⁹ Given that up to 4% of the world's adult population has headaches on 15 or more days every month, it is possible that a primary headache disorder could have been a reason for some of the trepanations.^{2,20} Also, it is conceivable that some trepanations might have been performed for secondary headaches or seizures resulting from intracranial mass lesions or bleeding, where decompression may have been a useful intervention.²

Successful trepanations from prehistoric times through the American Civil War likely involved shallow surgeries that did not pierce the dura mater. This series suggests that advances in prehistoric trepanation procedures, and the understanding of anatomy in Peru from 400 BC through the time of the Inca resulted in average long-term survival rates of 75%, and regional rates as high as 91%, whereas average mortality rates declined from 60% in the earliest time period, to 25% in the latest (Table 1).^{1,2,4,5} In contrast, the average cranial surgery mortality rate during the American Civil war was 46%-56%, and short- and long-term survival rates are unknown.¹⁷ Although there are still many unknowns about the procedure and the individuals on whom trepanation was performed, the contrast in outcomes highlights the astonishing success of ancient cranial surgery in Peru in the treatment of living patients.

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Table 1: Comparison of trepanations by time period, region of discovery, demographics, trauma association, survival, and techniques ^{1, 5, 6}

Number of crania with trepanations	Region of Peru where crania were discovered	*Demographics: % Adult Male, % Adult Female, % Adolescents & children	Location of trepanations on cranium	**Association with cranial trauma (fractures)	Long-term survival	Surgical Techniques
400 to 200 BC (n=59)	Paracas & the South Coast	68% Male, 29% Female, 3% Adolescents & children	43% Frontal, 21% Occipital, 14% Left vault 14% Midline 8% Right vault	10.3%	40%,	Grooving & scraping; use of stone tools for trepanation
AD 1000 to 1300 (n=9)	Northern Highlands	100% Male,	55% Frontal, 45% Left vault	67%	91%	Scraping & linear cutting
AD 1000 to 1400 (n=421)	Central Highlands	60% Male, 31% Female, 9% Adolescents & children	43% Frontal, 23% Left vault, 15% Right vault, 19% Other	26.5%	53%	Various methods: linear and curved cutting, circular grooving, scraping, and boring & cutting
AD 1400s to mid-1500s, Inca (n=160)	Southern Highlands around Cuzco	Males > Females (ratio varies by sample), two Adolescents	33% Left vault, 24% Frontal, 19% Right vault, 13% Midline 11% Occipital	11.9%	75-83%	Circular grooving & scraping; high frequency of multiple surgeries, (up to 7 successful trepanations in two subjects)

*Demographics for crania where sex and age could be determined with sufficient confidence ¹

**Rate of fractures may be higher but evidence of fractures may have been eradicated by large overlying trepanations, or a missing part of cranium. ¹

Table 2: Association of innovations and survival rates in Western cranial surgery through World War I ^{7-9, 12-20}

Time period	Short term survival	Innovations
End of 19th century	50-70%	1868: Cranial cerebral topography introduced by Broca ¹³ 1872: Lumbar puncture used to measure ICP ⁸ 1875: Localizing signs associated with mass lesions described ^{8, 14, 15} 1881: Increasing awareness of principles of surgical antisepsis ⁸ 1889: Microorganisms established as cause for infectious diseases ¹⁶ 1896: Trephination proposed as a means to reduce elevated ICP; and Rontgen's discovery of x-ray machine published. ^{8, 14} 1886-1889: "Motor cortex" mapped; Supra/infratentorial cranial surgeries performed by Horsley ^{8, 14, 17}
1898-1909 (H. Cushing: for head trauma)	20%	1901-1903: Bradycardia, irregular respiration and hypertension are associated with elevated ICP (Cushing's reflex) ^{7, 8, 18, 19} 1910: Concept of ICP control via cranial decompression established; and advances in neuro-anesthesia with regular blood pressure monitoring during surgery ^{7, 8, 19, 20}
Early WW I	40-56%	Early-mid WW I: Surgeons acquire increasing practical experience in the management of all types of head trauma
Late WW I (through 1918)	65-71%	By late WW I: Hemostasis improved; opening dura only if necessary; pericranium flaps where needed to substitute for dura; clean incisions rather than incorporating existing wounds; remove foreign bodies; use of radiographs if available; check pulse to determine if stable for transport to a base hospital (with advanced anesthesia, fluoroscopy, trained specialists and all necessary surgical instruments). ⁹

WWI=World War I; ICP=Intracranial Pressure

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

Figure 6.