AMERICAN JOURNAL OF PHYSICAL ANTHROPOLOGY 137:4–13 (2008)

Prehistoric Trepanation in the Cuzco Region of Peru: A View Into an Ancient Andean Practice

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KEY WORDS trepanation; Inca; cranial trauma; Cuzco

ABSTRACT In this study, patterns of prehistoric trepanation in the southern highlands of Peru were examined through an analysis of 11 Cuzco-region burial sites. Trepanations were found in 66 individuals, with several individuals exhibiting more than one trepanation, for a total of 109 perforations observed. The predominant methods used were circular cutting and scraping—methods that proved highly successful with an overall 83% survival rate and little ensuing infection. Survival rates showed a significant increase over time, apparently reflecting improvements in trepanation technique through experimentation and practical experience. Practitioners avoided certain areas of the cranium and employed methods that reduced the likelihood of damage to the cerebral meninges and venous sinuses. In many cases, trepanation as a medical treatment appears to have been prompted by cranial trauma, a finding that corroborates other studies pointing to cranial trauma as a primary motivation for the surgical procedure. Am J Phys Anthropol 137:4–13, 2008.

The prehistoric practice of trepanation, the surgical removal of part of the cranium, was first identified in 1865 by E. George Squier, in Cuzco, Peru (Weiss, 1958; Finger and Fernando, 2001). Since that initial discovery, trepanation has been documented in prehistoric and historic settings around the world—from Neolithic Europe and the Melanesian Islands to the Near East and parts of Africa (Tello, 1913; Lastres and Cabieses, 1960; England, 1962; Lisowski, 1967; Campillo, 1984; Zias and Pomeranz, 1992; Weber and Wahl, 2006). Trepanation has garnered intense interest, because it represents an early form of cranial surgery practiced well before the advent of modern medicine. Patients often survived the initial surgery and several subsequent surgeries (despite a lack of anesthesia and antibiotics), as shown by individuals with multiple, well-healed trepanations.

Peru has produced some of the largest samples of prehistoric trepanned individuals, since trepanation was practiced over a long period of time and across a broad geographical area (Stewart, 1958). The earliest Peruvian trepanations appear on the south coast of Peru circa 400 BC. The practice subsequently spread to various cultures of the Peruvian highlands and continued through the rise of the Inca Empire circa AD 1400 (Verano, 2003b). Moreover, trepanation was almost certainly performed at the time of European conquest in AD 1532, though it was not mentioned in Spanish colonial documents on Inca culture (Rowe, 1946). Geographically, trepanation was concentrated in certain regions of Peru, such as Paracas on the southern Peruvian coast (Tello and Mejía Xesspe, 1979), the Huarochiri and Jauyos provinces in the central highlands (Tello, 1913), and Cuzco in the southern highlands (Stewart, 1958). Trepanation was also practiced in the late Prehispanic period in the Chachapoya region of northern highland Peru (Jakobsen et al., 1987; Nystrom, 2007).

Proposed explanations for the practice of trepanation in Peru and other regions have varied widely (Clower and Finger, 2001). Many researchers have viewed trepanation as a medical treatment, thought to alleviate trauma-induced intracranial swelling and other maladies (Ortner and Putschar, 1981; White, 2000). In contrast, other individuals have proposed cultural purposes as an explanation, pointing to its uses to treat mental disorders and to acquire religious amulets of bone (Oakley et al., 1959). In this study, we evaluate possible explanations for trepanation among prehistoric groups living in Cuzco, Peru.

Cuzco served as the capital of the Inca Empire, the largest pre-Columbian polity in the New World. The Inca conquered vast territories throughout the Andes in less than a century (AD 1438–1532) and eventually ruled an area from Ecuador through Peru and into Chile, northwest Argentina, and Bolivia. With a large labor force of conquered peoples and numerous specialists, the Inca made great advances in engineering, arts, astronomy, and the construction of monumental architecture, exemplified by the imperial estate of Machu Picchu. They also excelled in medical treatment, with dedicated practitioners knowledgeable of the medicinal properties of plants such as the coca leaf (Marino and Gonzales-Portillo, 2000).

Grant sponsor: National Science Foundation (Dissertation Improvement Grant); Grant number: 0424213; Grant sponsor: Wenner-Gren Foundation for Anthropological Research (Individual Research Grant); Grant number: 7283.

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Received 5 September 2007; accepted 18 February 2008

DOI 10.1002/ajpa.20836
Published online 3 April 2008 in Wiley InterScience (www.interscience.wiley.com).

The present study investigates whether trepanation was used by these prehistoric medical healers to treat patients in the Cuzco region. Two main hypotheses were tested: 1) Trepanations in the Cuzco region were carried out as a medical treatment rather than for cultural purposes; and, if so, 2) The rise of the Inca Empire—and consequent medical advances—resulted in increased survival rates for trepanned individuals. To test these hypotheses, a comprehensive analysis was completed on burials from 11 Cuzco-region sites. Six of these sites provided 66 instances of trepanation throughout the department of Cuzco, in both pre-Inca and Inca contexts. Using data collected on trepanation location, morphology, and associated pathological conditions, interpretations are drawn regarding preferred methods and changes in survival rate over time—shedding light on possible reasons for trepanation in the Inca capital of Cuzco.

PREVIOUS TREPANATION ANALYSES IN THE CUZCO REGION

MacCurdy (1923) documented numerous trepanned crania in his analysis of 341 skeletons from the Urubamba Valley near Cuzco. These trepanned crania constituted 17% of the total sample, with one skull exhibiting healing from five separate trepanning episodes. MacCurdy (1923) found that trepanation often accompanied cranial trauma, and then linked these conditions to Inca warfare by asserting that the prevalence of left-sided injuries reflected face-to-face combat with right-handed foes. He also identified stellate-pointed clubs as the primary weapon responsible for cranial fractures and concluded that, in the "period of strife" during the Late Horizon, the Inca perfected trepanation to treat individuals with severe cranial injuries (MacCurdy, 1923).

Although many individuals exhibited trepanations in MacCurdy's sample, no such examples were found at Machu Picchu, located just 13 km from one of MacCurdy's sites (Eaton, 1916). MacCurdy (1923) attributed this disparity to sex differences between the sites, with a disproportionately high number of females at Machu Picchu. However, this alleged female overrepresentation came from an erroneous study of the Machu Picchu burials by Eaton (1916); once reanalyzed, the Machu Picchu sample was found to have a more normal distribution of sexes (Verano, 2003a). Another finding, however, seems to explain the lack trepanations at Machu Picchu. Recent research indicates Machu Picchu was a royal Inca estate, and individuals buried in the caves and crevices surrounding the ruins were non-native servants brought from different parts of the Inca Empire to tend the estate (Salazar, 2001; Burger and Salazar, 2004; Turner, unpublished data). The analysis of their skeletal remains confirmed they were an atypical group; skull fractures were uncommon, and no examples of trepanation were found (Verano, 2003a).

Another study of trepanation was completed by Quevedo (1939, 1942) at the site of Kinsarumiyoc in the Calca region, 20 km north of Cuzco. Quevedo (1942) analyzed 55 crania, 11 of which had trepanations. He noted that all of the trepanations from Calca were circular or oval in form, with no examples of linear cutting, boring, or scraping—distinguishing them from techniques typical of central highland Peruvian trepanations (Tello, 1913). Quevedo concluded that the circular/oval grooving was characteristic of the Cuzco region, despite finding some scraped trepanations at the site of Ollantaytambo. He also noted the consistent and small size of the Calca trepanations, most of which had diameters of 4–5 cm. He determined from his work that trepanation was mainly performed in response to cranial trauma and was carried out by trained practitioners with knowledge of cranial anatomy.

Recent studies by Verano of trepanned skulls in various Peruvian and U.S. museums (Verano, unpublished data) have documented a total of 161 trepanned skulls from the Cuzco region. Unfortunately, most of these skulls were collected from burial caves in the late nineteenth and early twentieth centuries, and thus lack good archaeological context and secure dating. The strength of the present study is that the trepanned skulls come from scientifically excavated burials with secure provenience and dating.

MATERIALS AND METHODS

Materials

Eleven sites in the Cuzco region were analyzed for the present study, six of which contained evidence for trepanation (Andrushko, 2007). These six sites are distributed throughout the department of Cuzco at a distance of 4.5–147.5 km from the Plaza de Armas in the city of Cuzco (see Fig. 1). The sites were divided into two groups: a "core" group, consisting of one site in the city of Cuzco (Qotakalli), and a "periphery" group, consisting of five sites greater than 30 km from Cuzco (Chokepukio, Colmay, Cotocotuyoc, Aqnapampa, Kanamarca). This core/periphery distinction loosely follows the inner Inca heartland/outer Inca heartland division illustrated by Farrington (1992), though the sites of Aqnapampa in the Quiquijana Valley and Kanamarca in Espinar province lie outside of the defined Inca heartland (within about 70 km of the city of Cuzco [Farrington, 1992]). Individuals from five other sites—Kusicancha, Sacsahuaman, and Qhataqasapatallacta in the core and Machu Picchu and Wata in the periphery—did not show any evidence for trepanation.

Sites occupied in the Early Intermediate Period (200 BC–AD 700) and Middle Horizon (AD 700–1000) (Chokepukio and Cotocotuyuc, respectively) provide a baseline for information on trepanation prior to the rise of the Inca Empire. The sites from the Late Intermediate Period (AD 1000–1400) (Aqnapampa, Chokepukio, Cotocotuyuc, Qotakalli) and the Inca Imperial Period/Late Horizon (AD 1400–1532) (Aqnapampa, Chokepukio, Qotakalli, Colmay, Kanamarca) present the means to investigate trepanation practices during the development and florescence of the Inca Empire.

All six sites served a variety of functions for their occupants. Qotakalli had a large portion of the site designated for residential use, along with regions for food storage and cemetery spaces (Bustinza, 2004). Similarly, Kanamarca supported an extensive Inca occupation with residential and storage areas and a variety of domestic and ceremonial artifacts (Benavides, 2004). Chokepukio, located 30 km southeast of the city of Cuzco, contained at least 150 buildings that were used for domestic, political, ritual, and burial purposes throughout 2,000 years of occupation (McEwan et al., 1995, 2002; Gibaja et al., 2005; Andrushko et al., 2006). Aqnapampa similarly contained rectangular buildings, patio spaces, and associated terraces and cultivated fields, as well as aboveground burial structures known as *chullpas* (Chatfield, 2007). Cotocotuyoc, the largest site in the Huaro complex located 46 km southeast of Cuzco, featured Wari and Lucre (LIP) domestic areas, a canal system, and a num-

TABLE 1. Trepanned individuals in the Cuzco sample

Site	Site location	Temporal association of trepanned individuals	Cranial MNI	No. of trepanned individuals	Prevalence of trepanations
Qotakalli	Core	Late LIP through Late Horizon (AD 1290–1532)	195	34	17.4%
Chokepukio	Periphery	Late Intermediate Period through Late Horizon (AD 1000–1532)	83	7	8.4%
Colmay	Periphery	Inca Imperial Period/Late Horizon (AD 1400–1532)	59	21	35.6%
Cotocotuyoc	Periphery	Late Intermediate Period (AD 1000–1400)	35	2	5.7%
Aqnapampa	Periphery	Late Intermediate Period through Late Horizon (AD 1000–1532)	21	1	4.8%
Kanamarca	Periphery	Inca Imperial Period/Late Horizon (AD 1400–1532)	18	1	5.6%
Total			411	66	16.1%

ber of mortuary contexts (Glowacki and McEwan, 2001). Finally, although Colmay has not been systematically studied, Max Uhle surveyed the site in the early part of the twentieth century and found large imperial Inca rectangular buildings, surrounding platforms, and cave tombs (Uhle, 1909), suggesting a mixed residential and mortuary use for the site.

The sites also varied by treatment of interred individuals. At Kanamarca, one trepanned individual was found in an elaborate circular stone tomb, associated with a spondylus necklace and polychrome Inca vessels. In contrast, the mortuary treatment of individuals at the site of Chokepukio was generally unelaborate, although a small number of individuals were recovered with artifacts of bone, ceramics, lithics, and metal (Andrushko et al., 2006). Although some individuals at Cotocotuyoc were buried in elaborate funerary contexts such as floor tombs covered by stone lids (Glowacki, 2002), the two trepanned individuals from Cotocotuyoc were found in a large ossuary. Little is known about the burial treatment of individuals from Aqnapampa and Colmay due to disturbance and preservation issues; however, reconnaissance of the latter site in August 2006 revealed well-preserved architecture in the imperial Inca style, suggesting a high status for some of its occupants. Finally, all of the trepanned individuals from Qotakalli were interred in one Inca building, a funerary context that appears to represent a single reburial event during which hundreds of individuals were relocated into one structure. Grave goods associated with these individuals were mainly small personal items such as *tupu* pins, needles, and spindle whorls, and no individual showed a noticeable distinction in artifact distribution.

Methods

The six sites with trepanned individuals yielded a combined sample of 709 individuals, yet only 411 individuals met the two criteria of the trepanation study: 1) sufficient cranial vault material available to view any possible trepanation (at least half of the calvarium present) and 2) an age-at-death greater than 5 years (infants and juveniles 5 years and younger showed no evidence for the procedure and were not included in the analysis).

Data collection on trepanation followed the standards detailed in Verano (2003b) and incorporated the following variables: location (frontal, parietal, occipital, or temporal), side (right, left, or midline in cases where a substantial portion of the trepanation crossed the midsagittal plane), perforation shape (circular, oval, rectangular, and irregular), perforation dimensions (endocranial and ectocranial), associated trauma and infection, impact to sutures, inferred impact to musculature (modification on or below the temporal and nuchal lines), amount of healing (none, short-term, or long-term), and method of modification (boring, scraping, circular grooving, or linear cutting). These variables were then tabulated to recognize patterns involving location of trepanation and associated trauma against sex and age affiliation. Survival rates were calculated by tabulating the total number of trepanations that showed long-term healing and dividing by the total number of trepanations observed.

RESULTS

Of the 411 individuals that met the two criteria for inclusion in the analysis, 66 (16.1%) exhibited at least one complete trepanation with perforation of both the outer and inner table (Table 1). Per cranium, the number of perforations varied from one to seven, for a total of 109 perforations recorded (Table 2, Fig. 2).

Trepanation methods

Of the four types of trepanation methods identified among Andean skeletal collections (linear cutting, circular grooving, scraping, and boring [Verano, 2003b]), circular grooving and scraping predominated in this sample (108 of 109 perforations). With scraping, a wide section of bone was scraped away on the ectocranial surface along with a smaller area on the endocranial surface (see Fig. 3). In contrast, circular grooving involved the removal of a round plug of bone through circular or ovoid incisions. These two methods can be difficult to differentiate (particularly in healed trepanations), as both techniques often resulted in external beveling to the trepanation margin. In those cases clearly resulting from the scraping method, the amount of scraping varied; some showed a small area of scraping surrounding the perforation, while in other cases a much larger area of scraped bone encircled a smaller perforation. This variation is seen in the wide range of dimensions recorded, with regions of scraping ranging from 1.2 to 8.99 cm in diameter.

The only other method of trepanation observed was linear cutting (also called crosscut sawing or rectangular intersecting incisions [Lisowski, 1967; Buikstra and Ubelaker, 1994]). This method was observed in an old adult (46+ years) Inca female from Kanamarca, discovered with a clump of unusual organic material over the trepanned area. (Analysis of the composition of this material is pending.) When the material was removed, the trepanation appeared as a rectangular incision with the excised piece of bone reinserted into the cranium.

Fig. 1. Map of Cuzco sites. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

TABLE 2. Number of trepanations per cranium

Trepanation count per individual	No. of individuals	Total no. of perforations
1	40	40
2	15	30
3	8	24
4	2	8
7	1	7
Total	66	109

Fig. 2. Individual with seven trepanations. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Fig. 3. Healed circular trepanation with remodeled area of scraping surrounding perforation. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Fig. 4. Rectangular incised trepanation (unhealed). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Around the trepanation margin and on the excised piece of bone, cutmarks remained as evidence of the sawing method used (Figs. 4 and 5). These cutmarks did not show signs of healing such as remodeling or reactive bone, leading to the conclusion that the individual did not survive the trepanation procedure.

Shape, size, and location

The trepanations varied in shape and size, with 67 circular, 41 oval or irregularly circular, and one rectangular. The circular diameters ranged from 0.20 to 6.0 cm, with an average of 2.21 cm. The oval dimensions varied from 0.28 to 7.34 cm (anterior–posterior) and 1.68 to 5.25 cm (medial–lateral). The lone rectangular dimensions were 3.98 cm (anterior–posterior) by 3.90 cm

Fig. 5. Excised bone from trepanation with cutmarks. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

TABLE 3. Area of trepanation by time period (in cm^2)

Temporal period	No. of trepanations	Mean	Std. Dev.	Min	Max
Late Intermediate Period	6	5.784	2.827	2.8491	8.699
Early Inca	59	3.448	4.185	0.032	21.010
Late Horizon	44	8.256[a]	8.542	0.073	28.274
Total	109	5.513	6.702	0.032	28.274

[a] Difference between Early Inca and Late Horizon means is statistically significant ($P \leq 0.001$).

TABLE 4. Distribution of trepanations by cranial region

Cranial region	Number of trepanations	Percent of total sample (%)
Left side—anterior	12	11
Left side—posterior	18	16.5
Midline section—anterior	35	32.1
Midline section—posterior	31	28.5
Right side—anterior	6	5.5
Right side—posterior	7	6.4
Total	109	100

(medial–lateral). Based on all of these dimensions, trepanation area was calculated by time period (Table 3).

These results show the largest area of trepanation in the Late Horizon group compared to earlier groups (Table 3), even though a general trend towards reduction of trepanation size over time has been documented in samples from all prehistoric periods in Peru (Verano, 2003b). In addition, the Late Horizon group exhibits the highest standard deviation in trepanation area. A single factor ANOVA test indicates that the observed difference in average area is highly statistically significant ($SS = 582.929$; $df = 2$; $MS = 291.465$; $F = 7.256$; $P \leq 0.001$), with the mean difference between the Early Inca and Late Horizon groups responsible for the majority of the variance (*Post hoc* Tukey's HSD test: Mean difference = 4.80796; $SE = 1.26248$; $P \leq 0.001$).

Certain cranial regions were preferentially chosen as surgery sites. The midline and left side of the cranium had the highest number of trepanations, with 66 and 30 perforations, respectively (Table 4). In contrast, the right side of the cranium was chosen for only 13 of the 109 trepanations (12%). The primary bone selected was the

Fig. 6. Healed oval trepanation with extensive remodeling and rounded margins. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

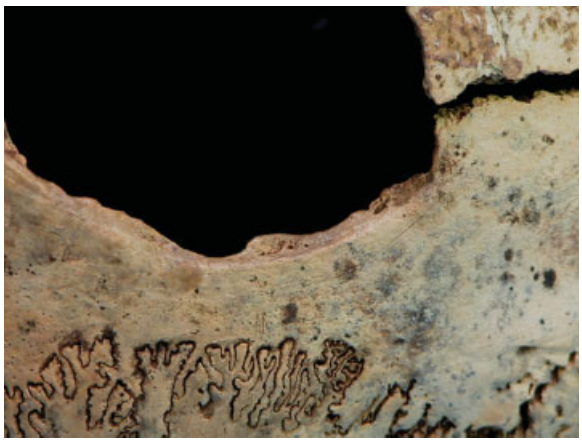

Fig. 7. Unhealed trepanation showing exposed diploë and cutmark inferior to trepanation margin. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Fig. 8. Unhealed trepanation by circular cutting with cutmark present. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Fig. 9. Unhealed trepanation with fractured inferior border. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

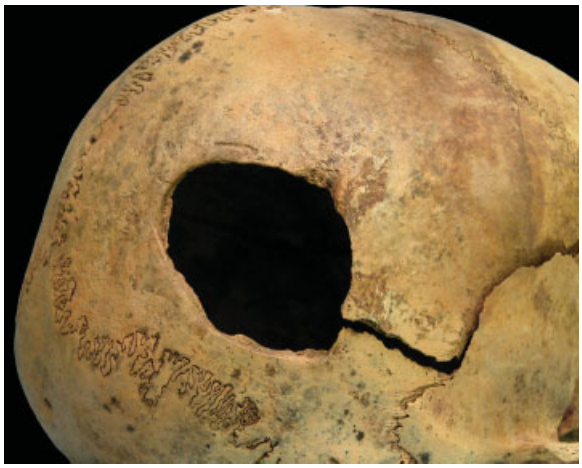

Fig. 10. Large unhealed trepanation with radiating fracture line. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

parietal (79 cases), followed by the frontal (24 cases) and the occipital (6 cases), while no trepanations were found on the temporal bones. In the majority of cases (89%), the cranial musculature was circumvented, with only 12 instances (11%) of inferred impact to the temporal or nuchal muscular regions. Sixty-five trepanations (60%) did not impact the sutures, while 44 trepanations (40%) crossed at least one suture line.

Healing, infection, and trauma

The degree of healing was separated into three categories: 1) no healing, such as the sole rectangular trepanation described earlier, 2) short-term healing, with osteoclastic activity surrounding areas of necrotic bone, and 3) long-term healing, with extensive remodeling and rounding of margins (Verano, 2003b). The third category comprised the majority of cases, with long-term healing documented in 89 instances for an overall survival rate of 83% (see Fig. 6). By contrast, short-term healing was seen in only one case, and no healing was seen in 19 cases (Figs. 7 and 8).

Degree of healing appears to relate to the location of the trepanation, in that trepanations located on regions of cranial musculature more often resulted in death. Although 26.3% of perimortem trepanations showed inferred impact to musculature, only 7.8% of healed trepanations impacted the muscular regions of the cranium. This difference is statistically significant ($\chi^2 = 5.503$; $df = 1$; $P = 0.019$). In contrast, sutural involvement does not appear to have influenced survival, since no statistical correlation exists between impact to sutures and perimortem trepanation ($\chi^2 = 0.029$; $df = 1$; $P = 0.865$).

Infection immediately adjacent to the trepanned area, apparent as additional bony deposits, occurred in only three individuals (4.5%). In two of these cases, the inflammation was only partially healed at the time of death, while in the third case the infected region showed long-term healing.

Cranial trauma retains a highly significant statistical correlation with trepanation ($\chi^2 = 29.13$; $df = 1$; $P \leq 0.0001$), as 29 individuals in the trepanned sample (44%) showed evidence of cranial trauma. In five of these cases, the injury involved perimortem fracture and/or radiating fracture lines adjacent to the trepanation site (Figs. 9 and 10). Two other individuals displayed large healed fractures abutting the margin of the healed trepanation. The remaining injuries—relatively small and shallow—were healed cranial fractures away from the trepanation site.

Another condition seen in trepanned individuals was mastoiditis, an infection caused by inner ear inflammation that can lead to earaches, headaches, swelling, and fever. However, this condition was found in only three trepanned individuals, and the statistical relationship lacks significance (Fisher's exact, $P = 0.481$).

Demography

The sex distribution of trepanned individuals was 35 males, 19 females, and 12 of indeterminate sex—an overrepresentation of males (male/female ratio of 1.84:1) that is statistically significant ($\chi^2 = 4.20$; $df = 1$; $P = 0.041$).

Apparent in the age distribution of trepanned individuals are two salient characteristics. First, there is a statistically significant under-representation of juveniles in the entire sample (Fisher's exact, $P = 0.024$), with only one trepanned juvenile, a 7- to 8-year-old from Chokepukio (Table 5). Second, adolescents and young adults (15 to 25-years-old) were far more likely to have perimortem trepanations than middle adults and old adults (26- to 46+-years-old). Almost 70% of the adolescents and young adults in the trepanned sample had a perimortem trepanation, compared to only 17% of middle and old adults—a highly statistically significant difference (Fisher's exact, $P = 0.001$). This difference in prevalence of perimortem trepanations by age group may reflect the age at which most individuals were trepanned: while healed trepanations could have been received many years before an individual's death, an unhealed trepanation (by definition) occurred near the time of death. These results suggest that trepanations were most often performed on adolescents and young adults and were not practiced on very young children—results that would be expected if trepanation were used to treat traumatic injuries (see Discussion). The rarity of trepanations in children is supported by Verano's study of 161 trepanned skulls from various Cuzco area sites, in which only a single

TABLE 5. Age distribution of trepanned individuals vs. nontrepanned individuals

Age	Number of trepanned individuals	Percent of trepanned sample (%)	Number of nontrepanned individuals	Percent of nontrepanned sample (%)
Juvenile (5–15 years)	1	1.5	47	13.6
Adolescent (16–17 years)	3	4.5	13	3.8
Young adult (18–25 years)	9	13	37	10.7
Middle adult (26–45 years)	33	50	139	40.2
Old adult (46+ years)	13	20	35	10.2
Adult other (age range indeterminate)	7	11	74	21.5
Total	66	100	345	100

case of a trepanned child was found (Verano, unpublished data).

Geographic and temporal distribution

To understand the geographic distribution of trepanation, the six sites with trepanation were compared to the other five Cuzco sites (analyzed in Andrushko [2007]) that did not contain trepanned individuals: Sacsahuaman, Kusicancha, Machu Picchu, Wata, and Qhataqasapatallacta (see Fig. 1). In the entire Cuzco sample of eleven sites, there are four sites from the core region of the Inca Empire and seven from the periphery; for the trepanation subset, there is one core site and five periphery sites, a distribution that is not significantly different from the entire sample. This geographic distribution indicates that trepanation was not restricted to the core region, but rather flourished in the periphery sites around the Inca capital.

The temporal distribution of trepanation suggests a later emergence in Cuzco than in other Andean regions, where trepanation was practiced as early as 400 BC (Verano, 2003b). This delay is apparent in the lack of trepanned individuals from the Early Intermediate Period and the Middle Horizon (200 BC–AD 1000). From the ensuing Late Intermediate Period (LIP, AD 1000–1400), three individuals were seen with trepanations from Chokepukio and Cotocotuyoc. Subsequently, one individual was loosely dated through associations to the LIP/Early Inca period from Aqnapampa. Following in the temporal sequence were the 33 Qotakalli individuals that dated to the late LIP/Early Inca period (AD 1290–1420) based on radiocarbon dates of nearby human skeletal remains associated with the trepanned individuals. The remaining 29 individuals date to the Inca occupation of the Cuzco region (AD 1400–1532) from the sites of Colmay, Kanamarca, Chokepukio, and Qotakalli. This temporal distribution accords with other findings from the Cuzco region, where little evidence of trepanation has been found prior to the LIP apart from one Middle Horizon cranium at Pikillacta (McEwan, 1987).

A second temporal pattern emerges in the rate of survival, which was lowest in the early trepanation cases from Cuzco but increased over time. The survival rate for the LIP individuals was 33%; however, in the subsequent late LIP/early Inca period, the survival rate improved to 90%—a highly statistically significant increase (Fisher's exact, $P = 0.004$). In the Late Horizon, the survival rate decreased slightly to 80%, yet this change is not statistically significant ($\chi^2 = 2.143$; $df = 1$; $P = 0.143$).

DISCUSSION

Trepanation and medical treatment in prehistoric Cuzco

The results of this study indicate that a successful trepanation practice developed over time in the Cuzco region, with a high survival rate and few ensuing infections. This high survival rate corroborates observations from Verano's study (2003b), which found a long-term healing percentage of 78.1% in the southern highlands around Cuzco, compared to 43.6% in the central highlands and 36.2% in the south coast. The Cuzco survival rate may have been improved by limiting bacterial infection after trepanation through the use of antiseptics such as balsam, saponins, cinnamic acid, and tannin (MacCurdy, 1923).

The results further suggest that Inca medical practitioners had an in-depth knowledge of cranial anatomy, perhaps acquired through apprenticeships with experienced skull surgeons, as has been documented in other traditional societies where trepanation is still practiced (Furnas et al., 1985). Trepanations were placed in cranial regions that avoided musculature and other vulnerable areas of the skull, apparent in the rarity of trepanations on the nuchal planum of the occipital bone and the complete absence of trepanations on the temporal bones. Surgeons also appear to have avoided cutting the meningeal vessels and underlying dura, which would have resulted in higher rates of infection and increased fatalities from hemorrhaging. In the event of hemorrhage of superficial vessels, circular tourniquets may have been used to control blood loss (Oakley et al., 1959), although there is no direct archaeological evidence for this.

Cuzco medical practitioners also apparently standardized their methods of trepanation. Of the four types of trepanation methods identified among Andean skeletal collections, the circular grooving and scraping methods were used for all but one of the Cuzco trepanations in this sample. The scraping method probably presented a slower, more subtle method that dissipated forces over a larger area of the skull while also avoiding forceful penetration of the inner table and tearing of the meninges—contributing to improved healing and survival. Also, the Inca likely used tools such as obsidian knives and metal *tumi* blades to achieve precise grooving and scraping (Marino and Gonzales-Portillo, 2000). Unfortunately, it is still unknown which specific tools were used to trepan Inca skulls, although some modern surgical experiments have been done in Peru using actual *tumi* knives from museum collections. These experiments demonstrated

that *tumis*—semicircular blades made of gold, silver, copper, or bronze—are effective scalp-cutting tools, but are not useful for cutting through bone. Smaller chisel-like tools, when struck with a hammer, proved capable of perforating the skulls of patients and allowing a disc of bone to be removed (Lastres, 1951; Graña et al., 1954).

Although the Cuzco practitioners seemed to rely on a standardized set of trepanation practices, methods in other regions varied. In the Chachapoya region of northern Peru, Nystrom (2007) documented circular grooving and boring trepanations, and suggested that the circular grooving technique contributed to a higher survival rate. Verano's (2003b) study found a range of techniques used throughout the Andes, with scraping representing the earliest adopted method, linear cutting being the most common in the central highlands, and circular grooving developing in the southern highlands during the Late Horizon.

Motivations for trepanation

Scholars have searched for the rationale for trepanation since Squier's initial discovery in 1865. Proposed explanations have included treatments for cranial trauma, epilepsy, and nonepileptic seizure disorders (Clower and Finger, 2001), as well as for mastoiditis and cultural purposes.

The cranial trauma hypothesis was advanced early on by physician J.C. Nott, who believed that puncture wounds, causing fluid build-up and inflammation, required surgical intervention. He found that the removal of bone fragments through trepanation, and subsequent release of fluid build-up, relieved seizures due to trauma (Finger and Clower, 2001). Nott dismissed the argument that trepanned skulls often lacked accompanying injury by noting that the trepanation surgery could remove evidence of trauma (Finger and Fernando, 2001). Nott's argument found support from anthropologist George MacCurdy, who asserted that trepanation often obliterated indications of fracture, based on his analysis of prehistoric Peruvian skulls (MacCurdy, 1923).

Because trepanation proved effective for treating trauma-related seizures, practitioners may have also attempted trepanation to treat epileptic seizures, despite an inability to alleviate symptoms stemming from this cause. Accounts of epilepsy among the Inca are found in the Spanish chronicles of Garcilaso de la Vega and Guaman Poma, the latter of which contains a depiction of Emperor Capac Yupanqui's wife suffering from a seizure (Guaman Poma de Ayala, 1936 [1615]; Burneo, 2003). Despite this known presence of epilepsy, it is unclear whether the Inca used trepanation in an attempt to treat the condition, as no mention of trepanation was made in the Spanish chronicles.

Other researchers have advanced nonepileptic seizure disorders as a reason for trepanation. The seizure disorder hypothesis was championed by Paul Broca, noted French physician, anatomist, and anthropologist. Broca believed that seizure disorders in childhood, brought on by rapid fever spikes or teething episodes, provided the impetus for prehistoric trepanation (Clower and Finger, 2001). He attributed healed trepanations in adults to surgeries performed early in life, possibly during infancy. However, Broca failed to find evidence of infant trepanations to support his theory, casting doubt on the seizure disorder hypothesis.

Another potential explanation for trepanation is mastoiditis, an infection of the mastoid bone due to inner ear inflammation. As a chronically painful condition with no externally visible cause, mastoiditis may have prompted surgical intervention to alleviate patient discomfort. Mastoiditis was suggested as a motivation for trepanation by Oakley et al. (1959). In addition, Mann (1991) attributes one case of a Peruvian trepanation to a chronic ear infection.

Of other possible reasons for trepanation, cultural and magico-religious purposes have been proposed since the earliest discovery of trepanation. Such explanations were often advanced by individuals who shunned medical justifications for trepanation. One individual was Sir Francis Galton, the renowned nineteenth-century eugenicist, who believed that prehistoric civilizations could not comprehend the medical benefits of trepanation, for this would have "... implied more intelligence than savages usually shewed [sic]" (Finger and Clower, 2001:915). However, Galton's assertion has been contradicted by mounting evidence throughout the last century.

Among all these possible explanations, the Cuzco study results support the cranial trauma hypothesis. The trepanation data show a strong correlation with cranial trauma, seen in 29 individuals (44%). Seven of these individuals exhibited perimortem and/or healed fractures adjacent to the trepanation site and therefore provide direct evidence for trepanation performed to treat skull fracture. The other 22 individuals—with cranial injuries away from the trepanation site—instead provide indirect evidence for the cranial trauma hypothesis, since trepanation surgery can obliterate evidence of injury by removing the area of fractured bone (Verano, 2003b). Consequently, such fractures may have occurred at an even higher prevalence among trepanned individuals. Altogether, the Cuzco results accord with other Andean studies attributing cranial trauma as a major reason for trepanation (MacCurdy, 1923; Chege et al., 1996; Verano, 1997, 2003b).

These cranial injuries mostly likely resulted from violent conflict, based on osteological and demographic evidence. Osteological evidence shows that the patterning of Cuzco trepanations, with a tendency towards left-sided, anterior perforations, mirrors the patterning of cranial trauma (Andrushko, 2007). This left-sided, anterior pattern appears frequently in studies of trauma and trepanation (Jørgensen, 1988; Verano, 2003b) and is often attributed to face-to-face combat with a right-handed opponent (MacCurdy, 1923; Stewart, 1958; Standen and Arriaza, 2000; Torres-Rouff and Costa Junqueira, 2006; Tung, 2007). The demographic data from the Cuzco trepanation sample further reveal an overrepresentation of adult males, the segment of society most often involved in warfare and interpersonal aggression (Lambert, 1994; Walker, 2001). Because adult males were more likely to suffer from cranial fractures, they were also more likely to require trepanation surgery to treat subsequent symptoms. Based on these combined data, cranial trauma due to violent conflict appears to be an impetus for performing trepanations in the Cuzco sample.

Finally, trepanation to treat the condition of mastoiditis appears as another possible explanation. In this study, three trepanned individuals showed evidence of mastoiditis, though no statistically significant relationship could be drawn between the two conditions. Oakley et al. (1959) report a case of mastoiditis in a trepanned individual and comment that "... this seems to be a clear

case of an operation undertaken for medical rather than ritual purposes, for there is definite evidence of mastoid inflammation, with a perforation through to the external auditory meatus" (1959:95). This anecdotal report from Oakley et al. (1959), along with the three Cuzco cases, suggests a possible connection between trepanation and mastoiditis that may be explored in future studies.

CONCLUSIONS

The present study evaluates two main hypotheses regarding trepanation among prehistoric groups in Cuzco, Peru: 1) Trepanations in the Cuzco region were carried out as a medical treatment rather than for cultural purposes; and, if so, 2) The rise of the Inca Empire—and consequent medical advances—resulted in increased survival rates for trepanned individuals.

Regarding the first hypothesis, the study results do indeed provide evidence that trepanation was used as a medical treatment, primarily for symptoms relating to cranial trauma. Such findings corroborate other Andean studies attributing cranial trauma as a primary impetus for trepanation. In addition, the demographic profile reveals an over-representation of adult males and a paucity of juveniles. This profile lends further credence to the cranial trauma hypothesis by suggesting that the individuals most likely to engage in conflict were also most likely to receive trepanations.

The second hypothesis is also supported by the study results: trepanation practices reached a high degree of success during the Late Horizon in the southern highlands of Peru near Cuzco, as evident by crania with multiple, well-healed perforations. The trepanation survival rate reached 90% at one point and was accompanied by a low frequency of infection (4.5%). This high survival rate suggests that skill and mastery were achieved by trepanation practitioners.

The impressive survival rate was, in addition, likely aided by the development of a precise, standardized trepanation procedure. Our analysis produced a demonstrable pattern with trepanations predominantly located on the midline and left side of the skull. Specific bones of the cranium were also targeted, with a preference for the frontal and parietals over the occipital and temporal bones. Meanwhile, certain areas of cranial musculature were avoided, likely to facilitate cerebral access and to circumvent areas with a high risk of bleeding and other complications. This pattern also includes the predominant use of the circular scraping and grooving methods, which produced perforations with an average area of 5.5 cm^2, surrounded in some cases by a larger region of scraped ectocranial surface.

Altogether, this analysis demonstrates that trepanation was an important medical treatment in the Cuzco region, carried out with precision and knowledge of cranial anatomy. Trepanation was also practiced with some frequency: combining the present sample (109 perforations in 66 individuals) with the various museum samples documented by Verano (unpublished data) (227 perforations in 161 individuals), it is clear that the Cuzco region was a major center for trepanation in late Prehispanic Peru.

ACKNOWLEDGMENTS

The first author gratefully acknowledges the support of the Wenner-Gren Foundation and the National Science Foundation, and the assistance of the following individuals: Gordon McEwan, Viviana Bellifemine, Elva Torres, Kenneth Nystrom, Kenneth Maes, Nicholas Tripcevich, Christopher Milan, and Deborah Andrushko. Verano's museum research in Lima was supported by a lectureship from the Council for the International Exchange of Scholars (Fulbright Commission), and in Cuzco by the Research Opportunities Fund of the National Museum of Natural History, Smithsonian Institution, and the Roger Thayer Stone Center for Latin American Studies at Tulane University. Mellisa Lund Valle of Peru's National Museum of Anthropology, Archaeology, and History kindly assisted with data collection in Cuzco in 2002. Verano's data analysis and library research were made possible by a 2006–2007 fellowship in Pre-Columbian Studies at Dumbarton Oaks Research Library and Collections, Washington, D.C. For their insight and extremely useful comments, the authors gratefully acknowledge Christopher Ruff, Lori Wright, Tiffiny Tung, and one anonymous reviewer.

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