ARSENIASIS AND TERATOGENIC ANOMALIES IN THE ATACAMA DESERT COAST OF ANCIENT CHILE

Christine E. Boston and Bernardo T. Arriaza

SUMMARY

The model that chronic arsenic (As) exposure causes many teratogenic consequences is tested. Ancient northern Chilean populations appear to be optimal to undertake such a study as these populations are believed to have been largely stationary and ingested significant As levels over time. The Camarones River water, along the Atacama Desert, has extreme As values, 100 times above the norm. We tested the hypothesis that ancient populations, starting with the Chinchorro culture, 5000 years B.C., were significantly affected by this heavy metal and massive arsenic contamination played a role in the origin of Chinchorro artificial mummification practices. We examined 199 skeletons, housed at the Museo Arqueológico San Miguel de Azapa, Universidad de Tarapacá, Arica, Chile, searching for seven teratogenic related pathological conditions: cleft palate, polydactyly, syndactyly, spina bifida, club foot, eye malformations, and hip joint dislocation. Of the seven pathological conditions under assessment, only spina bifida was clearly found in the surveyed sample. Thus, the As teratogenic hypothesis cannot be fully demonstrated. However, the presence of spina bifida in the three valleys suggests a genetic-environmental interplay within the populations. The endemic presence of As in both the Chinchorro mummies and their material culture do strongly support the As hypothesis as a valid explanation for why the Chinchorro first began to anthropogenically mummify their dead.

Introduction

The Chinchorro were specialized fishermen who resided on the coastal deserts of southern Peru and northern Chile from 7020 to 1110 B.C. (Standen *et al*., 2004; Arriaza *et al*., 2008). Their material culture is characterized by a variety of fishing technologies, utilitarian items, and semipermanent house structures fashioned out of stone and vegetal matter (Rothhammer, 1990; Standen, 1997; Standen, *et al*., 2004; Arriaza *et al*., 2008). The Chinchorro also produced the world's oldest anthropogenic mummies (Arriaza, 1995; Standen *et al*., 2004; Arriaza *et al*., 2008).

The origins of the Chinchorro mummification practices remain unknown, and several different hypotheses on these origins exist. They include the Spiritual Concerns, Environmental Factors, and Adoration of Children hypotheses (Arriaza, 1995, 2005; Arriaza *et al*., 2008). The Spiritual Concerns and Environmental Factors hypotheses posit spiritual and environmental motivations for the

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ARSENICISMO Y ANOMALÍAS TERATÓGENAS EN LA COSTA DEL DESIERTO DE ATACAMA EN CHILE PREHISPÁNICO

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RESUMEN

En este trabajo se evalúa el modelo que la exposición crónica al arsénico (As) juega un rol importante en el desarrollo de anomalías teratógenas. Las poblaciones ancestrales del norte de Chile son adecuadas para ello, ya que por varios milenios han estado expuestas a cantidades importantes del elemento y tienen continuidad biocultural. El agua del río de Camarones, en el Desierto de Atacama, contiene niveles de As muy elevados, 100 veces lo recomendado por normas internacionales, por lo cual se testeó la hipótesis que los primeros habitantes de esta zona, los Chinchorros, estaban afectados por este metal a partir del 5000 A.C. y que el mismo influyó en el origen de complejas prácticas de momificación. Fueron examinados 199 esqueletos del Museo Arqueológico San Miguel de Azapa, Universidad de Tarapacá, Arica, Chile, buscando evidencias de siete patologías supuestamente teratógenas y relacionadas al As: labio leporino, polidactilia, sindactilia, espina bífida, pie equino, deformaciones de los ojos y dislocación de la cadera. Los hallazgos revelan que el impacto del As varía regionalmente y que las poblaciones del valle de Camarones tuvieron mayores frecuencias de lesiones a la piel y espina bífida. Los datos no avalan la hipótesis teratógena, ya que solo se encontró espina bífida en las poblaciones estudiadas. Sin embargo, la presencia de espina bífida en los tres valles muestreados implica una compleja interacción genética y medioambiental. La presencia endémica del As en las momias y en su cultura material refuerza la hipótesis del As para explicar el surgimiento de la compleja momificación artificial en poblaciones Chinchorro.

ARSENICISMO Y ANOMALIAS TERATÓGENAS EM POPULAÇÕES DA COSTA DO DESERTO DE ATACAMA NO CHILE PREHISPÁNICO

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RESUMO

Neste trabalho foi avaliado o modelo de que a exposição crônica ao arsênico ("As") desempenha um papel importante no desenvolvimento de anomalias teratógenas. As populações ancestrais do norte do Chile são adequadas para isso, já que por vários milênios têm estado expostas a quantidades importantes do elemento e têm continuidade biocultural. A água do rio de Camarones, no Deserto de Atacama, contêm níveis de "As" muito elevados, 100 vezes o recomendado por normas internacionais, pelo qual foi testada a hipótese de que os primeiros habitantes desta zona, os Chinchorros, tinham sido afetados por este metal a partir de 5000 A.C. e que o mesmo influiu na origem de complexas práticas de mumificação. Foram examinados 199 esqueletos do Museu Arqueológico San Miguel de Azapa, Universidade de Tarapacá, Arica, Chile, procurando por evidências de sete patologias supostamente teratógenas e relacionadas ao "As": lábio leporino, polidactilia, sindactilia, espinha bífida, pé equino, deformações dos olhos e deslocamento da cadeira. Os achados revelan que o impacto do "As" varia regionalmente e que as populações do vale de Camarones tiveram maiores frequências de lessões na pele e espinha bífida. Os dados não validam a hipótese teratógena, já que somente achou-se espinha bífida nas populações estudadas. No entanto, a presença de espinha bífida nos três vales amostrados implica uma complexa interação genética e meio-ambiental. A presença endêmica do "As" nas múmias e em sua cultura material reforça a hipótese do "As" para explicar o aparecimento da complexa mumificação artificial em populações Chinchorro.

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origination of these practices. The Adoration of Children hypothesis puts forward the idea that the Chinchorro began their mummification practices as a means of assuaging community grief caused by the heavy loss of children, particularly newborns (Schiappacasse and Niemeyer, 1984; Arriaza, 1995; Arriaza *et al*., 2001).

There was, however, no adequate explanation for this high infant mortality rate until recently. The Arsenic hypothesis accounted for this mortality rate as it could be associated with the consumption of naturally occurring As endemic to the region (Arriaza, 2005). Arsenic exposure is associated with causing several deleterious effects to humans, but these are poorly understood and imprecisely known at this time, especially concerning the teratogenic consequences of As exposure (Schoen *et al*., 2004). The purpose of this paper is to explore the possibilities of the Arsenic hypothesis through a paleopathologic analysis, as well as test models concerning the teratogenic consequences of As exposure.

Arsenic Literature Review

Arsenic is a heavy metal ubiquitous in the earth's crust found in varying concentrations around the world (Hsueh *et al*., 1998; Mandal *et al*., 2004). Two types of As exist both naturally and anthropogenically: organic and inorganic (Figueroa, 2001; Hughes, 2002). Organic As (e.g. arsenobetaine and arsenosugars) is found in different types of marine resources such as fish, bivalves, and seaweed; inorganic As (e.g. arsenate and arsenite) is found in contaminated water, soil, air, plants, pesticides, medicines, etc. (Concha *et al*., 1998a, b; Figueroa, 2001; Hall, 2002; Lai *et al*., 2004; Waalkes *et al*., 2003). The chemical forms of As determine its toxicity to humans (Mandal *et al*., 2004). Organic As is considered nontoxic to humans, but inorganic As is considered extremely toxic (Figueroa, 2001; Hall, 2002; Lai *et al*., 2004; Mandal *et al*., 2004; Wanibuchi *et al*., 2004).

Arsenic exposure occurs usually from the consumption of contaminated water or foods or through inhalation at the work place (Figueroa, 2001; Hsueh *et al*., 1998; Mandal *et al*., 2004; Sun, 2004; Watanabe *et al*., 2004). Arsenic exposure can also occur in uterus. Several studies have established that As is readily passed through the placental walls to the developing fetus, although at dramatically reduced rates as compared to the mother's exposure levels (Concha *et al*., 1998a; Fangstrom *et al*., 2008). Also, up to 10% of As consumed by the mother can enter the breast milk, increasing exposure amongst infants (Concha *et al*., 1998b; Ratnaike, 2003; Fangstrom *et al*., 2008).

Arsenic is metabolized through a methylization process. Arsenic methylization can increase the toxicity of As through breaking it down into dispersed, smaller, but highly toxic compounds (Styblo *et al*., 2000; Aposhian *et al*., 2004; Mandal *et al*., 2004; Thomas *et al*., 2004; Wanibuchi *et al*., 2004). Methylization successfully removes the majority of the As from the body, but this is relative to the amount consumed, length of exposure, nutritional status, age of the individual, and genetics (Chowdhury *et al*., 2000; Hughes, 2002; Lai *et al*., 2004; Mandal *et al*., 2004; Schoen *et al*., 2004; Fangstrom *et al*., 2008). Arsenic which is not removed from the body is stored in various hard and soft tissues and can disrupt the normal bodily functions (Hseuh *et al*., 1998; Vahter and Concha, 2001; Mandal *et al*., 2004; Suzuki *et al*., 2004). Chronic As exposure is associated with an assortment of pathological conditions, including internal organ cancers, skin lesions, birth defects, still births, spontaneous abortions, underweight infants, and more (Hopenhayn-Rich *et al*., 2000; Mazumder *et al*., 2000; Smith *et al*. 2000; Ahmad *et al*., 2001; Figueroa, 2001; Hughes, 2002; Hopenhayn *et al*., 2003; Yoshida *et al*., 2004).

In uterus, As exposure is also associated with a number of birth malformations, including cleft lip and palate, polydactyly, syndactyly, spina bifida, club foot, eye malformations, and hip joint dislocation (Nordstrom *et al*., 1979). These malformations were discovered in newborns from mothers exposed during their tenure at a factory with high As use, but further testing of in uterus As exposure has failed to show similar results (DeSesso *et al*., 1998; Hopenhayn-Rich *et al*., 2000; Hopenhayn *et al*., 2003; Milton *et al*., 2005; Rahman *et al*., 2007; Fangstrom *et al*., 2008). Only animal studies (Holson *et al*., 2000), have produced similar results as that seen Nordstrom *et al*., (1979), but animal studies as proxies for humans is scrutinized due to differential levels of As exposure and toxicity between animals and humans (Aposhian, 1997; DeSesso *et al*., 1998; Vahter and Concha, 2001; Hughes, 2002; Schoen *et al*., 2004). Scholars have called for further research to be conducted to elucidate the inherent consequences occurring from acute and chronic exposure. It is known, however that there is a direct correlation between numbers of years living in an As contaminated area and its accumulation in the body.

The Arsenic Hypothesis

The northern Chilean environment presents arsenic levels that far exceed the World Health Organization's (WHO) designated safe levels: 10-50$\mu g \cdot l^{-1}$ (Chowdhury *et al*., 2000; Ratnaike, 2003; Schoen *et al*., 2004; Tchounwou *et al*., 2004). The Camarones River has arsenic levels of 1000$\mu g \cdot l^{-1}$, the Lluta River has levels of 200$\mu g \cdot l^{-1}$, and the San José River has levels of 50$\mu g \cdot l^{-1}$ (Figueroa, 2001; Arriaza, 2005). Today's technology makes the water safe for consumption, alleviating modern populations from the environmental stress of the region, but ancient populations were adversely affected by the arsenic in the region. Inca period mummies from the Camarones Valley exhibited arsenic related cancers and high levels of As in their soft tissues (Figueroa *et al*., 1988). A follow up study on pre-Columbian mummies from the Camarones Valley concluded that 100% of the studied sample exhibited As related lesions (Figueroa *et al*., 1992). Another study of their material culture showed the presence of As in these materials, further suggesting that the ancient Camarones people suffered from As exposure (Figueroa, 2001). Also, evidence suggests that the Chinchorro, the earliest inhabitants of the Camarones Valley, had a high infant mortality rate, and analysis of Chinchorro statuette mummies determined that they represent mummies of involuntarily aborted fetuses (Schiappacasse and Niemeyer, 1984; Arriaza *et al*., 2001). Arriaza has since supposed these occurrences were linked to As poisoning and proposed the Arsenic hypothesis.

Further evidence to support the Arsenic hypothesis is difficult to collect and assess based on current models of As toxicity. Chinchorro morticians removed internal organs during mummification, thus scholars are unable to study As related pathological conditions, such as cancers (Arriaza, 1995). Furthermore, arsenical skin lesions can manifest at low exposure levels, making these poor indicators of detrimental As toxicity which could support the Arsenic hypothesis. This leaves osteological analyses as an alternative means of investigation.

An osteological analysis of teratogenic pathological conditions associated with As exposure was undertaken in order to investigate the Arsenic hypothesis and to test the teratogenic effects of ar-

TABLE I
NUMBER OF INDIVIDUALS IN THE SAMPLE DIVIDED BY AGE AND SEX

Sites	Cultural Phase	Dates	Number of Subadults	Number of Adults	Adult Males	Adult Females	Indeterminate Adults
Morro 1 (N=44)	Chinchorro	Ca. 4500-1700 B.C.	14	30	13	13	4
Morro 1-6 (N=33)	Chinchorro	Ca. 2360-1610 B.C.	3	30	15	15	1
Camarones 15D (N=10)	Chinchorro	Ca. 2290-1000 B.C.	0	10	4	6	0
Quiani 7 (N=8)	Quiani	Ca. 1500-1300 B.C.	3	5	4	1	0
Cam 15 (N=22)	Faldas del Morro	Ca. 1000-800 B.C.	1	21	8	10	3
Morro 1-6 Sec D (N=15)	Faldas del Morro		6	9	2	7	0
Camarones 8 (N=20)	Gentilar	Ca. A.D. 1100- 1470	8	12	4	7	1
Camarones 9 (N=25)	Inca	Ca. A.D. 1400-1500	18	7	3	4	0
Lluta 54 (N=22)	Inca	Ca. A.D. 1400-1500	13	9	6	2	1
Total (199)			66	133	59	65	10

senic on ancient populations exposed to toxic levels. The northern Chilean populations appear to be optimal populations for the study of this latter area of investigation as these populations are believed to have been largely stationary and ingested significant levels of As over time (Figueroa, 2001; Sutter and Mertz, 2004; Sutter, 2006). These criteria match those suggested by previous work indicating that they must be met so as to identify the exact effects of As exposure (Tchounwou *et al.*, 2004).

Materials and Methods

A large geographical and temporal sample was used for this study. It included 199 adult and subadult individuals from the Chinchorro (n=87), Quiani (n=8), Faldas del Morro (n=37), Gentilar (n=20), and Inca (n=47) cultures from the Azapa, Camarones, and Lluta Valleys in northern Chile (Table I). These collections are housed at the Museo Arqueológico San Miguel de Azapa (MASMA) of the University of Tarapacá, Chile. These cultural complexes represent a span of ~8500 years, and despite vast cultural differences, it appear that each valley specific-group was exposed to similar levels of As poisoning over time (Figueroa *et al.*, 1988, 1992; Figueroa, 2001).

All of the individuals employed in this work, with the exception of those from Lluta, came from coastal contexts. These coastal populations were specialized fishers who subsisted primarily on marine resources and supplemented their diets with terrestrial and agricultural products, although this is believed to have been minimal (Ramírez de Bryson *et al.*, 2001; Romero *et al.*, 2004; Rivera, 2008). These groups were chosen due to their geographical and dietary similarities to the Chinchorro, whose diets were mostly composed of marine resources (Aufderheide, 1993, 1996). This specialized diet would have also limited inorganic As exposure experienced by these populations which occurred primarily from consuming contaminated water and terrestrial resources. Marine resources are known to contain inorganic As, but this is considered least harmful to humans and therefore would not cause detrimental effects (Lai *et al.*, 2004).

The Lluta sample chosen was the only available osteological collection from the valley at the time of this analysis. The Lluta sample was an inland, agricultural population whose diet was vastly different from the remainder of the sample.

Individuals were sexed and aged according to methods outlined in Buikstra and Ubelaker (1994). Pelvic and cranial sexing methods were employed for adults, although the pelvic assessment was given greater weight. Sex determinations for subadults were not completed as there are no accurate sex determination methods for subadults (Sutter, 2003). Age at death determinations between adults and subadults were done separately, with the pubic symphysis methods conducted for adults while dental calcification methods were conducted for subadults (Ubelaker, 1989; Moorrees *et al.*, 1963).

The osteological remains were also closely examined for supposed teratogenic arsenic-related lesions: cleft palate, polydactyly, syndactyly, spina bifida, club foot, eye malformations, and hip joint dislocation. It should be noted that while none of these pathological lesions are specifically or uniquely related to As poisoning; they are believed to suggest As poisoning when found together. There was an expectation that there would be an increased prevalence of these pathological lesions in those samples coming from As areas. All individuals, adult and subadult, were examined for the presence or absence of these lesions, even if the lesion was considered a condition of age.

Results

Of the seven pathological conditions under assessment, only one (spina bifida) was clearly found in the surveyed sample. Spina bifida was present in both adults and subadults from all three valleys. There were two definitive incidences of spina bifida in the Azapa Valley, four definitive and three possible incidences present in the Camarones Valley, and one possible incidence in the Lluta Valley. The possible incidences belonged to subadult individuals and can only be considered possible due to age dependent factors (Broome *et al.*, 1998). Because of this, the presence of these lesions in subadults is speculative.

Discussion and Final Remarks

It had been suggested that in order to understand the true toxicity of As a study would need to be conducted on stationary populations who consumed a set amount of As over an extended period of time (Tchounwou *et al.*, 2004). Ancient northern Chilean populations seemed to present an optimal case study to test the toxicity of As in human populations, particularly its teratogenic effects, as based on previous evidence which suggested that the exposure negatively affected populations in the region (Figueroa *et al.*, 1988, 1992; Schiappacasse and Niemeyer, 1984; Arriaza *et al.*, 2001). Thus, the present study examined As teratogenic pathological conditions in order to assess two hypotheses: the probability of As causing particular teratogenic effects as described by Nordstrom *et al.* (1979), and Arriaza´s Arsenic poisoning hypothesis as a means of explaining Chinchorro mummification practices. The results show only one definitive pathology, spina bifida. The presence of spina bifida in the three valleys suggests that As exposure may have been detrimental to these populations, but its presence in the Azapa Valley was unexpected. The presence of spina bifida in this valley is suggestive of a genetic-environmental interplay within the population. The Azapa Valley populations were expected to experience safe levels of As exposure and not exhibit arsenic-related pathological conditions (Chowdhury *et al.*, 2000; Ratnaike, 2003; Schoen *et al.*, 2004; Tchounwou *et al.*, 2004). The presence of spina bifida could be a hereditary condition, evidence that the Azapa populations experienced greater than expected As exposure, or that $50\mu g \cdot l^{-1}$ is not a safe level of exposure. In fact, today's health standards have been lowered to $10\mu g \cdot l^{-1}$. Environmental and genetic predisposition may explain why it was present in the Azapa sample (Aufderheide and Rodríquez-Martín, 1998; Ortner, 2003).

This may have also been the case within populations from the Camarones and Lluta Valleys. However, ancient mobility cannot be ruled out affecting residence patterns and environmentally induced pathology. In any case, the few cases presenting spina bifida suggests that As exposure *per se* does fully explain this condition. This is in agreement with modern populations exposed to similar As levels as those experienced by ancient Chilean populations that had not suffered the expected pathological and teratogenic trend (Hopenhayn-Rich *et al.*, 2000; Hopenhayn *et al.*, 2003; Milton *et al.*, 2005; Rahman *et al.*, 2007; Fangstrom *et al.*, 2008).

Several factors could potentially complicate the results of this analysis. First, the coastal populations had diets rich in marine resources and therefore consumed mostly organic As, which is not considered harmful to humans and may not cause the aforementioned arsenic-related conditions (Hall, 2002; Lai *et al.*, 2004). At this time, it is unclear how much and what type of As these populations were consuming. It could be that these populations were consuming inorganic As at levels that were not detrimental to them, but this is inconsistent with previous evidence that shows high infant mortality and arsenic-related soft tissue lesions existed within these populations (Schiappacasse and Niemeyer, 1984; Figueroa *et al*., 1988, 1992). Further study into inorganic As exposure within these populations is ongoing, but at present, and based on results and supporting evidence, it is concluded that the teratogenic model proposed by Nordstrom *et al*. (1979) is not supported, although further research is needed. However, it is felt that the previous evidence of high infant mortality, fetal representations of the Chinchorro statuette mummies, and presence of As in both the Chinchorro mummies and their material culture do strongly support the possibility of the Arsenic hypothesis as a valid explanation for why the Chinchorro first began to anthropogenically mummify their dead.

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