Radiologic Evaluation of the Llullaillaco Mummies

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OBJECTIVE. Our purpose was to determine the imaging findings in three 500-year-old frozen mummies of sacrificial Inca children.

MATERIALS AND METHODS. CT, conventional radiography, and dental radiography of Inca mummies were reviewed. Different techniques, which were adjusted to the anatomic position of the bodies, were used for radiologic analyses. Working sessions were limited to 20 min because of the fragility of these mummies and to prevent thawing of the specimens.

RESULTS. Internal organs in good condition with a natural shrinkage caused by dehydration were shown on CT scans. Both white and gray matter were clearly observed in the brain and cerebellum. The white matter and the fatty tissue of the bodies were visibly white. This condition was possibly caused by the transformation of the fatty tissue into a waxlike substance and the deposition of calcium salts. The lungs were expanded in all three mummies. The ages of the three children at the time of their deaths were estimated by means of radiographs of the teeth and long bones. Bone mineralization, the muscular volume, and the thickness of the adipose panniculus indicated the good nutritional state of the three Inca children. The spleen was not visualized in any case.

CONCLUSION. Radiology helped us determine the state of the internal organs, the nutritional conditions, and the physical abnormalities of the naturally mummified children. These mummies can be considered among the best preserved mummies currently known.

Three frozen bodies belonging to three children were found by an archaeological team led by two of the authors. The scientific excavation was carried out at an altitude of 6,739 m above sea level on the summit of Mount Llullaillaco in the northwestern Argentinean Andes at an average temperature of –15ºC. These children had been sacrificed 500 years ago in times of the Inca Empire to appease the mountain deities and to ensure the emperor's well-being. In addition, the mummies were buried with more than 100 objects, including textiles, gold and silver statues, pottery, and feathered headdresses.

The children had been buried in three pit tombs built by the Incas by enlarging natural niches in the bedrock at the summit shrine of Mount Llullaillaco, which is considered to be the highest archaeological site in the world [1]. The mummies were individually buried 1.7 m deep with their associated offerings. The funerary sites were covered with a mixture of soil and stones, which was also used to fill in the platform that was later built to cover the burials. The extraordinary state of preservation of the mummified bodies and the careful recording of the associated offerings during the scientific excavations have given the discovery particular importance. The discovery and subsequent research have awakened the public's imagination and aroused the interest of specialists [2, 3].

In 1896, only a year after the discovery of X rays, radiography was used at the Museum of Natural History in Vienna to determine the contents of an Egyptian coffin. What appeared at first to be the mummy of a person turned out to be that of a large bird, the ibis [4]. Since then, radiologic methods have proven to be valuable tools for examining mummies, offering distinct advantages over the older methods of unwrapping followed by autopsy [5–13]. Radiologic imaging of bodies preserved from ancient times, such as mummies, is currently defined as "paleoradiology."

One of the first steps in the investigation of these frozen mummies was the use of radiologic methods to evaluate the state of preserva-

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tion of the internal organs, the possible causes of death, nutritional conditions, and abnormalities. The outstanding state of preservation of the mummies offered a unique opportunity for comparative diagnosis by noninvasive and nondestructive methods such as CT and conventional radiography. The CT and conventional radiography performed on the Llullaillaco mummies have contributed to the pioneering field of the radiology of pre-Hispanic frozen bodies.

The antecedents in this field of research in the Andes are limited. In 1954, conventional radiography was performed on the body of an Inca child from Mount El Plomo [14]. In 1966, an adult male mummy from Mount El Toro was subjected to radiologic studies [15]. CT and conventional radiography were performed on the male Inca mummy recovered from Mount Aconcagua in 1985 [16] and the female Inca mummy found on Mount Ampato in 1995 [17]. However, none of these bodies showed the extraordinary state of preservation of the Llullaillaco mummies. We present the results of the radiographic studies on the three frozen Inca bodies from Mount Llullaillaco.

Materials and Methods

The Llullaillaco mummies are currently preserved in a laboratory specially designed for this purpose at the Catholic University of Salta. Each one is placed in its own freezer, which is connected to a power generator. The temperature and humidity inside the freezers are monitored by thermometers and hygrometers. A double wrapping of sterilized surgical material serves as the first layer and acid-free cotton cloth, as an outer one. Finally, a transparent plastic layer, carefully sealed to avoid the loss of humidity from the bodies and to protect the mummies from the surrounding environment, serves as a means of preservation. They are kept at a temperature of –13°C. The microenvironment that surrounds the mummies inside the freezers is controlled using silica gel, with relative humidity values between 55% and 65%. Because of the aforementioned preservation conditions of the mummies and the danger of thawing, they could only be taken out for 20 min.

CT of the three frozen mummies was performed on a nonhelical scanner (Tomoscan M/EG, Philips, Eindhoven, The Netherlands) at Tomografía Computada Sociedad del Estado in the city of Salta. The techniques used were adapted to the particular anatomic position of each body and its rigid nature. Because of time constraints, multiple sections of 5 mm thick were obtained at 5-mm intervals. This timing allowed us to complete the study in 20 min. The scanning parameters were 120 kV, 40 mA, and 2-sec scanning time. The amperage was adjusted to that level to prevent the overheating of the X-ray tube. Reformatting in other projections had been considered but was not possible because of the lack of suitable software.

Radiographs and orthocclusion radiographs were obtained to observe the dental maxillofacial structures of the Llullaillaco children. Teleradiography plate holders were used, and a distance of 152 cm from the emitting focus to the sagittal line of the skull was established. The exposure was 2.5 sec with 70 kV and 25–30 mA.

Conventional radiography was performed on a portable unit because the equipment had to be transported to the laboratory where the mummies are kept. In this nonradiology environment, we used a table without a grid. The parameters were 35–48 kV and 30–50 mAs at a distance of 80–100 cm, depending on the region to be studied. In all cases, fast rare-earth screens were used.

Results

A clear differentiation of white and gray matter in the brain and cerebellum due to the change of fat into adipocere and the deposition of calcium salts were shown by the cranial CT scans (Figs. 1A, 2A, and 3A). The fatty tissue of the bodies and the white matter also underwent this transformation, and they were visibly white on the CT scans [18, 19].

Another feature that was observed was the loss of volume of the soft tissue due to dehydration. Air between the skull and the cerebral hemisphere and the prominence of the ventricles were clearly visualized; both were caused by volume loss. The pons, medulla oblongata, and the spinal cord could also be seen (Fig. 2A).

In the thorax, the lungs appeared expanded, with a comparatively smaller loss of volume with respect to the rest of the organs because the composition of the lungs is primarily air. A defect in the left thoracic wall of the youngest mummy was produced by a lightning strike after death (Fig. 3B). This was deduced by members of the archaeological team who observed burned skin on the left side of face and body and burned clothing. The trachea, main bronchi, lung arteries, aorta, and heart could also be seen. The thymus was visualized only in the male mummy (Fig. 2B). The upper lobe of the right lung of the older female showed a triangular hypodense zone corresponding presumably to an abnormal air-trapping area (Fig. 1B). In the same mummy, a clear image of the left maxillary sinus and a mucosal enlargement of the right one could be perfectly observed (Fig. 1C).

Most of the organs in the abdomen were in an excellent state of preservation. The size of the liver and the kidneys was reduced, although they maintained their shape. The pancreas was easily identified, although it is the first one among the glandular organs to decay, according to forensic medicine [20]. There were feces in the intestines, but the spleen was not seen in these specimens (Fig. 1D).

The CT image of the pelvic cavity showed well-preserved primary genital organs such as the uterus in the older female and the phallus in the male child. A thick layer of fat tissue, excellent bone mineralization, and muscular volume could also be observed (Fig. 2C). The frontal and lateral cranial radiographs of the three mummies showed no fractures (Fig. 1E) but did show occipital–parietal cranial deformation in the male and both frontal–parietal and occipital–parietal deformation in the younger female (Fig. 3C). The radiographs of the body allowed us to rule out any bone disease (Fig. 2D). We saw no Harris lines, which would have been an indication of periods of malnutrition or illness that interfere with normal growth and metabolism [21].

Findings of radiography of the long bones allowed us to make anthropomorphic measurements that led to estimates of the children's ages [22]. Such measurements were difficult because of the superimposition of the bones caused by the particular position of the bodies (Fig. 1F).

The radiographs of the individuals' teeth showed no cavities. In the two younger mummies, the wear and tear of the crowns of the teeth, which were not present in the older mummy, can be clearly observed (Fig. 3D). The dental age was determined using Nolla's developmental table [23].

The ages of the three individuals at the time of their deaths, determined by a combination of findings of radiographs of the teeth and long bones, were 7 years for the male, 6 years for the younger female, and 15 years for the older female. In the latter case, there was a disparity between the radiographs; whereas the dental radiographs indicated an age of 15 years, the radiographs of the long bones indicated a slightly younger age.

Discussion

According to research records of mummified bodies from different cultures, we found two different types of mummification. One is the artificial mummification—for example, the Egyptians. The other is the natural process as in the case of these three Inca chil-

dren who were mummified by freezing, caused by the ambient temperature of Mount Llullaillaco summit that reaches well below the freezing point.

Because freezing permitted the excellent preservation of the bodies, the appearance of organs and soft tissues at the time of the studies resembled that of a living human being except for the loss of volume. This phenomenon may have been produced by sublimation. During this process, which is favored by low pressure and low temperature, ice changes into water vapor without first becoming liquid.

The findings from Mount Llullaillaco offer a unique view into the Inca sacrificial ceremonies, providing a privileged chance to crosscheck the bioanthropological evidence from the mountaintop shrine with the information given by the Spanish chroniclers about Inca rituals involving human sacrifice.

The Incas spoke the Quechua language, and it was the Quechua term "Capacocha" that was used by Spanish chroniclers when describing the most important of Inca religious ceremonies, which involved human sacrifice and the burial of corpses and offer-

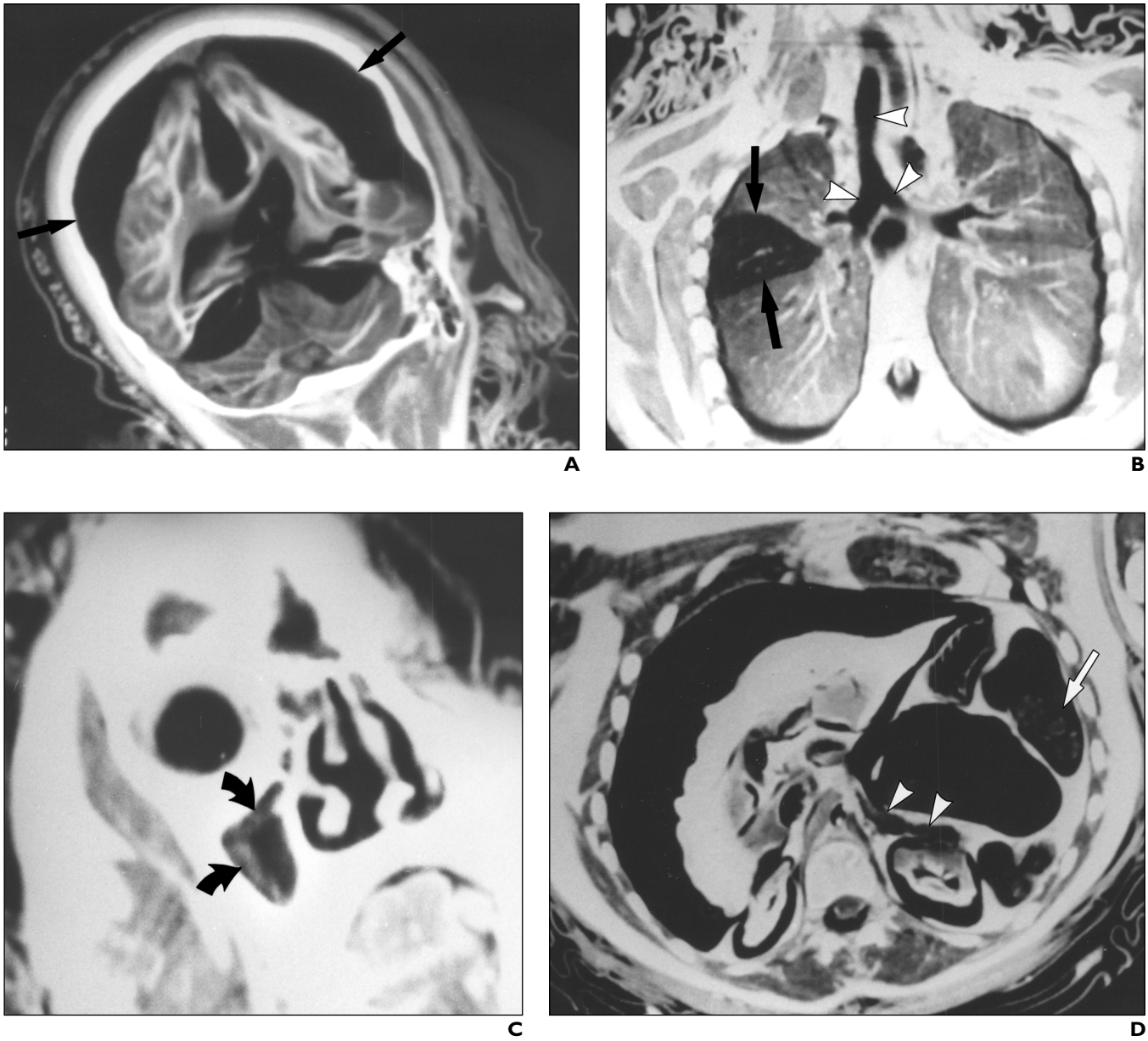

Fig. 1.—15-year-old female mummy.
A, Coronal cranial CT scan shows clear differentiation between white and gray matter of cerebral hemispheres. Note air (*arrows*) surrounding brain.
B, Coronal thoracic CT scan shows that both lungs are expanded. Note triangular hypodense area (*arrows*) in upper lobe of right lung and trachea and main bronchi (*arrowheads*).
C, Coronal cranial CT scan shows right maxillary sinus with mucosal thickening (*arrows*).
D, Axial abdominal CT scan shows liver, pancreas (*arrowheads*), and kidneys to be perfectly preserved. Spleen is not seen. Note feces (*arrow*) in intestines.
(Fig. 1 continues on next page)

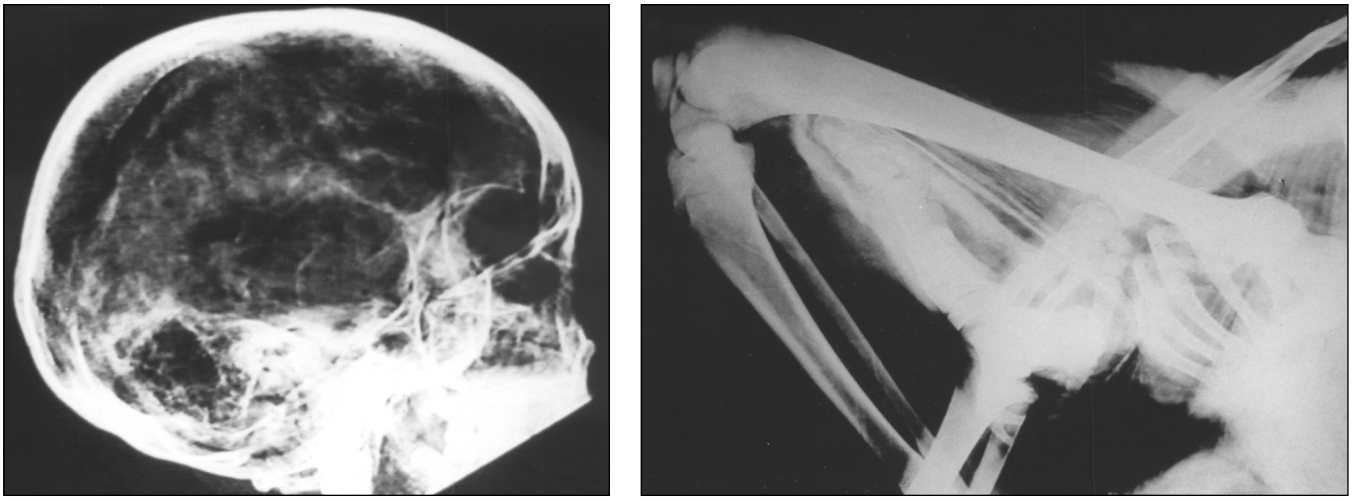

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Fig. 1. (continued)—15-year-old female mummy.
E, Lateral radiograph of skull shows neither fracture nor deformation.
F, Radiograph of lower limbs reveals excellent bone mineralization. Measurement of long bones was difficult because of superimposition of bones. Note absence of Harris lines.

ings. Capacocha ceremonies were undertaken at times of key events in the Inca emperor's life, including his illness, his death, his declaring and joining the war, his son's birth, and his succession to the throne. They were also performed to stop natural calamities such as droughts, epidemics, earthquakes, and volcanic eruptions. In the extremely cold and arid environment of the Andes, human offerings were also consecrated periodically to propitiate the mountain deities to bring water and good weather for the crops and herds. On top of the highest Andean peaks, sacrificial victims were sent into the afterlife as messengers to the main deities of the Inca pantheon: the creator god, Viracocha; the sun god, Inti; and the thunder god, Illapa. Children were selected because of the shared belief that their purity made them more acceptable to the gods. Reaching the distant sacred mountains could require months of traveling over thousands of kilometers. Processions would have included priests, their assistants, and inhabitants of the region through which the pilgrimage passed. A difficult climb to the summit preceded the climax of the Capacocha ceremony.

The Spanish chroniclers described different techniques used by the Inca priests to sacrifice the human victims in ceremonial contexts. The most frequent were strangulation, a blow to the head, asphyxia, or burying the victim alive after being ritually inebriated [24]. There is no medical evidence of strangulation in the bodies from Mount Llullaillaco. The findings of the CT scans and conventional radiographs ruled out cranial trauma as a cause of death for the three individuals. A more probable cause could have been asphyxia or live burial in a state of unconsciousness.

The fatty tissue of the bodies and the white matter of the cerebrum and cerebellum undergo a postmortem transformation caused by autolysis of the fatty tissue. In this process, the fatty tissue is divided into glycerine on the one hand and free fatty acids on the other. Because of the lack of oxygen, the free fatty acids become converted into soap by a process called "saponification." When free fatty acids saponify, they are combined with calcium, potassium, magnesium, ammonium, and sodium ions to form adipocere. For this reason, the fatty tissue of bodies of these specimens is visibly white on the CT scans. The term "adipocere" was first used by Fourcroy in 1786 and is derived from the French term "adipocire," which means waxlike fat [18, 19].

Cranial deformation, a traditional practice among some Andean communities during the time of the Incas, was observed on the radiographs of the younger Llullaillaco mummies [25]. One historical source revealed that beliefs about sacred mountains played a part in the practice of cranial deformation because heads were expected to reproduce the shape of the volcanoes that were considered to be the "place of origin" of each community [26].

CT scans showed feces in the intestines, which proved that the consumption of food had continued until a few hours before the deaths of the children. Historical sources tell us that sacrificial victims were fed to guarantee their happiness going into the world of gods [27]. Historical and ethnographic research in the Andes shows that the consumption of food and beverages in ritual contexts is rooted in the belief that the body can act as a channel to transfer the nutritious essences to the spirits, which can sometimes include the spirits of the ancestors [28].

Findings of CT also revealed that the Llullaillaco mummies had a good muscular volume and a thick layer of fat tissue, indicating that the children had been properly nourished. In addition, the perfect bone mineralization and the absence of Harris lines suggest that the individuals may have belonged to a high social class. Some historical accounts indicate that sacrificial victims were chosen from the children of tribal chiefs. They were sometimes voluntarily offered to seal an alliance with the Inca emperor [29].

The boy and the youngest girl present evidence of excessive dental abrasion with occlusive wearing-away facets, compatible with a diet based on corn meal. The typical Andean diet, based on a high proportion of maize, can cause patterns of dental wear due to the grinding of grain with pestles, a process in which silica particles are incorporated into the flour. Dental abrasion in children can also be related to bruxism (dental grinding) or to parasites [30].

The disparity in the ages determined by the radiographs of the teeth and the long bones

was probably due to the superimposition of the bones because the victims were usually buried in a "seat-flexed" position with the knees drawn up toward the chest and often with the arms and legs crossed. For this reason, we believe that the age determined by dental radiographs is more accurate.

Regarding paleopathologic analysis, we observed a radiolucent area in the right lung of the older female of Llullaillaco, presumably caused by an abnormal air-trapping area. Our best hypothesis is that this finding may represent a constrictive bronchiolitis [31]. The etiology of the constrictive bronchiolitis is varied, and in this case, it could have been caused by an infection, particularly given the long period of time that the individuals were expected to walk from the capital city of Cuzco toward the mountain where they would be sacrificed [32]. The same mummy showed evidence of a right maxillary sinusitis.

We could not visualize the spleen because this organ is composed mainly of blood cells. These decay rapidly after death. In many spontaneously mummified bodies, the spleen is not even recognizable grossly at the time of dissection [33].

In conclusion, the death of the three young individuals on top of Mount Llullaillaco took place during a ceremony controlled by the Inca empire 500 years ago. Buried at an altitude exceeding 6,700 m, the mummies are extraordinarily well preserved because of the cold, hypoxic, and arid environment of their mountain tomb. The ages and social profiles

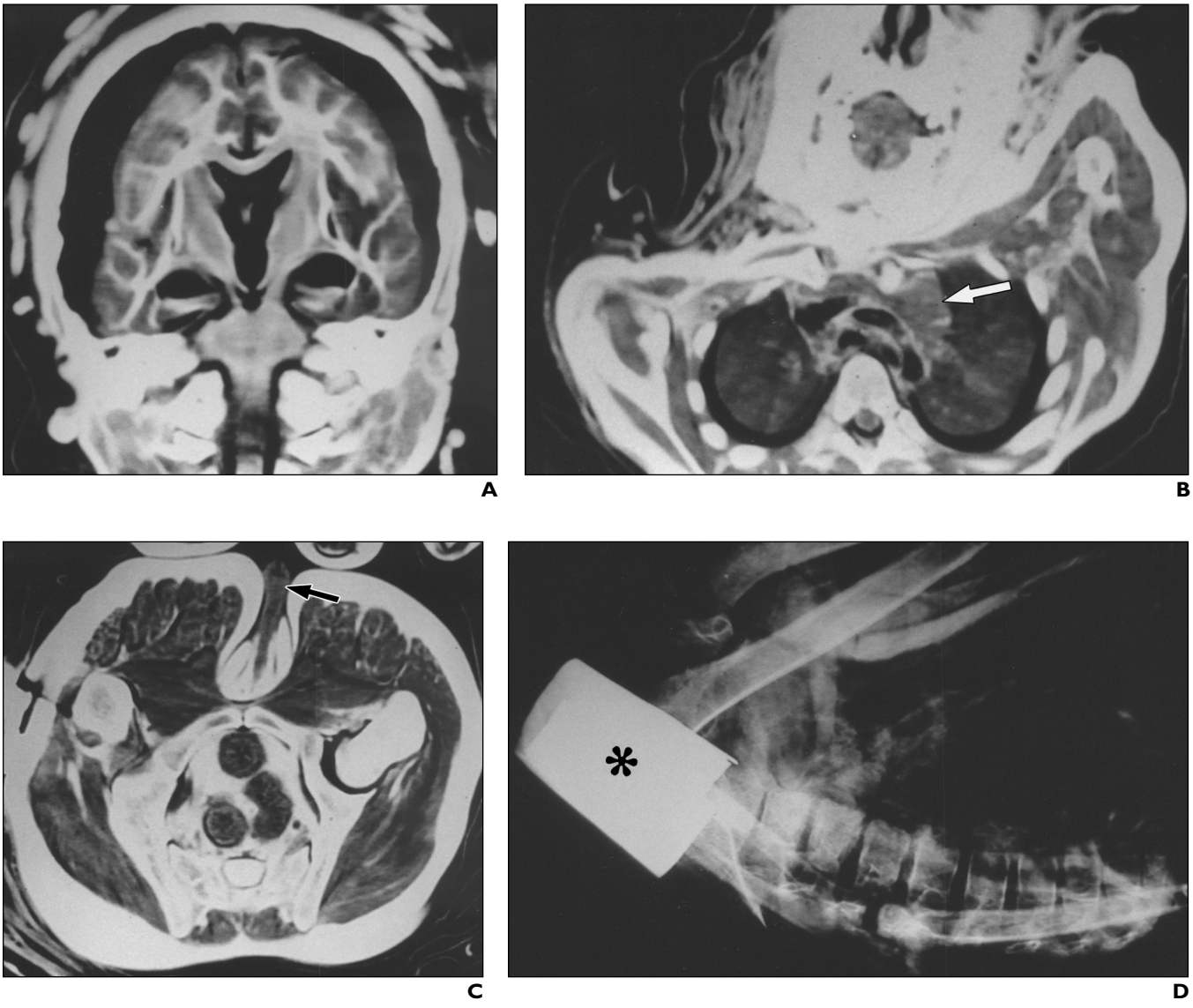

Fig. 2.—7-year-old male mummy.
A, Coronal CT scan shows excellent state of preservation of cerebrum, pons, and medulla oblongata. Ventricles are prominent.
B, Coronal CT scan of face and thorax shows lungs and mediastinum, in which thymus (*arrow*) is well observed. Note muscular volume and thickness of subcutaneous fat.
C, Axial CT scan of pelvis shows well-preserved phallus (*arrow*), muscles, and fatty tissues.
D, Lateral radiograph of spinal column shows that thoracic and lumbar vertebrae have excellent mineralization and height. Metallic bracelet (*asterisk*) on right wrist is also seen.

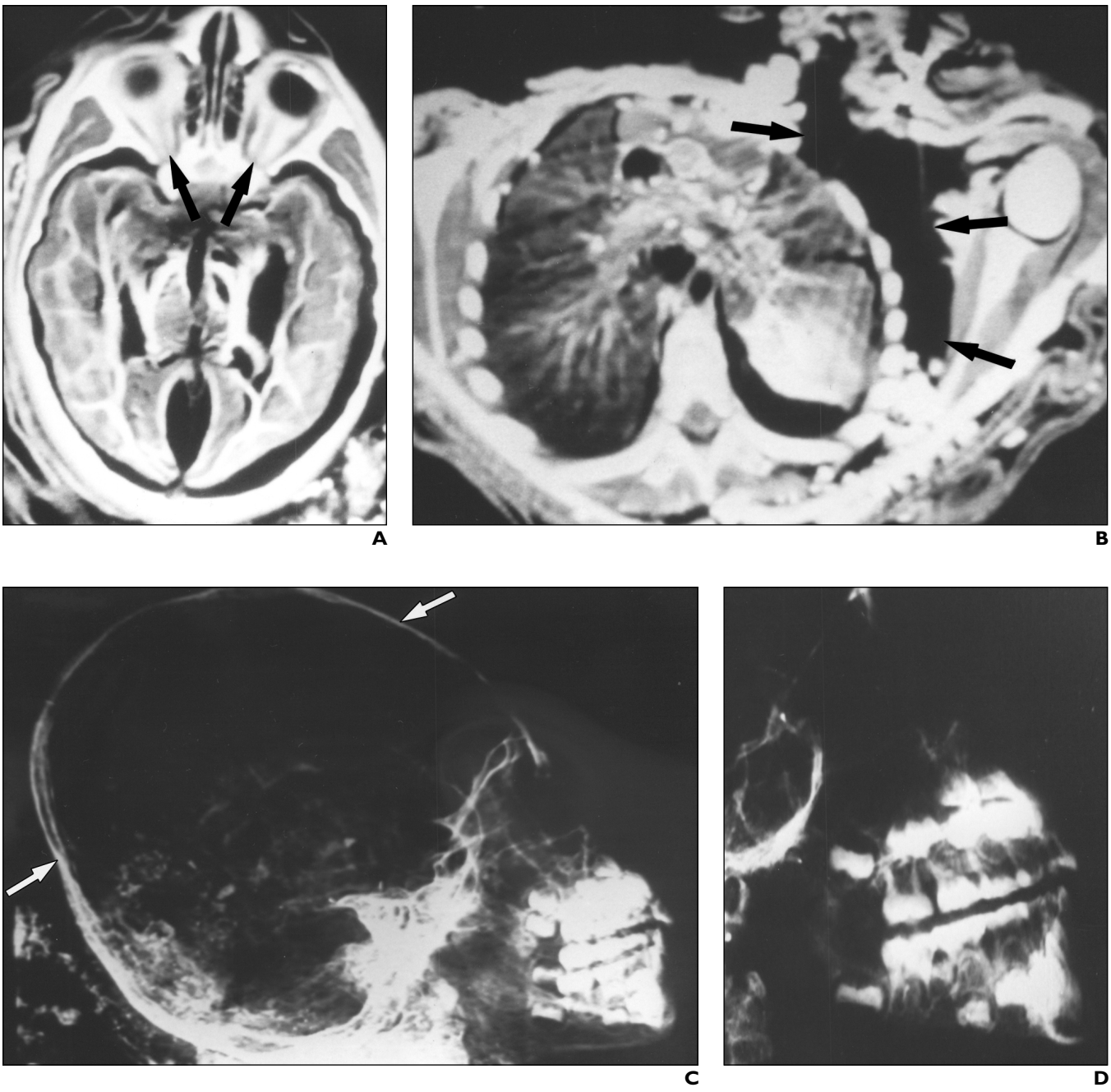

Fig. 3.—6-year-old female mummy.
A, Axial cranial CT scan shows orbits with presence of eyes, optic nerves (*arrows*), and orbital muscles.
B, Axial CT scan of thorax shows that both lungs are expanded. Defect in left thoracic wall (*arrows*) was produced by lightning strike after death.
C, Lateral radiograph of skull reveals frontal–parietal and occipital–parietal flattening, intentional cranial deformations (*arrows*).
D, Dental radiograph shows wear of teeth crowns.

of the chosen victims of Llullaillaco and the sacrificial techniques involved in their ritual executions are all in correspondence with the descriptions presented in the historical sources of Inca ceremonies involving human sacrifice.

This investigation is a significant contribution to the field of radiology studies in Andean pre-Hispanic frozen mummies. Paleoradiology has helped us to evaluate the state of preservation of the bodies, the possible causes of death, the nutritional condition, and abnormalities. Because of the external appearance and the extraordinary condition of the internal organs, the frozen bodies of Llullaillaco, so far, are among the best-preserved mummies ever found.

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