Radiology

The Iceman: Discovery and Imaging[1]

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The anatomic features of a 5,300-year-old mummy, the iceman, were documented with conventional radiographic, portable computed radiographic, and conventional and spiral computed tomographic images obtained between September 1991 and June 2001. A team of scientists and radiologists from Austria, Italy, and the United States supervised the examinations and interpreted the images. The images demonstrated excellent preservation of the mineralized skeleton with profound dehydration of the soft tissues. The skeleton exhibited several types of trauma, including *(a)* healed rib fractures, *(b)* hairline skull fractures and a compression deformity of the thorax, probably acquired while encased in the glacier, and *(c)* damage acquired during the effort to recover the corpse. Skeletal variants were present, as was evidence of degenerative arthritis, frostbite, vascular calcification, and adaptation to cultural and geographic influences. In terms of anatomy and apparent health-related conditions, the iceman was very similar to modern humans. An arrowhead lodged between the rib cage and the left scapula was the probable cause of the iceman's death. Study of the images also provided insight regarding postmortem processes that led to the iceman's mummification.

Supplemental material: *radiology.rsnajnls.org/cgi/content/full/2263020338/DC1.*

On Thursday, September 19, 1991, while hiking across a snowfield in the Tyrolean Alps near a natural pass called the Hauslabjoch, a German couple from Nuremberg discovered a human corpse (1–3). The body was face down, frozen, and encased in ice except for the head, neck, shoulders, and upper back. After a cursory examination of the corpse, the couple continued hiking to a mountain rest hut where the host notified authorities in both Italy and Austria of the body. Later that afternoon, the hutkeeper and his cook visited the scene and took note of nearby exposed artifacts, including a prehistoric ax and some pieces of fur.

The next day, on Friday afternoon, an Austrian gendarme experienced in alpine rescue began the recovery effort. Because the body was located at a remote site more than 10,000 ft (3,000 m) above sea level, a helicopter was used for access. A small pneumatic jackhammer was used to chip the ice that encased the corpse. At times, the 30-cm-long pneumatic chisel was submerged in icy opaque water. After 1 hour, ice had only been removed to the level of the hips, with the legs still encased. The jackhammer quit working and the weather suddenly worsened, so the rescuer departed the mountain before the recovery was completed.

The official recovery team was unable to return on Saturday, but several mountain climbers reached the site and continued to chip the ice with ski poles and a wooden stick. They were unable to completely release the body from the glacier but recognized that it was mummified. On Sunday, local rescuers continued to work until the body was released. They covered the corpse with plastic and collected some of the associated artifacts. When they returned to the mountain hut, they notified the Austrian authorities that the body had been freed of the ice and was ready for recovery. Overnight, the corpse became refrozen in the snow and ice.

On Monday, September 23, 1991, Rainer Henn, MD, from the Department of Forensic Medicine at the University of Innsbruck, Austria, and another gendarme dug the corpse out of the ice once more by using a ski pole and an ice pick. The corpse was flown to the valley in a helicopter and then transferred into a coffin and driven to Innsbruck. Once in Innsbruck, Konrad Spindler, PhD, from the Department of Archeology at the University of

Innsbruck, identified the artifacts that accompanied the corpse as prehistoric. The importance of the discovery quickly became apparent (4–7). The next day (Tuesday), the body was transferred to the Department of Anatomy at the University of Innsbruck to assure safety and preservation.

In 1991, at least six corpses were released from glaciers in the Alps. Glacial corpses are typically persons lost in recent decades, often mountain climbers or soldiers from World War I or II. This corpse, however, was older. Results of carbon dating showed the body to be more than 5,000 years old (before present), or by comparison, more than 2,000 years older than the mummy of King Tutankhamun. These results, in addition to analysis of the associated personal artifacts (eg, bow, quiver, arrows, flint knife, copper-headed ax, leather, and grass clothing), indicated that the iceman had lived during the Copper Age (8).

The frozen mummy has been referred to by many names, including "Similaun man," for the glacier near which it was found; "the man from Hauslabjoch," for the nearby mountain pass; "Ötzi," an affectionate nickname patterned after the nearby Ötztal valley; and simply, "the iceman." In Austria and Europe, "Similaun man" and "Ötzi" are common names used to refer to the frozen man, while in the United States and other parts of the world, "iceman" is the common form of reference for this mummy.

IMAGING

Imaging studies of the iceman were performed as an international cooperative effort. Because surveyors eventually determined that the corpse was discovered a few meters within South Tyrol, Italy, the government of South Tyrol acquired final ownership of the mummy and voluntarily cooperated with the government of Tyrol, Austria, to make the mummy available for study. The Austrian and Tyrolean governments provided support for the Departments of Forensic Medicine, Anatomy, and Radiology II at the University of Innsbruck. These departments coordinated several examinations during which images were obtained. Design of the imaging protocols and interpretation of the resultant images were a collaborative effort of investigators at the University of Innsbruck, Austria; University of Vienna, Austria; Washington University, St Louis, Mo; University of Texas M. D. Anderson Cancer Center, Houston, Tex; and General Regional Hospital, Bolzano, Italy. Between September 1991 and January 1998, the iceman was preserved and studied in Innsbruck, Austria. Currently, the mummy is conserved, exhibited, and studied in Bolzano, South Tyrol, Italy.

In essence, the mummy had been freeze-dried through natural processes and was therefore dehydrated, brittle, and fragile. Because the body was frozen in its natural state with no artificial preservation, the risk of bacterial and fungal growth and the potential for resultant rapid tissue decomposition were great. Therefore, the conservators expended considerable effort to protect the mummy from physical and environmental hazards during preservation in the Department of Anatomy at the University of Innsbruck. The mummy was kept frozen in an environmentally controlled chamber with a constant temperature (−6°C) and humidity (96%–98%) closely resembling that of the glacier from which it was released. Sanitary procedures were followed whenever the corpse was removed from the chamber and handled for study. The mummy was manipulated carefully and minimally. Opportunities for investigation were limited, and requests for access to the mummy were scrutinized for adequate justification before permission for investigation was granted. Security near the environmental chamber was monitored electronically, and the chamber itself had an alarm system. Similar precautions exist in the museum setting in Bolzano.

Imaging provided an opportunity for maximal gain of anatomic information, with minimal risk and with full preservation of the integrity of the body. Of the several imaging methods available for nondestructive testing of the iceman, some were thought to have excellent potential for important yield, and others were determined to have less potential. Conventional computed tomography (CT) and conventional radiography were used immediately. Portable computed radiography was used 1½ years later. Two spiral CT examinations were performed approximately 2½ years after the initial set of conventional CT images were obtained. A third set of spiral CT images was acquired almost 10 years after acquisition of the initial CT images. Magnetic resonance imaging was not performed because the body was extremely dehydrated and essentially devoid of fat. For similar reasons and because air was present throughout the dehydrated soft tissues, ultrasonography was not used.

Conventional radiography with screen-film cassettes was performed on September 26, 1991. These radiographs were limited in number and scope. They were performed in conjunction with CT, an approach that was expected to provide more images and information within the limited time allotted for radiologic examination.

CT was performed with the mummy in supine position on both September 25 and 26, 1991. A commercially available CT scanner in routine clinical use at the University of Innsbruck (Somatom Plus; Siemens, Erlangen, Germany) was used. Because the window of time available to perform CT studies was limited, section thickness varied between 1 and 8 mm to optimize both anatomic detail and total anatomic area surveyed (9).

Because of a desire to restrict the travel time of the mummy and the potential for melting, portable computed radiography was used to expand the conventional display of the skeleton in May 1993.

Additional CT protocols were developed, and the mummy was imaged with CT on two occasions in April and May 1994 by using a spiral CT scanner at the University of Innsbruck (Somatom Plus 40; Siemens). The temperature of the room with the CT scanner was maintained at 8°C–10°C. Again, the time available for study was limited in an effort to retard thawing.

An additional spiral CT examination was performed on March 3, 2001, at the General Regional Hospital in Bolzano (Somatom Plus; Siemens). This CT examination was possible because the mummy was temporarily safeguarded at the General Regional Hospital in Bolzano while modifications to the environmental chamber were completed at the museum. These CT images were very similar to the CT images obtained in 1991 and 1994. They constituted an archive for study in Bolzano.

On June 27, 2001, six digital radiographs of the mummy's ribs were obtained in anticipation of other possible scientific studies of bone structures. At that time, an arrowhead was detected in the left shoulder region. This discovery prompted additional analysis of all prior CT and radiographic images from both Innsbruck and Bolzano.

In all, 38 radiographic and approximately 2,190 CT source images were obtained for interpretation (Table 1). Many two- and three-dimensional reconstructed images were derived from the CT data sets. These were used to gain additional anatomic perspective and to aid anthropologists and other investigators in their studies. Spiral

TABLE 1
Chronologic Record of Imaging Examinations

Date	Imaging Method	No. of Images Acquired	Anatomy Studied
September 25, 1991	CT, 4 mm thick	40	Head
	CT, 1 mm thick	47	Head
	CT, 5 mm thick	21	Maxilla, mandible
	CT, 5 mm thick	8	Mandible
	CT, 5 mm thick	26	Neck
	CT, 8 mm thick with 2D and 3D reconstructions	108	Chest, abdomen, pelvis, proximal thigh
	CT, 5 mm thick with 3D reconstructions	38	Head
September 26, 1991	CT, 4 mm thick	54	Midfemora to distal tibiae
	CT, 2 mm thick	44	Ankles
	Conventional radiography	9	Skull, spine, chest, pelvis, knees, ankles
May 25, 1993	Portable computed radiography	23	Skull, spine, chest, abdomen, extremities, hands, feet
April 14, 1994	Spiral CT, 1 mm thick with 2D and 3D reconstructions	222	Head, neck
May 3, 1994	Spiral CT, 5 mm thick with 2D reconstructions	178	Neck, chest, abdomen, pelvis
	Spiral CT, 5 mm thick with 2D reconstructions	196	Pelvis to midfemora
	Spiral CT, 5 mm thick with 2D and 3D reconstructions	298	Acetabulae to feet
March 3, 2001	Spiral CT, 4 mm thick with 2D reconstructions	134	Skull, maxilla, mandible
	Spiral CT, 4 mm thick with 3D reconstructions	104	Chest
	Spiral CT, 2 mm thick	164	Abdomen, pelvis, hips
	Spiral CT, 2 mm thick with 2D reconstructions	368	Midfemora to distal tibiae
	Spiral CT, 1 mm thick with 2D reconstructions	137	Ankles, feet
June 27, 2001	Digital radiography	6	Ribs

Note.—The iceman was imaged on seven separate occasions with a combination of CT and radiography. In all, the examinations generated approximately 2,190 CT and 38 radiographic source images. Many more images were derived from the spiral CT data sets. These images are not tabulated, but they include many two- and three-dimensional reconstructions, postprocessed images for measurement in Hounsfield units, and images optimized to emphasize certain anatomic features. 3D = three-dimensional, 2D = two-dimensional.

CT data sets were used to accomplish stereolithographic reconstruction of the iceman's skull (10). In all, three stereolithographic skull reconstructions were obtained, the last of which included the cervical spine. Other postprocessed images were obtained to provide measurements of various structures in Hounsfield units. Still other CT images were optimized to emphasize certain anatomic features for study, discussion, and display.

FINDINGS

In this article, we present many observations, offer our interpretations, and suggest mechanisms to account for the findings. These results are a summation of a group effort spanning 10 years. Authors met in Innsbruck, Austria, on multiple occasions. Other meetings took place in Bolzano, Italy; St Louis, Mo; Houston, Tex; and Chicago, Ill. Between face-to-face meetings, discussions continued by means of telephone and e-mail. The observations, interpretations, and hypotheses described in this article emerged by means of consensus opinion, often as a result of debate and research. Individual contributions became embedded in group consensus. We present this summary as representative of our current best understanding of the facts revealed by means of imaging.

Visually, the most striking feature of the corpse was its degree of dehydration (Fig 1). Surface inspection showed exceptionally dry tissues devoid of water and fat. In fact, the mummy weighed only about 40 pounds. Dehydration of all soft tissues was evident on every radiograph and CT image.

Head and Brain

Initial images of the mummy's head were dramatic. They revealed a skull of normal size and bone structure surrounding a visible but shrunken brain (Fig E1, *radiology.rsnajnls.org/cgi/content/full/2263020338/DC1*). The space between the brain and the inner table of the skull was replaced with air and small amounts of water and ice. The mummy was imaged in the supine position, and it was apparent that the brain was tethered at the foramen magnum by the spinal cord. Because of supine positioning and gravity, the shrunken brain rotated posteriorly within the vault. The meninges had not shrunken as much as the brain and could be demonstrated separately from the brain tissue.

The brain tissue became visible because it was shrunken and surrounded by air. Moreover, the brain tissue attenuation was inhomogeneous, as demonstrated with both radiography (Fig 2) and CT (Fig E2, *radiology.rsnajnls.org/cgi/content/full/2263020338/DC1*). The variable attenuation did not conform to a known pattern of normal anatomy nor did it seem to reflect a pattern expected for common clinical conditions. In general, the major divisions (cerebral and cerebellar hemispheres, brain stem, and spinal cord) and fissures of the brain were preserved. However, no distinction between gray and white matter was apparent (Fig E2, *radiology.rsnajnls.org/cgi/content/full/2263020338/DC1*). Of interest, nonanatomic cracks, fractures, and spaces were present in the brain substance.

By some natural physical means, the brain partially shrank and was reasonably well preserved for over 5,000 years. Shrinkage of the brain was not as severe as that of other soft tissues. An explanation for this relative preservation of brain volume may be that the skull created a microenvironment for the brain that differed from the general environment to which the rest of the body was exposed. In other words, the brain could have experienced higher ambient humidity than that of the rest of the corpse, thereby retarding shrinkage and permitting other chemical changes to develop.

Skull

At initial inspection, the skull appeared intact and of normal configuration. When scrutinized more closely, the CT images showed the presence of numerous hairline fractures or cracks of the facial bones and the base of the skull (Fig 3). These were associated with slight widening of sutures—in particular, the lambdoid suture. In spite of the number of cracks and tiny fractures, there were no typical linear skull fractures, depressed fractures, or areas of bone depression or deformity, as might have been expected in a case of violent trauma.

A reasonable mechanism to account for the many isolated and subtle cracks and fractures is postulated on the basis of the known expansion of water when it freezes. A glass container full of water will crack one or more times without becoming deformed as a consequence of the contents freezing. The skull may be considered a similar closed vessel, and the brain provides the water (though mostly bound into tissue). Freezing could cause the brain to expand and thereby crack some of the skull bones or widen some of its sutures. If several freezing and thawing cycles occurred, there would have been several opportunities for tiny fractures to arise. Moreover, with brain shrinkage, water could have filled the intracalvarial void. Again, freezing and thawing cycles could crack both the skull and the partially shrunken brain. Also, movement of the body during and following recovery could have damaged the altered brain.

The tip of the nasal bone was fractured, and the fragment was angled approximately 90° downward (Fig E3, *radiology.rsnajnls.org/cgi/content/full/2263020338/DC1*). This fracture was different from the other skull fractures because it was on the surface of the face in an exposed location and because it manifested considerable angulation. If the fracture was acquired from an injury during life, as from a direct blow, it shows no evidence of healing. If it was acquired after death rather than at the time of death, it probably resulted from a different mechanism than did the other calvarial fractures. If postmortem, the nasal fracture might have been acquired through contact with the rock on which the body was discovered, or perhaps it was caused by pressure from the weight of the snow and ice as the glacier formed over the body or movement of the corpse during the 5,000-year interval.

Figure 1. Frontal photograph of the iceman (obtained in September 1991) shows dry contracted skin resulting from the natural mummification process. The eyeballs are completely collapsed because of dehydration. The upper lip is deformed, and the nose is flattened secondary to lying in the prone position and probably bearing the weight of ice and snow.

Figure 2. Radiograph shows variable shrinkage of the brain. Frontal view of the head (obtained on May 25, 1993, with the body in the supine position) shows the shrunken brain surrounded by dura mater (arrows) that did not shrink as much as the brain did. Note the falx cerebri (arrowheads) within the interhemispheric fissure. The brain exhibits variable opacity, probably due to variation in the physical and chemical alterations that accompanied an intermittent or inhomogeneous mummification process.

Radiography (Fig E3, *radiology.rsnajnls.org/cgi/content/full/2263020338/DC1*) and CT (Fig 3) also revealed prominence of the supraorbital ridge. This feature would have given a prominent brow line to the iceman's facial appearance. The adjacent frontal sinuses were relatively underdeveloped. There are no comparable skeletons from a population contemporary to the iceman with which to gauge the population frequency of this or any other anatomic feature discovered in the iceman.

Because many investigators were interested in the osseous anatomy of the skull, the skull's features were further investigated by using methods of two- and three-dimensional reconstruction (Fig E4, *radiology.rsnajnls.org/cgi/content/full/2263020338/DC1*). Several available reconstruction and measurement algorithms were used, and images were created to emphasize multiple external and internal perspectives. Anthropologists and experts in human biology studied these images and used measurements derived from them to characterize the iceman's skull (11). Because the iceman's head was intact and covered with skin and because no conventional autopsy would be permitted to visualize the interior surfaces of the skull, plastic replicas of the skull were manufactured by using stereolithographic methods (10). As postprocessing methods improved, additional stereolithographic models were prepared (Fig E5, *radiology.rsnajnls.org/cgi/content/full/2263020338/DC1*). These reproductions were made available to scientists who wished to study certain features of the skull, which otherwise would not be accessible.

Transverse CT images showed multiple unhealed facial cracks and fractures (Fig 3). The derived two- and three-dimensional reconstructions confirmed an associated craniofacial deformity. Stereolithographic reproduction (Fig E5, *radiology.rsnajnls.org/cgi/content/full/2263020338/DC1*) demonstrated recession of the face with slightly greater displacement on the left side compared with the right side. The skull and facial bones were characterized mathematically (12), and results confirmed recession of the midface and base of the skull. The cause was interpreted as consistent with the combined effect of complex glacial mechanics due to expan-

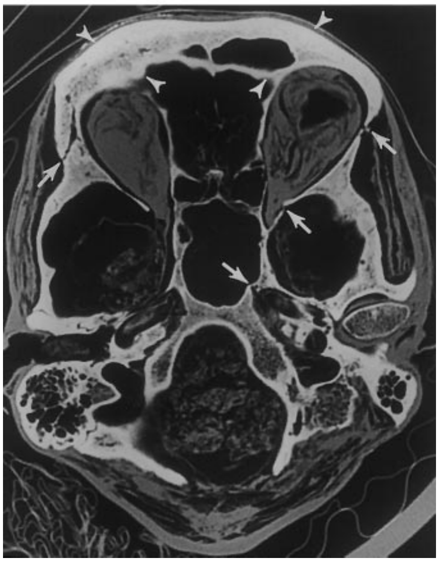


Figure 3. Transverse CT section through the orbits and foramen magnum (obtained on September 25, 1991) shows examples of multiple hairline fractures (arrows) in the facial bones and at the skull base. The fractures are consistent with the combined effects of freezing and thawing cycles and the weight of ice and snow. Note the thick frontal bone (arrowheads) and prominent supraorbital ridge.

Figure 4. Photograph of the iceman's mouth (obtained in September 1991) shows diastema (widely spaced central incisors, arrow). Shrinkage and deformation of the lips are due to dehydration and pressure from external forces. There is retraction of the gums around the maxillary teeth, and portions of the roots are exposed. Note the flattened surfaces of the incisors and canines, attributed to wear.

sion of water as it froze, weight of ice and snow, and small amounts of body movement controlled by the glacier. The deformity of the surface soft-tissue anatomy (lips and nose) provided additional evidence of pressure from external weight and of slight linear and rotary motion due to external forces.

Mouth and Teeth

Among the facial features that define a person's appearance, the mouth, lips, and teeth are important. Because of mummification and deformation due to environmental factors, the iceman's lips do not provide an accurate indication of his appearance during life (Fig 4). Visual inspection of the face and interpretation of the various images revealed diastema, a wide-set spacing of the maxillary central incisors (Figs 4, 5).

At initial evaluation of the images, all teeth appeared to be present. However, closer evaluation revealed that all four third molars were absent. Otherwise, the teeth were arrayed in normal arches and were spaced normally (except for the diastema). Of importance was the fact that nearly all occlusal surfaces were worn smooth, and most teeth were shortened as a result (Figs 4, 6). This feature was attributed to cultural factors, including diet and work habits believed to be operative in the period during which the iceman lived. Because of restricted jaw mobility due to dry and brittle tissue, it was not possible to obtain bitewing and periapical dental images. Similarly, because of physical restrictions due to overall rigidity of the body, panoramic radiography was not practical. No tooth decay was evident at limited visual inspection or at imaging with nondental methods.

Spine

The neck as imaged with CT was characterized by dehydrated soft tissues. Fat was grossly absent, and many natural inter- and intramuscular or subcutaneous planes were filled with gas. Because of the degree of mummification, it was difficult to identify individual muscles, lymph nodes, and blood vessels. One calcification on the left side of the neck was interpreted as possibly related to the carotid artery, an indication of arteriosclerotic cardiovascular disease. The lateral radiograph of the neck (Fig E6, *radiology.rsnajnls.org/cgi/content/full/2263020338/DC1*) showed nearly normal mineral content of the cervical spine. All disk spaces were a bit narrow, a feature generally attributed to mummification. However, the C6–7 disk space was slightly narrower than the others, and this finding was associated with mild endplate sclerosis with dorsal and ventral spurs. These features satisfied diagnostic criteria for degenerative disk disease. Similar but less prominent findings were present at C5–6. Very small uncinate spurs were present at several levels. The pattern of degenerative disk disease was indistinguishable from that encountered in modern clinical practice.

Apophyseal joint osteoarthritis was documented at C4–5 with deformities of the lateral masses, irregularities of the facet joint surfaces, sclerosis, and spur formation. Again, the pattern was identical to apophyseal joint osteoarthritis encountered in current practice.

CT and radiographic surveys of the thoracic spine showed normal thoracic vertebrae with narrow disk spaces due to the degree of dehydration. No degenerative disk disease, spurs, or fractures were detected. Only 11 rib-bearing vertebrae were present. T12 was lumbarized.

As in the thoracic region, the lumbar vertebral bodies were remarkably normal in appearance, with excellent mineral content and without substantial degenerative disk changes (except for a tiny spur at the superior endplate of L5) or fractures. A transitional lumbosacral segment was present, with full sacralization on the left and partial sacralization on the right. CT demonstrated the features of Schmorl nodules within the superior endplate of the transitional lumbosacral segment (Fig E7, *radiology.rsnajnls.org/cgi/content/full/2263020338/DC1*). Minor apophyseal joint osteoarthritis was encountered between the final lumbar segment and the transitional segment. These findings included sclerosis, small spurs, and small subcortical lucencies.

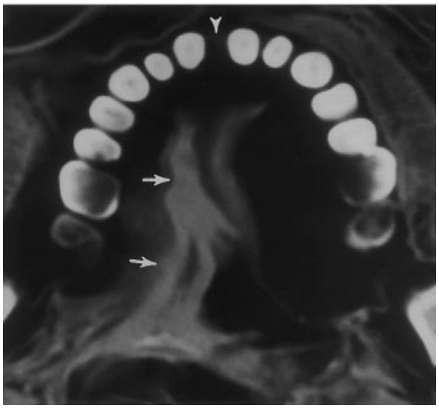


Figure 5. Transverse CT section through the maxillary teeth (obtained on September 25, 1991) shows 14 teeth and bilaterally absent third molars. Note the diastema (arrowhead) and the dehydrated tongue (arrows).

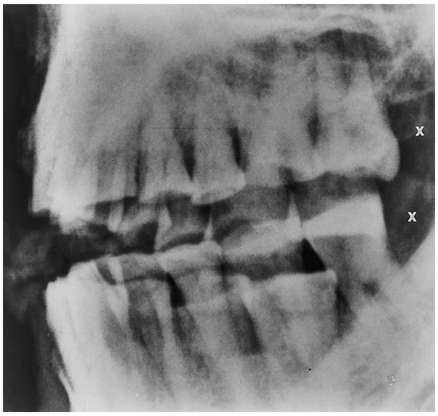


Figure 6. Detail of the teeth from a lateral radiograph of the skull (obtained on May 25, 1993) shows that all teeth are worn and flattened, presumably from mechanisms of wear specific to the lifestyle of the iceman. Note absence of third molars (*X* = expected molar positions).

Figure 7. Photograph of the mummy's chest and abdomen (obtained in September 1991) dramatically illustrates the severity of dehydration and anterior thoracic collapse. The ribs have rotated in a caudal direction and are pressed against the spine, as is the sternum. The left arm is extended across the chest and is held in that position by the brittle dehydrated and frozen tissues.

Thorax

As was true with the head, the thorax demonstrated profound dehydration at visual inspection (Fig 7). The other striking surface feature of the thorax was how adherent the anterior chest wall skin seemed in relation to the outline of the thoracolumbar spine. This resulted from collapse of the anteroposterior dimension of the thorax. The corresponding chest radiograph (Fig 8) showed rotation of the ribs, with the anterior aspect of the rib cage moving in a caudal direction while the posterior ribs pivoted at the costotransverse and costovertebral joints (Fig E8, *radiology.rsnajnls.org/cgi/content/full/2263020338/DC1*). The result of the rib rotation was an exaggerated elongation appearance of the ribs on the frontal radiograph. Otherwise, the general configuration of the ribs seemed normal according to modern standards.

CT images showed that the entire thorax was compressed (Fig 9). We attributed the combined features of rib rotation and thoracic compression to a single dominant mechanism. Theoretically, the weight of the snow and ice caused sufficient pressure to rotate the ribs in a caudal direction, thereby allowing the anteroposterior diameter of the thorax to compress or collapse until the migration was resisted by the spinal column.

Completely healed rib fractures were present in the fifth through ninth ribs on the left side (Fig 10). These were located along the posterior axillary line in a linear array and were interpreted as evidence that the iceman had experienced one or more episodes of thoracic trauma during his lifetime from which he totally recovered. On the basis of the similarity of the fractures, we suggest that a single episode of trauma was more likely than two or more episodes.

The conventional radiographic (Fig 8) and CT (Fig 9) images of the thorax revealed dehydrated organs with little anatomic similarity to normally hydrated organs. These intrathoracic tissues were shrunken, flattened, and wispy. We derived little useful information from the intrathoracic organs relating to health issues or to cause or manner of death. There appeared to be pleural adhesions in the right hemithorax that prevented total collapse of the right lung (Fig E9, *radiology.rsnajnls.org/cgi/content/full/2263020338/DC1*), possibly a result of pulmonary infection.

Pelvis and Hips

In addition to profound dehydration, extensive destruction of the soft tissues of the left buttock were demonstrated at visual inspection of the iceman's pelvis and thighs (Fig 11). This damage occurred during the effort to release the corpse from the ice. Radiography showed extensive skeletal injury associated with the soft-tissue destruction (Fig E10, *radiology.rsnajnls.org/cgi/content/full/2263020338/DC1*). Portions of the left femur, innominate bone, and sacrum had been chipped away. The combined soft-tissue and bone injuries permitted dislocation of the left hip. Except for the preserved anteromedial soft tissues, the left lower extremity was nearly disarticulated. CT images provided a detailed display of the skeletal destruction, including the loss of much of the dorsal aspect of the left ilium and the left sacral segments. As a result, the left sacroiliac joint was disrupted.

As shown on the frontal radiograph of the pelvis, the right hip joint appeared normal. However, CT sections provided better detail and showed evidence of right hip osteoarthritis (Fig 12). Because of dehydration, the right hip articular cartilage was artificially thinned. Therefore, an accurate measurement of joint space width was not possible. Subarticular subcortical sclerosis and rounded lucencies were present in the anterior column contribution to the acetabulum. Small amounts of surface bone proliferation were found around the articular margins of the femoral head and acetabulum. These features were attributed to osteoarthritis. They appeared consistent with the degenerative alterations found in the spine, which served as confirmation that the iceman had acquired degenerative arthritis during his life. No evidence of inflammatory arthropathy was detected.

Figure 8. Frontal radiograph of the chest and upper abdomen (obtained on May 25, 1993) confirms the caudal rotation of the ribs and shows the folded soft tissues at the thoracolumbar junction (compare with Fig 7). Only 11 rib-bearing thoracic vertebrae are present. The usual shadows of the heart, pulmonary vessels, and lungs are absent because of severe shrinkage of these organs. The fracture (arrow) of the left humerus was acquired during the recovery effort.

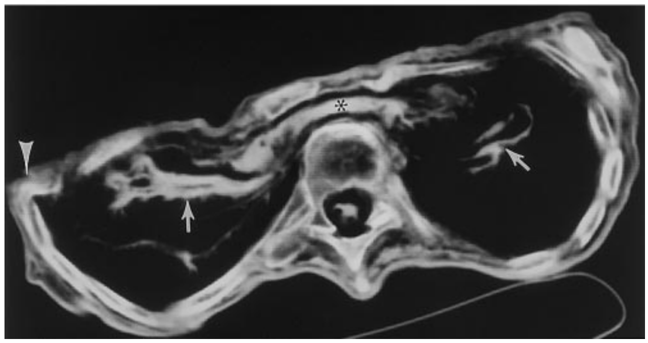


Figure 9. Transverse CT section through the thorax (obtained on May 3, 1994) confirms the compressed anteroposterior diameter of the thorax and displays the right-angle deformity (arrowhead) of the rib cage that was acquired as the corpse adjusted to the changing forces brought about by progressive dehydration and increasing pressure from the weight of snow and ice. The wafer-thin heart (*) is sandwiched between the juxtaposed sternum and spine. The dehydrated lungs (arrows) are only wisps of tissue.

Extremities

In general, bone cortical thickness and cancellous pattern and mineralization appeared normal throughout the upper extremities. No evidence of systemic osteopenia or metabolic bone disease was detected in the upper extremities.

Features of skeletal trauma consistent with injury acquired during the recovery effort were present. Chief among these was a fracture of the distal left humeral diaphysis (Fig 13). This fracture occurred as the corpse was loaded into a wooden coffin in preparation for transportation to Innsbruck. Because the left arm stretched across the chest and thus extended well beyond the corpse's right side, the body would not fit into the coffin. When an attempt was made to reposition the frozen arm, a snap was heard, and the arm assumed a position parallel to the long axis of the body in contrast to the perpendicular position it held only moments before. CT images showed a "clean" fracture without evidence of healing, as would be expected.

Other evidence of upper-extremity trauma caused by tools used in the effort to release the body from the glacial ice included splintering of the right radial diaphyseal cortex (Fig 14), penetration of the right ulnar middiaphyseal cortex, and puncture of the right second metacarpal shaft. Ice picks, ice axes, ski poles, sticks, rocks, and a pneumatic jackhammer were some of the devices used to break up the ice. The full complement of "tools" used to chip away ice is not known. Thus, it is difficult to confidently pair an individual instrument with a particular skeletal injury.

The limited images of the iceman's hands and wrists are of good quality. They show normal anatomy with normal mineralization. There was no evidence of healed fracture, arthritis, or frostbite.

As observed in the upper extremities, the cortical and cancellous mineralization of the lower-extremity bones showed no evidence of osteopenia. In fact, the cortices of the femora, tibiae, and fibulae were thicker than what is typically encountered in modern populations. The linea asperae were well developed and prominent (Fig E11, *radiology.rsnajnls.org/cgi/content/full/2263020338/DC1*), as were the vascular nutrient canals within the thickened cortices. The anteroposterior diameters of the tibiae and fibulae were much greater than the mediolateral diameters (Fig 15). The anterior tubercles of the tibiae were wide, thick, and prominent. The thick lower-extremity long-bone cortices, prominent nutrient canals, exaggerated anteroposterior diameters, and conspicuous linea asperae and tibial tubercles suggested presence of powerful lower-extremity musculature. Unfortunately, the profound dehydration obscured the actual original muscle bulk.

A few faint Harris lines (13) were detected in the proximal and distal metaphyses of the tibiae (Fig 16). These were more numerous distally than proximally. No other Harris lines were discovered in the remaining long bones, as displayed on the survey images; however, optimized images of all metaphyseal regions have never been obtained. Harris lines are traditionally attributed to changes in nutrition or stress during growth and development. These lines are also termed growth "arrest" or "recovery" lines to emphasize either the inciting factor in their appearance or the new bone formation necessary for their appearance. Nutritional and/or stress events in the life of the iceman are speculative.

Lower-extremity skeletal injury acquired during the recovery effort included a shatter fracture of the midshaft of the left fibula and a puncture of the distal cortex of the left tibia. The right tibia was penetrated in midshaft, and a crack extended longitudinally along the posterior aspect of the bone (Fig 15). While it was difficult to correlate specific lower-extremity skeletal injuries with individual devices used to break up the glacial ice, certain injuries had distinctive characteristics. For example, there was a rectangular penetration of the right tibial plafond and adjacent preachilles soft tissues (Fig E12, *radiology.rsnajnls.org/cgi/content/full/2263020338/DC1*) that appeared to correlate with the blade of the pneumatic jackhammer.

Arthropathy was detected in the little toe of the left foot (Fig 17). The lateral aspect of the proximal phalangeal head contained a rounded subarticular lucency surrounded by faint sclerosis. The juxtaposed lateral aspect of the middle

Figure 10. Detail of the left side of the rib cage from a frontal computed radiograph of the iceman's chest (obtained on May 25, 1993) shows several well-healed rib fractures. The most conspicuous fracture is in the eighth rib (arrow). The multiple healed fractures indicate that the iceman survived one or more serious injuries during his life.

phalangeal base was definitely sclerotic, a feature associated with a degenerative spur. These combined features were categorized as osteoarthritis. Examination of the hands and feet demonstrated no other evidence of arthritis. After consideration of primary osteoarthritis and various causes of secondary osteoarthritis, the findings in the left little toe were attributed to the sequelae of frostbite.

At several sites in the extremities, the bone marrow exhibited an unusual pattern of focal lucency in cancellous regions (Fig 18). These findings were particularly pronounced in several lower-extremity metaphyses and tarsal bones. The patterns changed over time, a feature that provided insight into the cause. We interpreted the findings as evidence of water (ice) and air replacement of profoundly desiccated marrow. When ice filled the marrow space, homogeneous water and mineral density pattern were present, which we interpreted as normal. When some of the medullary ice thawed and the melted water drained from the diaphyseal or intertrabecular marrow spaces, air filled the vacated portion(s) of the marrow. This situation created irregular lucent zones without obvious normal anatomic boundaries. Additional thawing and air infiltration extended the size of these lucent zones. Measurements

Figure 11. Photograph of the posterior aspect of the iceman's pelvis and thighs (obtained in September 1991) demonstrates dehydration and shows the extensive left pelvic injury acquired as the body was recovered from the ice. The various tools used to break up the ice chipped much frozen soft tissue and some bone away. The left hip is disarticulated, as manifested by the exposed left femoral head (arrow).

obtained in the medullary cavities of long-bone diaphyses in Hounsfield units showed numbers consistent with those of water or air, according to which element existed in the marrow space being studied.

Organ Systems

Because of profound dehydration, the organs were shrunken and deformed. Some organs were difficult to identify with confidence, and several small organs were never located.

The central nervous system was relatively well preserved, as described and illustrated earlier. The peripheral nerves were never identified. The respiratory system had shriveled, with only wispy remnants of lung. The gastrointestinal system provided two landmarks for orientation: a dehydrated liver and a desiccated stool-filled transverse colon (Fig

Figure 12. Detail of the right hip joint from a transverse CT section (obtained on May 3, 1994) shows evidence of osteoarthritis, as manifested by proliferative bone (arrows), osteosclerosis, and small round subarticular lucent areas. True joint space width cannot be determined because dehydration of the hyaline articular cartilage caused artificial narrowing.

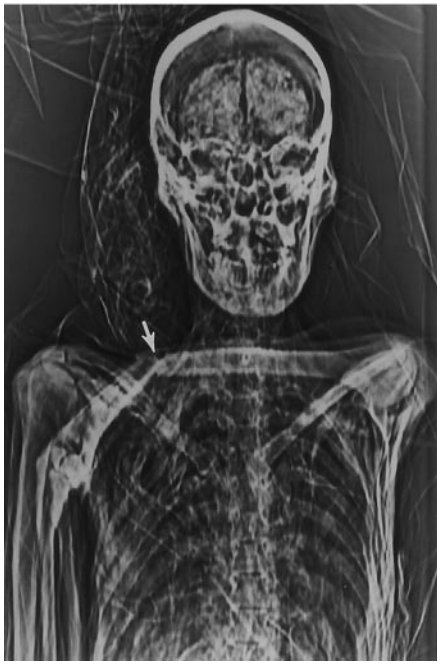


Figure 13. Frontal digital computed radiograph of the head and chest (obtained on September 25, 1991) acquired as a scout image in preparation for CT of the head and thorax shows the left humeral fracture (arrow) acquired when the completely recovered corpse was forcefully placed into a wooden box for transportation from the mountain by helicopter. Because the fixed position of the left arm extended across the chest prevented the body from complete enclosure in the coffin (the left arm and hand extended well beyond the right side of the mummy), a reduction of the unusual position was attempted. Because the shoulder was stiff and frozen, the force applied to the forearm caused the humerus to snap.

Figure 14. Anteroposterior radiograph of the distal right forearm (obtained on May 25, 1993) shows injury from an instrument with a sharp tip. Linear bone shards (arrows) were chipped away from the ulnar aspect of the radial cortex. The presumption is that an ice pick used to break up ice during the recovery effort inadvertently penetrated the arm.

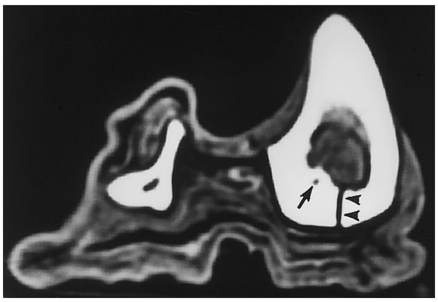


Figure 15. Transverse CT section through the diaphysis of the right tibia and fibula (obtained on May 3, 1994) shows thick cortices, a well-developed nutrient canal (arrow), and an elongated anteroposterior diameter of the bones, also present on the left side. It is surmised that this configurational oddity indicates a biomechanical adaptation to the requirements of life and labor on the slopes of the Alps. The cracked tibia (arrowheads) is attributed to trauma acquired during the recovery effort.

Figure 16. Detail of the distal right tibia from an anteroposterior computed radiograph of the right leg (obtained on May 25, 1993) shows several horizontal Harris lines (arrows) in the dimetaphyseal cancellous bone.

19). The stomach and small bowel were present but shriveled. The genitourinary system was so desiccated that the kidneys, ureters, and bladder were difficult to identify confidently, as was the spleen. Endocrine glands were never identified. The cardiovascular system had collapsed and withered. The heart and great vessels were identified as a flat, thin structure sandwiched between the sternum and the thoracic spine. None of the great vessels or their major branches were identified in the thorax or abdomen because all had lost their normal contours and surrounding soft-tissue relationships. Several calcifications were discovered in areas where arteries would normally be located. These included both carotid arteries at the sella turcica, the left carotid artery in the neck, the distal aorta (Fig 20), and the right iliac artery. No lymph nodes were identified. Thus, we were unable to derive much anatomic or pathologic information from study of the organs with CT.

In 2001, additional digital radiographs of the ribs and spiral CT images of the whole body were obtained at the Regional General Hospital in Bolzano. The rib images revealed an arrowhead lodged between the rib cage and the left scapula (Fig E13, *radiology.rsnajnls.org/cgi/content/full/2263020338/DC1*). In retrospect, the conventional chest radiograph from September 26, 1991, showed an opacity in the same location (Fig 21), now recognized as consistent with an arrowhead. A similar shadow was present on the image obtained with portable computed radiography on September 25, 1993. CT images obtained in Innsbruck (September 25, 1991, and May 3, 1994) and Bolzano (March 3, 2001) showed a linear structure between the ribs and left scapula (Fig 22), subsequently interpreted as an arrowhead on the basis of its detection on the rib images and its optimized demonstration on three-dimensional reconstructions from the CT data sets obtained earlier (Fig E14, *radiology.rsnajnls.org/cgi/content/full/2263020338/DC1*).

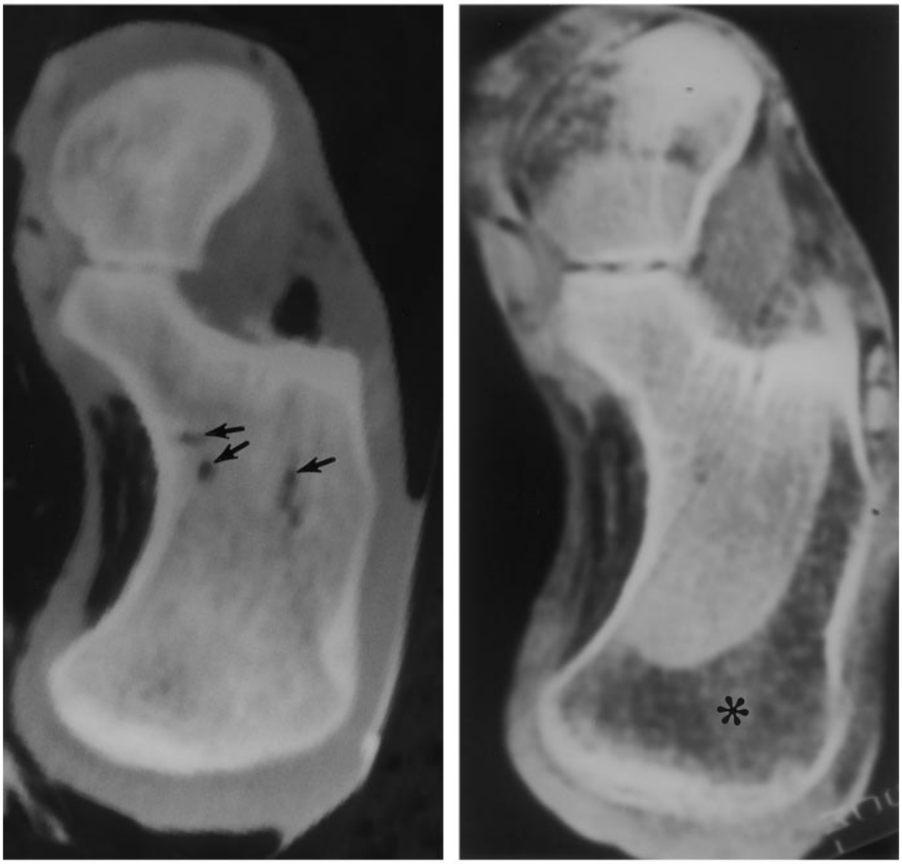
In addition to demonstration of the prehistoric arrowhead, the CT images displayed inhomogeneous areas of attenuation in the regional soft tissues around the left shoulder (Fig 23). These areas were relatively large and did not conform to known anatomic structures but rather were located in natural planes between normal anatomic structures. Anterior and lateral hyperattenuating areas were detected immediately caudal to the current location of the arrowhead. Taking into account their location, nonanatomic nature, and association with the arrowhead, these hyperattenuating areas were interpreted as the dehydrated remnants of a hematoma.

One CT image (Fig 23) showed what appeared to be evidence of penetration (perforation) of the ossified body of the scapula. In this location, the mineralized scapula was discontinuous. A small portion of the deep hematoma seemed to pass through the bone discontinuity. These findings were interpreted as evidence that the arrow passed through the scapula and injured a major vessel in the axilla, with a resultant hematoma.

When the iceman was found frozen in the glacier, there was no arrow protruding from him. Inspection of his back following discovery of the arrowhead in June 2001 revealed a small skin laceration over the scapula, close to the region where the discontinuity was present in the scapula. It was hypothesized that an arrow entered the iceman's left shoulder from the rear and caused a vascular injury. Furthermore, it is speculated that when the arrow was withdrawn, the overlying scapula interfered and caused the arrowhead to separate from the shaft. Thus, the arrowhead remained trapped between the rib cage and the scapula.

On the basis of discovery of the arrowhead and correlation with a tract verified with a probe, the cause of the iceman's death appears to be bleeding secondary to a puncture wound caused by an arrow. The manner of death, based on the location of the arrowhead and the fact that it entered from the rear, can be classified as either accidental or homicide. All of these image-derived findings and hypotheses remain to be corroborated in other future investigations.

Figure 17. Detail of the left little toe from an anteroposterior radiograph of the foot (obtained on May 25, 1993) shows a degenerative arthritic appearance of the proximal interphalangeal joint, manifested by sclerosis and spur formation (white arrow) at the base of the middle phalanx and a subarticular lucent area (black arrow) with minimal sclerosis at the head of the proximal phalanx. It is surmised that this lone abnormality of the digits represents healed frostbite.



a. b.

Figure 18. Marrow air distribution changes with time. **(a)** Transverse CT section through the left calcaneus (obtained on September 26, 1991) shows generally homogeneous water attenuation in cancellous marrow. Several small collections of air (arrows) are present in the marrow. Air is also present in soft-tissue planes and spaces. **(b)** Transverse CT section through the left calcaneus (obtained on May 3, 1994) more than 2½ years later shows a different marrow appearance, with much more air (*) in the calcaneal marrow space. Note a similar change in the talus and the soft tissues. It is postulated that the bones of the feet partially thawed in the interval. Air replaced marrow water that drained from portions of the marrow space.

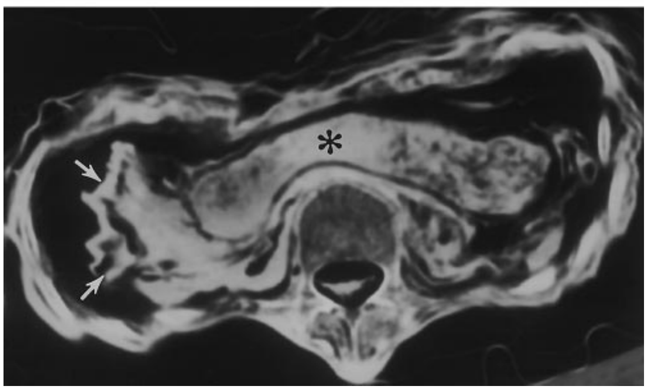


Figure 19. Transverse CT section through the upper abdomen (obtained on September 25, 1991) shows dehydration and severe shrinkage of the liver (arrows) and other organs. Only the transverse colon (*) has a reasonably normal shape. Stool from a prior meal(s) is present.

DISCUSSION

Conservation and Discovery

Conservation and discovery of the iceman's corpse were serendipitous occurrences. While much is unknown, some things are understood about the geographic and environmental factors required for conservation of the body. First, it was necessary for the corpse to avoid the activity of predatory animals that might encounter the body and regard it as a food source. Since there is no evidence of scavenger interference, it is clear that local environmental circumstances protected the body.

Second, climatic and geographic factors had to permit natural preservation and protection for more than 5 millennia. These criteria were met at an altitude of over 10,000 ft (3,000 m), where the sun was direct and hot but the ambient air was dry and cold. The corpse mummified. A glacier formed and was more or less constant for the duration necessary to protect the iceman.

During the 5,300-year interval, it is possible that one or more local glacial thaws occurred and that the iceman was partially or fully released from the glacier and defrosted. The corpse could have been exposed to water and air for periods

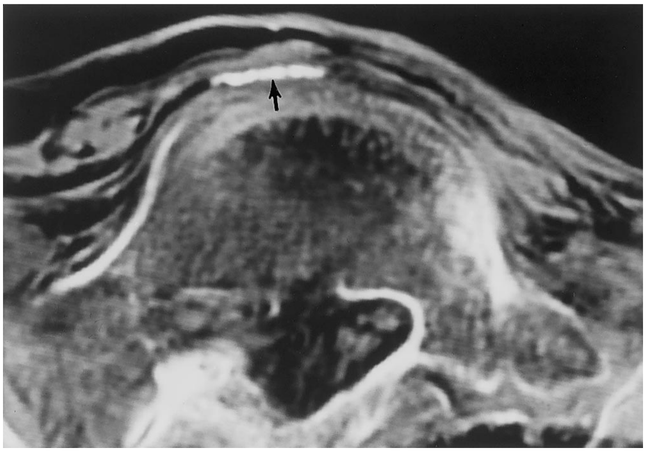


Figure 20. Transverse CT section through the lower abdomen (obtained on May 3, 1994) shows a linear calcification (arrow) closely juxtaposed to the anterior cortex of the transitional vertebral body. We interpreted this feature as calcification in the aorta, now collapsed following desiccation.

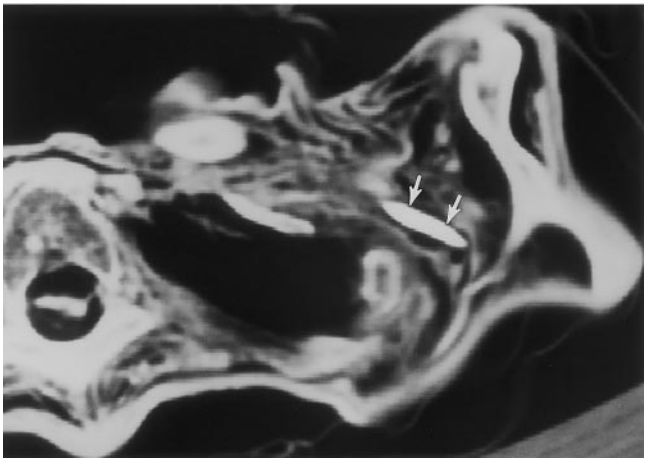


Figure 22. Transverse CT section through the shoulder region (obtained on September 25, 1991) shows a fusiform opacity (arrows), later shown to be an arrowhead lodged between the ribs and the left scapula.

Figure 21. Irregular opacity (arrows) in the left shoulder retrospectively detected on a conventional frontal radiograph of the chest (obtained on September 26, 1991) has the general configuration of an arrowhead. Also in retrospect, the arrowhead is visible on the radiograph obtained on May 25, 1993 (Fig 8).

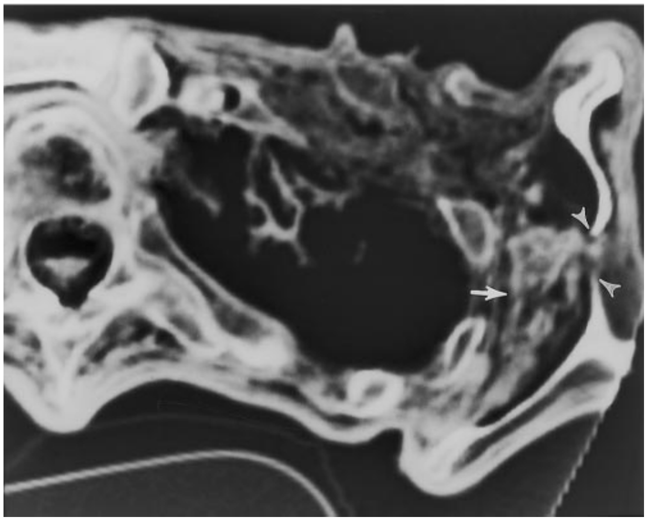


Figure 23. Transverse CT section (obtained on May 3, 1994) through the left shoulder region (caudal to the prehistoric arrowhead) shows an inhomogeneous area of attenuation (dehydrated hematoma, arrow) between the lateral rib cage and the scapula. Note the discontinuity in the ossified body of the scapula and the wispy soft-tissue opacity (hematoma) that extends through the bone defect (arrowheads). We speculate that the arrowhead and a portion of the arrow shaft penetrated the scapula in this location and that blood from the deep hematoma followed the arrow track into the subcutaneous tissues.

of days or weeks. If this happened, then the iceman avoided scavenger activity or other harm each time and subsequently regained safety within newly fallen snow and a refrozen glacier.

Because glacial ice moves and therefore slowly and relentlessly destroys anything in its path, the body required protection from glacial motion. The iceman was found frozen in ice in a natural trench oriented transverse to the glacial flow. Thus, while the body lay frozen in the ice-filled trench, the glacier passed over the iceman and left the corpse undisturbed.

Third, when the corpse partially emerged from the glacier in September 1991, circumstances needed to be such that the body would be discovered before it was harmed or became reencased in the glacier. Speculation is that the time window for discovery was very narrow, probably less than a week in duration. It is estimated that the iceman's head and upper back had been uncovered for no more than a few days at the time of discovery. Within several days of the discovery, snow again covered the scene. Thus, the circumstances of discovery were particularly serendipitous.

Preservation of the Corpse

It was necessary for the corpse to achieve a natural state of preservation capable of

- Frontal bone pacchionian granulations
- Prominent frontal eminences (supraorbital ridges)
- Diastema
- Absent third molars
- Eleven rib-bearing thoracic vertebrae
- Transitional lumbosacral segment

Figure 24. Anatomic variants discovered in the iceman.

TABLE 2
Evidence of Skeletal Trauma due to the Glacial Environment

Location of Trauma	Description
Skull	Mildly widened squamous and lambdoid sutures
	Many hairline cracks of facial bones
	Many hairline cracks at base of skull, including right occipital condyle
	Recessed facial bones
Thorax	Subluxation of costotransverse and costovertebral joints with rotated ribs
	Anteroposterior collapse of thorax
	Sternum shifted to right, slightly rotated, and juxtaposed to spine

Note.—The many hairline fractures of the skull and facial bones could have developed as a consequence of one or more freezing and thawing cycles, when the freezing water within the skull expanded and caused sutural diastasis and cracks in the bones. The weight of the snow and ice could have caused facial and skull fractures, facial deformity, and compression of the thorax.

withstanding the 5,300 years between death and discovery and any environmental challenges in the interim. The combination of natural factors that resulted in preservation of the iceman is incompletely understood. However, some general principles provide insight with regard to the iceman's preservation.

When a human dies, a sequence of processes begins that eventually leads to decomposition of the body (14,15). The categories of postmortem change that affect the soft tissues are putrefaction, adipocere formation, and desiccation (dehydration). Postmortem tissue change is modulated by environmental factors that include temperature, humidity, aerobic versus anaerobic conditions, and the types of microorganisms present. In combination, these factors yielded the degree of preservation encountered in this mummy. The dominant form of postmortem change evident now is desiccation.

Putrefaction, a sequence of chemical events initiated and maintained by bacteria, begins under the surface of the skin and mucous membranes. Typically, the epidermis detaches from basement membrane and sloughs. Bacteria produce gas throughout the body, and the distention causes rupture of tissues. The combination of bacterial enzymatic activity and autolysis causes liquefaction of all soft tissues. Eventually, only bones remain. Putrefaction can be prevented or interrupted by environmental factors such as dryness, cold, or anaerobic conditions.

Adipocere is a soapy, greasy, or waxy substance composed of saturated fatty acids derived from hydrolysis and hydrogenation of body fat (and possibly protein) that is mediated by anaerobic bacteria and facilitated by semidry or wet conditions. Any fatty tissue, including brain tissue, may be preserved by means of adipocere formation. The exact mechanism of this transformation is unknown, but the result is preservation of the altered tissues (14,15). The dominant form of postmortem change found in most glacial human remains is adipocere, and glacial bodies tend to be diffusely infiltrated by this substance. As opposed to this common situation, the iceman had no visible adipocere (microscopic evidence was present).

Desiccation (dehydration) leads to mummification. The typical environment necessary for mummification is one that is dry at any temperature.

Although the dominant mechanism of preservation in the iceman is desiccation, environmental conditions also permitted some degree of putrefaction and adipocere formation. In fact, by using a skin sample from the iceman, Bereuter et al (16) detected evidence of putrefaction (absence of the epidermis) and adipocere formation (presence of solid fatty acids).

Our imaging findings correlate well with the gross findings of desiccation, with little evidence of putrefaction or adipocere formation. The only finding that departs from the total picture of mummification is that compared with the liver, spleen, and kidneys, proportionately more brain volume is present. A possible explanation for this relative difference might be a difference in the balance of postmortem mechanisms of preservation. The fact that brain tissue is relatively protected from the ambient environment by the skull provides an opportunity for a higher-humidity environment for the brain than that for the rest of the body. This difference could lead to relatively greater adipocere formation in the brain, and hence, less desiccation.

Normal Variation

While the iceman's corpse is remarkably preserved and fascinating to study in an effort to learn about humans 5,000 years ago, it is important to remember that this mummy is only one representative from the population that existed in that part of the world at that time. This corpse may or may not reflect general characteristics of the contemporary population. DNA studies of the iceman's tissue were performed but were complicated by degradation due to postmortem alterations. The analysis did show that the iceman's mitochondrial type corresponded to that found in the present-day central and northern European population (17). Still, it seems wise to be cautious when forming interpretations or drawing conclusions based on observations of the iceman. Figure 24 shows the major anatomic variants detected in the iceman's body. All the variants found in the iceman are also found in current European and North American clinical populations. While it is interesting to note the number, type, and combination of anatomic variants discovered together in the iceman, we should probably do no more than record their presence.

Skeletal Injury

Inspection of the radiographic and CT images revealed extensive skeletal injury. We subcategorized these injuries into three groups: *(a)* fractures that occurred during the iceman's life, *(b)* cracks and deformities that probably developed during encasement in the glacier, and *(c)* damage acquired during the effort to recover the corpse.

With the images available for study, we are confident that the iceman experienced at least one episode of trauma to the thorax sufficient to cause rib fractures. The fifth through ninth ribs on the left side have posterolateral deformities that are typical of healed rib fractures. The deformities are arrayed lin-

TABLE 3
Trauma Acquired during the Recovery Effort

Location of Trauma	Description
Pelvis and proximal femora	Left posterior iliac spine absent
	Left S2 through S5 vertebrae absent
	Left sacroiliac joint disrupted
	Coccyx absent
	Left ischium absent
	Left femoral head and neck, greater trochanter, and intertrochanteric zone damaged
	Left femoral head dislocated
	Dorsal soft tissues of left buttock and proximal thigh absent
	Portions of pelvic contents absent
Upper extremities	Left humerus: transverse fracture of distal shaft due to rough handling
	Right radius: cortical splinters of medial distal shaft due to puncture
	Right ulna: cortical penetration of lateral midshaft due to puncture
	Right second metacarpal: cortical penetration of distal lateral shaft due to puncture
Lower extremities	Left fibula: nondisplaced shatter fracture of midshaft due to puncture
	Left tibia: cortical penetration of lateral distal shaft due to puncture
	Right tibia: cortical penetration of medial midshaft due to jackhammer puncture
	Right tibia: cancellous penetration of posteromedial plafond and adjacent talar dome due to jackhammer puncture

Note.—When the corpse was discovered, the head, neck, and dorsal upper torso of the iceman had emerged from the glacial ice. The remainder of the body was trapped in solid ice. To recover the body, the ice was fragmented with available tools, including sticks, ice picks, ski poles, and a pneumatic jackhammer. Because the recovery was accomplished in haste, the mummy acquired many injuries.

early across the adjacent ribs, a good sign that they occurred at the same time. The cortices are remodeled and without active callous formation. Thus, these fractures occurred well before the iceman's death. We found nothing about these ordinary fractures that shed any light on the manner in which they were acquired.

Glacial Trauma

Table 2 lists skeletal injuries categorized as hypothetically resultant from forces applied to the corpse during imprisonment in glacial snow and ice or as a result of changes the glacier underwent during the intervening 5,300 years. These skeletal injuries are of two types: *(a)* cracks in the skull and face and *(b)* deformity of the thorax.

CT images showed many cracks in the facial bones and the base of the skull. These were numerous and difficult to enumerate; typically, they were short hairline cracks. They were associated with slightly widened squamous and lambdoid sutures.

By the time we studied the iceman's head with CT, it had been exposed to the Alpine late summer sun for several days, followed by 2 days in the morgue in Innsbruck, much of the time at room temperature. The first CT images showed a shrunken brain surrounded by air in the calvarium. Any water that had been present within the calvarium had mostly drained by the time the examination was performed. It is reasonable to assume that the skull had previously been filled with water and that the corpse could have been subjected to more than a single freezing and thawing cycle. If that were true, then the expansion caused by intracranial freezing water would be sufficient to cause the multiple hairline cracks. One or more freezing and thawing cycles could also account for some of the cracks detected in the residual shrunken brain.

The thoracic deformity combines caudal rib rotation, rib subluxation at the costotransverse and costovertebral joints, and compression of the thorax. This combination suggests a balance of forces sufficient to cause these deformities. During early putrefaction, the soft tissues could acquire a degree of laxity. The desiccation process could augment rib rotation as skin shrinkage acted to move ribs. The weight of the snow and ice would provide sufficient force to collapse the thorax.

Damage during Recovery

Because the temperature was cold and the weather was expected to become stormy, there was great urgency to recover the body quickly. Since the corpse was frozen in ice and the site was remote, the recovery effort was complicated. Necessary tools were unavailable, and it was inconvenient to send for better tools. Therefore, whatever was handy was used to break up the ice. This included ice picks, ski poles, rocks, sticks, and a small pneumatic jackhammer. On the whole, the recovery effort was uncoordinated, incompletely and intermittently supervised, hastily accomplished, and performed without proper tools. As a result, the iceman's body was damaged (Table 3).

Because the head, shoulders, and upper back were naturally exposed and therefore did not require manual release from the glacier, there is no evidence of trauma to these parts of the iceman that may have been acquired during recovery. However, the parts of the body below the surface of the ice were variably damaged. It is easy to imagine how this happened because the trench continuously refilled with slushy water as the recovery effort progressed.

In all, both upper extremities, both lower extremities, and the pelvis were damaged. On the basis of the pattern of skeletal injury, it is possible to hypothesize the type of instrument that may have caused a few of the individual injuries, and there is evidence to implicate ice picks, ski poles, ice axes, and the blade of the jackhammer. Except for injuries on the left side of the pelvis, the damage consisted of limited puncture of soft tissues and bones rather than extensive destruction. In light of the conditions in which the recovery was performed, it is fortunate the damage to the corpse was not more severe.

Health-related Conditions

Information concerning the health of the iceman is of general interest. Table 4 lists evidence of injuries and health-related conditions the iceman may have experienced.

Among the various skeletal injuries documented in the iceman, most seemed to result from glacial mechanics and accidents that occurred during recovery. Only the healed left rib fractures are evidence of skeletal trauma that occurred during the iceman's life. These appear to be uncomplicated simple fractures, similar to those encountered in modern clinical practice. We know that such fractures are painful and that spontaneous recovery is expected, unless the injury is more extensive or a complication such as pneumonia occurs.

Evidence of degenerative arthropathy was present in the spine. In the cervical spine, the features of degenerative disk disease and apophyseal joint osteoarthritis were similar to the features seen in modern clinical practice. The C4-5, C5-6, and C6-7 locations are the same as those most commonly encountered today. Likewise, the L3-4 and L5–S1 features of apophyseal joint osteoarthritis are no different than those seen in modern experience. While it is an interesting exercise to speculate what life was like in the Alps over 5,000 years ago and how activities in those years might have contributed to degenerative spinal changes, it is sobering to realize that we do not understand the biologic or biomechanical inducers of modern spinal arthritis, particularly on an individual basis. Thus, it is not likely that we will pinpoint the cause of the iceman's arthropathies of the axial skeleton.

Similarly, there is evidence of mild osteoarthritis in the right sacroiliac joint and right hip joint. Even though we do not know the cause of the arthritis, we can speculate that the degenerative changes of the spine and hip were probably painful.

Of all 20 digits, only the left little toe shows any evidence of arthritis. The proximal interphalangeal joint shows minor sclerosis, subcortical lucency, and spur formation. These features are consistent with osteoarthritis, but since primary osteoarthritis does not typically manifest in this manner, a form of secondary osteoarthritis is a better interpretation. Of the few options (trauma, deformity, osteochondrosis, and cold damage) for causes of secondary osteoarthritis, frostbite is a logical choice. While joint changes typical of osteoarthritis are rare following injuries attributed to cold, they are known to occur (18–20). A reasonable hypothesis is that the iceman was part of a population that was well aware of injuries caused by the cold. Normalcy of the other 19 digits is good evidence that the iceman knew how to insulate himself from freezing temperatures.

A few calcifications were detected in locations where arteries are normally located. The arteries themselves cannot be identified because of mummification and distortion, but the calcifications are fairly typical of arteriosclerotic calcifications encountered on images in patients today.

TABLE 4
Evidence of Health-related Conditions

Condition	Evidence
Injuries	Arrowhead in left shoulder with hematoma
	Well-healed rib fractures of the posterolateral fifth through ninth ribs on the left side
Degenerative arthritis	Cervical degenerative disk disease at C6-7
	Cervical apophyseal joint osteoarthritis at C4-5
	Cervical uncinate spur formation at C5-6 and C6-7
	Lumbar spur formation at L5
	Lumbar apophyseal joint osteoarthritis at L3-4 and L5–S1
	Right sacroiliac joint osteoarthritis
	Right hip osteoarthritis
	Symphysis pubis osteoarthritis
Frostbite	Damage to left little toe
Vascular calcifications	Calcifications in both carotid arteries at sella turcica
	Calcifications in left carotid artery in neck
	Calcifications in distal aorta
	Calcifications in right iliac artery

Note.—During his lifetime, the iceman recovered from substantial trauma of the left ribs, developed moderate degenerative arthritis in his spine and right hip, probably had an episode of severe frostbite, and developed vascular calcifications. His death appeared to result from a vascular injury from an arrow wound.

TABLE 5
Evidence of Adaptation to Environment

Adaptation Type	Evidence
Cultural	Flattened, worn incisors
	Flattened, worn premolars and molars
Geographic	Thick lower-extremity long-bone cortices
	Prominent lower-extremity long-bone nutrient canals
	Prominent linea aspera of femora
	Prominent tibial tubercles
	Exaggerated anteroposterior diameters of tibiae and fibulae

Note.—The flattened and worn teeth may have been caused by dietary factors and by the additional use of the teeth as tools. The robust configuration of the lower-extremity long bones may be evidence of adaptation to a lifetime of work and travel in the mountains.

In combination, these calcifications may present a surprising amount of evidence for arteriosclerotic cardiovascular disease, particularly if we share the perspective that this condition is a modern affliction facilitated by lifestyle, diet, and tobacco use.

Age at Death

Determination of the iceman's age at death is difficult and inexact. Because all epiphyses were closed, the lowest estimate of age is young adulthood. Bone mineral content was excellent, and the lower-extremity long-bone cortices were particularly thick. While these features might favor a person in their 20s or 30s, it must be remembered that the iceman's life was probably spent in the Alps, where exercise favored thick cortices as long as the person remained active. Evidence of osteoarthritis and vascular calcification might favor an older age, perhaps 50s or 60s. However, a mountain lifestyle might accelerate wear and tear, and perhaps diet and/or genetic factors favored vascular calcification. Lacking better justification, 40–50 years of age seems a reasonable estimate for the iceman when he died.

Adaptation

Certain features detected in the corpse suggest that the iceman's body had adapted to cultural and environmental influences (Table 5). The teeth show evidence of cultural adaptation. All teeth were worn flat, with the exception of the last cusps on second molars, where they were not apposed by portions of teeth above or below. The flattened premolars and molars are assumed to result from the grinding action of chewing. It is known that einkorn wheat grain was ground, made into meal, and baked into bread. Stone particles in the ground meal

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and crust from the hard bread would cause abrasive action. Uniform wear of the grinding teeth would result (21).

The worn incisors probably reflected use of the teeth as tools to work leather strips for clothing and other requirements. Saliva wets the leather, and the teeth act to soften and form the leather into the desired length and shape. Constant drawing of leather strips back and forth across the incisors would cause uniform wear. Additionally, no caries were discovered by means of conventional radiographs, CT images, or limited inspection of the visible aspect of the front teeth.

Of interest were the conformational alterations of the lower-extremity long bones. First, the cortical thickness of the long bones was greater than that usually encountered in the average modern clinical population. Thick cortices were associated with prominent nutrient canals and attachments for muscles (linea asperae) and tendons (tibial tubercles). These features suggest adaptation to a lifestyle that required constant use of the lower extremities, with development and maintenance of powerful muscles. It is speculated that constant climbing and hiking through the Alps would be sufficient to cause such muscle and bone development.

Second, the tibiae and fibulae exhibited exaggerated anteroposterior diameters. These femoral, tibial, and fibular diaphyseal shapes appear to reflect the mechanical force or loading placed on them during lifetime activity (22).

Nondestructive Testing

Conventional and computed radiography coupled with CT provided a means to achieve nondestructive testing of the iceman mummy. Imaging yielded basic anatomic information of use to anthropologists and other scientists and permitted investigation of internal structures without performing a traditional autopsy. When scientists wished to attempt endoscopic or laparoscopic investigations, images helped plan approaches that would minimize technical difficulty and maximize yield. As an example, initial CT study showed convincing evidence of stool in the transverse colon. By using CT images as a map, a small stool sample was obtained. Evaluation showed that the iceman's recent diet consisted of unleavened bread made from finely ground einkorn wheat. The tiny particles of charcoal associated with the bran suggested a baking process. Fragments of muscle fiber and burned bone indicated that meat was part of a recent meal. These results and others have helped scientists understand much about the natural and cultural environment in which the iceman lived. Thus, imaging played a faciliatory role in the investigations of other scientists.

Cause and Manner of Death

On the basis of the finding of an arrowhead in the soft tissues of the shoulder, the cause of the iceman's death is postulated to be bleeding from a vascular injury. A small tear was present in the skin of his back, and this permitted insertion of a probe that followed a track toward the arrowhead (23,24). The fact that the arrow entered the iceman from behind suggests that the manner of death was either accidental or homicide. Without other evidence, we will not be able to determine more about the circumstances surrounding the iceman's death (25).

In conclusion, while imaging provided sensational information regarding the cause or manner of the iceman's death, it just as importantly provided much information about his postmortem mummification, encasement in the glacier, recovery from the ice, anatomy, health, and adaptations to culture and environment. Although more than 5,000 years have passed since the iceman lived and died, the similarities between him and modern humans are impressive. Because of the unusual circumstances of his preservation and discovery, modern humans have the opportunity and good fortune to be transported more than 5,000 years back in time. The richness of the iceman's remains and personal belongings provides a unique window into our common heritage.

In January 1998, the iceman was transferred from Innsbruck, Austria, to a permanent museum facility in Bolzano, South Tyrol, Italy. The government of South Tyrol remodeled a building and installed a sophisticated environmentally controlled chamber to preserve the iceman. The museum is about 30 miles from the glacier that held him until 1991. At the museum, a visitor may view the mummy and learn about the iceman by studying exhibits concerning his belongings and culture.

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References

1. Spindler K. Der mann im eis: die Ötztaler mumie verrät die geheimnisse der steinzeit. Munich, Germany: Bertelsmann, 1993.
2. Spindler K. The man in the ice: the discovery of a 5000-year-old body reveals the secrets of the Stone Age. New York, NY: Harmony Books, 1994.
3. Fowler B. Iceman: uncovering the life and times of a prehistoric man found in an Alpine glacier. New York, NY: Random House, 2000.
4. Elmer-Dewitt P. The 4000-year-old man: mummified remains of an ancient mountain climber give scientists a rare glimpse into life in the early Bronze Age. Time, 7 October, 1991; 138:48.
5. Eijgenraam F, Anderson A. A window on life in the Bronze Age: the remains of a 4000-year-old man may shed light on the racial structure and culture of early Europe. Science, 11 October, 1991; 254:187–188.
6. Jaroff L. Iceman: the discovery of a frozen 5,300-year-old wanderer—the world's most ancient intact human—stirs passion and controversy and opens a window on life in the Stone Age. Time, 26 October, 1992; 140:62–66.
7. Roberts D. The iceman: lone voyager from the Copper Age. National Geographic 1993; 183:36–67.
8. Barfield L. The iceman reviewed. Antiquity 1994; 68:10–26.
9. zur Nedden D, Wicke K. Der eismann aus der sicht der radiologischen und computertomographischen daten. In: Höpfel F, Platzer P, Spindler K, eds. Der mann im eis, Band I, bericht über das Internationale Symposium 1992 in Innsbruck, the University of Innsbruck 187, Innsbruck, Austria, 1992; 131–148.
10. zur Nedden D, Knapp R, Wicke K, et al. Skull of a 5300-year-old mummy: reproduction and investigation with CT-guided stereolithography. Radiology 1994; 193: 269–272.
11. Seidler H, Bernhard W, Teschler-Nicola M, et al. Some anthropological aspects of the prehistoric Tyrolean ice man. Science, 16 October, 1992; 258:455–457.
12. Wilfing H, Seidler H, zur Nedden D, et al. Cranial deformation of the neolithic man from the Hauslabjoch. Coll Anthropol 1994; 18:269–282.
13. Garn SM, Silverman FN, Hertzog KP, Rohmann CG. Lines and bands of increased density: their implication to growth and

Radiology

development. Med Radiog Photog 1968; 44:58–89.
14. Haglund WD, Sorg MH, eds. Forensic taphonomy: the postmortem fate of human remains. Boca Raton, Fla: CRC, 1997.
15. Micozzi MS. Postmortem change in human and animal remains: a systematic approach. Springfield, Ill: Charles C. Thomas, 1991.
16. Bereuter TL, Mikenda W, Reiter C. Iceman's mummification: implications from infrared spectroscopical and histological studies. Chem Eur J 1997; 3:1032–1038.
17. Handt O, Richards M, Trommsdorff M. Molecular genetic analyses of the Tyrolean ice man. Science, 17 June, 1994; 264:1775–1778.
18. Ellis R, Short JG, Simonds BD. Unilateral osteoarthritis of the distal interphalangeal joints following frostbite: a case report. Radiology 1969; 93:857–858.
19. Selke AC Jr. Destruction of phalangeal epiphyses by frostbite. Radiology 1969; 93:859–860.
20. Tishler JM. The soft-tissue and bone changes in frostbite injuries. Radiology 1972; 102:511–513.
21. Müllner A, Platzer W, Wilfing H, zur Nedden D. Zur morphologie des zahn- und kieferapparates des mannes vom hauslabjoch: vorläufige makroskopische befunde und mögliche interpretationen. In: Höpfel F, Platzer P, Spindler K, eds. Der mann im eis, band I, bericht über das Internationale Symposium 1992 in Innsbruck, the University of Innsbruck 187, Innsbruck, Austria, 1992; 227–232.
22. Ruff CB. Biomechanical analyses of archeological human skeletons. In: Katzenberg MA, Saunders SR, eds. Biological anthropology of the human skeleton. New York, NY: Wiley-Liss, 2000; 71–102.
23. Holden C. Ötzi death riddle solved. Science, 3 August, 2001; 293:795.
24. Kluger J. Who done it? Murder in the ice. Time, 6 August, 2001; 158:55.
25. Gostner P, Egarter Vigl E. Report of radiological-forensic findings on the iceman. J Archaeol Sci 2002; 29:323–326.