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New radiological insights into the life and death of the Tyrolean Iceman

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ABSTRACT

The radiological examinations carried out on the Tyrolean Iceman (5300 B.P.) in Bolzano between 2001 and 2006 have undergone a new, systematic re-appraisal, during which new findings have been added to those already known beforehand. Until now, it has been assumed that the Iceman's stomach was empty (due to the fact that this organ could not be localised), the colon contents constituting the Iceman's last meal. During this re-appraisal, however, the stomach could not only be exactly identified, but was also found to be well-filled, shedding new light on the scenario leading to his violent death. In addition, several other novel aspects were observed: three gallbladder stones were found which, in combination with the previously identified atherosclerosis, indicate that the Iceman's diet may have been richer in animal products than previous studies have suggested. The signs of enthesopathy in the knees indicate that he spent many hours wandering in the mountains. Several radio-opaque objects superficially embedded within the soft tissue were identified as being of taphonomic origin. The right humerus was found to be postmortally fractured.

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On the 19th of September 1991, the mummified body of a man was discovered in the Ötztal Alps at an altitude of 3210 m. It soon became clear that this glacier mummy was the remains of a man who lived around 3300 B.C. and died at an age of approximately 40–50 years in the high alpine area (Seidler et al., 1992; Gaber, 1999). The "Iceman", also referred to as "Ötzi" after the region in which he was found, is now kept together with his well-preserved clothing and equipment at the Archaeological Museum in Bolzano in a specially constructed, permanently monitored climatic cell.

Upon request of the museum, the Iceman was examined by the radiological team at the Bolzano Central Hospital, in the hope of obtaining further information through computer tomography, as well as to evaluate the preservation status of the valuable mummy.

Although numerous radiological studies on the Iceman have already been published (Gostner et al., 2004; Murphy et al, 2003; zur Nedden and Wicke, 1992; zur Nedden et al., 1994), further investigations using new technology, as well as repeated re-appraisals and re-evaluations of the image material can still be of great value. This is exemplified by the fact that an arrowhead lodged within the mummy's left shoulder region was not discovered until ten years after the first x-ray images were taken (Gostner and Egarter Vigl, 2002). By means of multislice CT scan technology with an improved work station, researchers were able to obtain detailed images of the damage caused to the blood vessel by the arrowhead (Pernter et al., 2007).

This paper presents five new radiological findings and investigates as to how far these add further historical insight into the Iceman's lifetime habits and the circumstances leading to his death, which remain unclear to this day.

1. Material and methods

The conventional X-ray images of the mummy were made in June 2001 and March 2002 at the Institute of Radiological Diagnostics of the Central Hospital of Bolzano using portable X-ray equipment (Siemens Erlangen, combined with the digital radiography system ADC, Agfa) at the South Tyrolean Archaeology Museum. The images were then evaluated in the Institute for Radiological Diagnostics at the Central Hospital of Bolzano.

For the first computer tomography examination carried out in Bolzano, the mummy was transported to the aforementioned Institute of Radiological Diagnostics in February 2001, where a Somatom 4 (Siemens Erlangen) computer tomograph was available at that time.

The second examination was performed at the same institute in August 2005 with a Sensation 16 multislice computer tomograph and Leonardo Leo Syngo 2004A VD10B work station (Siemens Erlangen).

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To prevent further decomposition, the valuable mummy was not thawed for any of the radiographic examinations. As the reliable performance of the CT equipment is only guaranteed at room temperature, a swift examination was essential. The left arm of the mummy is frozen in an upward-transverse direction (Fig. 1), hindering the examination of the neck and upper thoracic region. Therefore, to obtain a complete series of images, the stiffly frozen body had to be introduced into the CT machine from two different directions, once head-first and once feet-first.

Fig. 1. The Neolithic glacier mummy from the Ötztal Alps in the laboratory cell of the South Tyrolean Archaeology Museum.

1.1. General preservation

The radiological images reveal a remarkably high mineral content within the mummy's skeletal structure, resulting in an optimum preservation of bone and joint morphology. The anatomical details are comparable to those of contemporary humans. There are, however, several regions of varying sizes of increased radiological transparency with loss of bone substance. These do not constitute a pathological condition, but are signs of post mortem change. The long bone marrow cavities are mainly filled with air.

The soft tissue has shrunk extensively due to the desiccation process. These areas all appear relatively homogenic with density values comparable to those of fat due to the fatty decomposition of the tissue. Many muscles and internal organs cannot be differentiated at all or at least not without considerable difficulty. On the other hand, gas and air accumulation have caused several anatomical structures, such as the hardened meninges, the costal pleura, several nerves, tendons and joint parts, to become even more distinct than they would appear in the X-ray image of a living person.

A qualitative and quantitative comparison of the CT examinations in 2001 and 2005 revealed no further changes of these taphonomic bone and soft tissue modifications during this time period. The visual aspect of the radiological images of bone and different soft tissues, such as brain, liver and muscles, and the distribution of gas inside the mummy showed no differences between 2001 and 2005. Radiological density measurements (HU) revealed that the values for bone and soft tissues has not undergone any changes.

2. Results

Within the subcutis of various body regions and the directly underlying tissue layers, numerous radio-opaque particles of up to 2 mm size are visible. These are found in the neck, back and shoulder region, predominantly on the right side and in those regions where desiccation processes had caused shallow depressions (Fig. 2). Furthermore, they are to be found in the anterior part

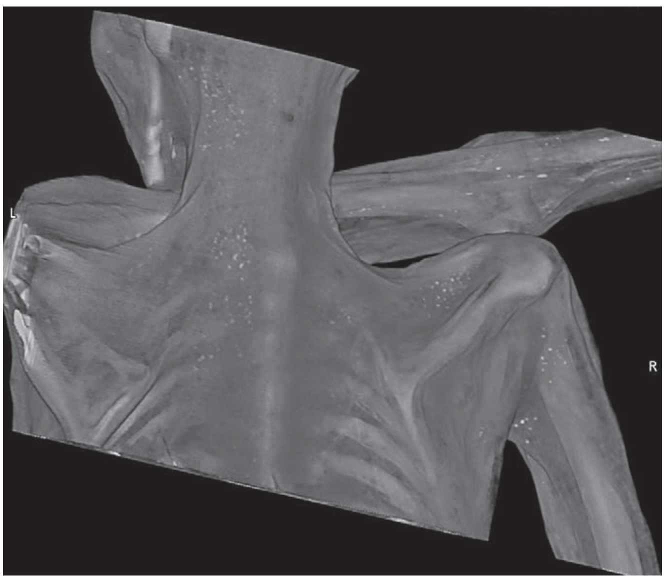

Fig. 2. Three-dimensional reconstruction of the shoulder region, dorsal view: numerous grouped radio-opaque inclusions are visible in the superficial tissue layers, predominantly situated in the shallow depressions in the body surface.

of the left arm and the antecubital fossa, in the dorsal and lateral side of the right arm, in the right orbital, buccal and maxillary region of the face (Figs. 3 and 4) and in the region of the anterior iliac horns. These are missing in the anterior thoracic wall, in the abdominal wall and in the lower extremities.

Another remarkable observation was made within the abdominal area: In the upper abdomen, a transversely situated, inhomogenous structure is visible, corresponding to a hollow organ of the digestive system. Sagittal reconstructions show that this organ stretches from the region of the cardia first in caudal direction, then towards the right into the upper right abdomen. The shape and topographical site of this organ (Figs. 5 and 6) show that it is not, as hitherto assumed, the colon transversum (Murphy et al, 2003), but is in fact the stomach. The contents are largely inhomogenous. The transverse colon is recognisable as a narrow, horizontal strip situated caudal of the stomach.

In the putative gallbladder site, at least 3 small (up to 3.5 mm), round objects with a mean density of 614 HU (ranging from 241 to 988 HU) are visible and recognizable as gallstones. These are surrounded by inhomogenous, softer material (Fig. 5).

With regard to the skeleton, additional findings in the ulnae, right humerus and the knee joints are of particular note. Both ulnae appear noticeably shorter than the radii. The right humerus shows a simple fracture of the shaft with an oblique fracture line, AO classification I2-A2, with neither displacement of the fragments (Fig. 7) nor signs of soft tissue swelling, haematoma or callus formation. The skin surrounding the fracture site is intact.

The right knee joint is slightly rotated inwards, the left extensively rotated outwards. Size and configuration of the articulations are within a normal range on both sides, but both show a modified

Fig. 4. Three-dimensional reconstruction of the shoulder region, ventral view: radio-opaque inclusions are to be seen in the right facial side and the right shoulder region.

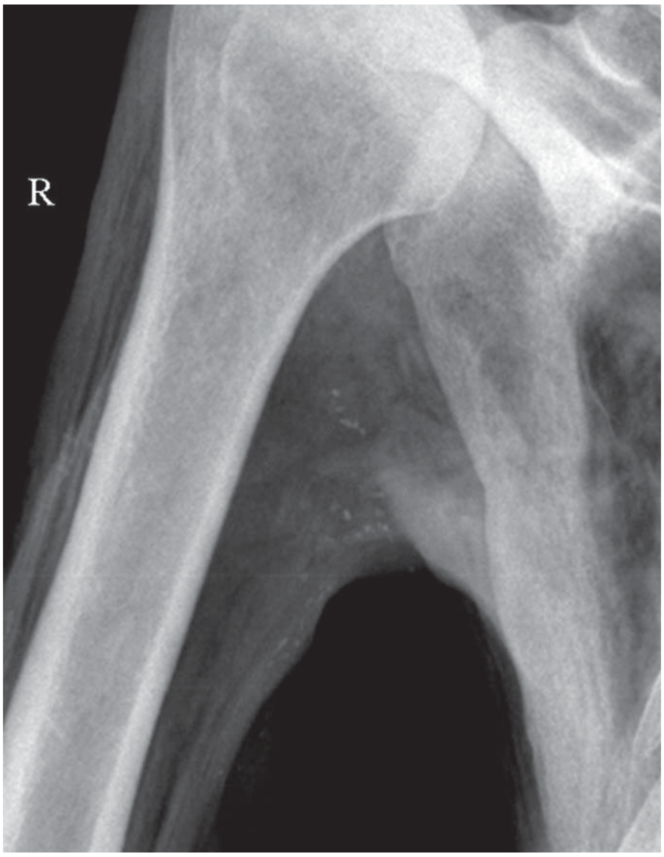

Fig. 3. The x-ray image of the right shoulder and the soft tissue image of the left side of the neck show multiple dot- and strip-shaped soft tissue inclusions.

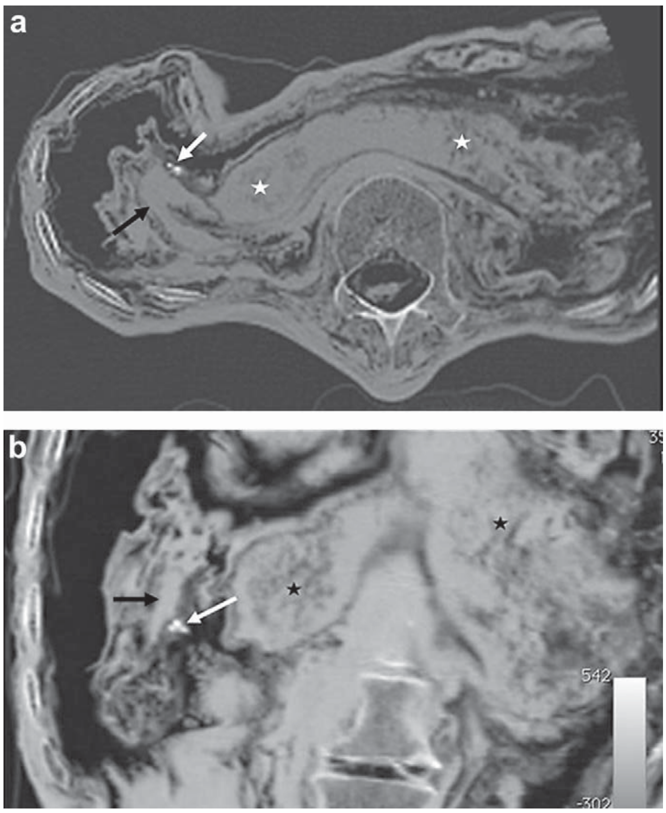

Fig. 5. In the axial CT images of the abdomen (a) a tubular, inhomogeneous organ is visible below the diaphragm, which can be identified as the full stomach due to its topographical site (asterisks). The right-view paravertebral reconstruction (b) show, respectively, two and three calcifications in the putative gallbladder site, which can be identified as gallstones (white arrows) and to the right of the stomach the extensively shrunken liver can be seen (black arrows).

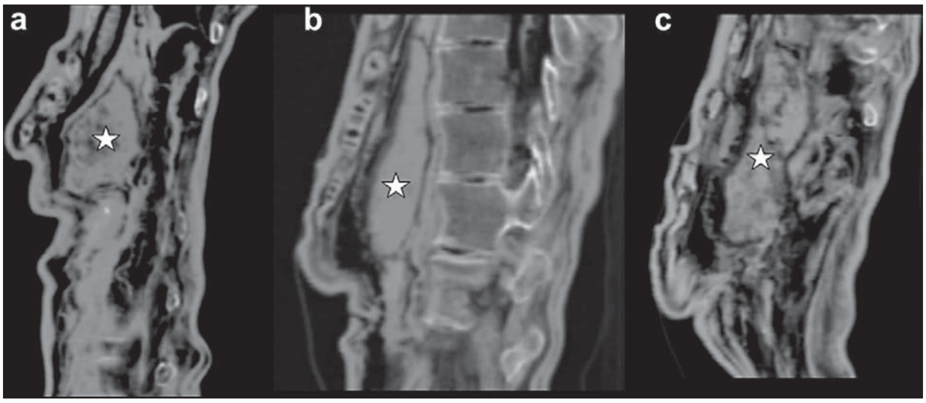

Fig. 6. Three sagittal CT reconstructions through the upper abdomen, right paravertebral (a), median sagittal (b) and left paravertebral (c): the organ in the upper abdomen shows the typical form and topographic site of the stomach (asterisks). Below, intestinal loops are visible.

structure. Patchy, inhomogeneous zones of varying sizes and reduced density are visible. Within the right tibia and left femur, these zones extend without interruption into the bone cavity. Marginal loss of bone substance is observed along the lower outline of both patellae. These modifications are signs of post mortem bone degradation.

The articular surfaces are smoothly defined. The medial tibia condyles show a slightly increased subchondral mineralization, as do the lateral articular facets of the kneecaps, indicative of knock knees. At the tendinous attachment of the M. quadriceps femoris, the cortical bone of both patellae is thickened and roughened with small calcium deposits on the right (Fig. 8). Numerous small calcifications are visible also in other tendons and ligaments (Fig. 9). Air is present within both knee joints. In the left knee joint, the lateral part of the intra-articular space is widened, the medial part narrowed. In the right knee, the medial part of the intra-articular space is broadened and the lateral part completely closed. The menisci are well defined on both sides, appearing homogenous with no indication of calcium deposits or fractures. The right lateral and left medial menisci are slightly compressed; the right lateral meniscus is additionally subluxated outwards. The cruciate ligaments are well defined along their entire lengths.

3. Discussion and conclusions

3.1. Vivianite inclusions

The grain- or strip-shaped radio-opaque skin inclusions in various body parts have hitherto been disregarded in radiological evaluations; they do not correspond to any clinical picture and are therefore interpreted as post mortem inclusions. However, as some of these are macroscopically visible as blueish-black dots, they were already examined in 1992 at the University in Innsbruck. These consist of iron phosphate (vivianite: $Fe_3(PO_4)2\text{-}8(H_2O)$), a compound which is commonly found in fossil bones and molluscs, and also develops in mummies when iron salts from the surrounding area enter the body tissues (Edwards et al., 1996; Tessadri et al., 1996). The ground at the site where the Iceman was found does indeed contain iron and the particles are radio-opaque. Other macroscopically visible dots and patches, such as those in the vicinity of the tattoos, are not visible in radiographic images. These were found to contain charcoal particles (van der Velden et al., 1994).

The vivianite inclusions show a special distribution pattern. These are not only present in those parts of the body which had lain directly upon the rocky ground (right facial side and upper arms), but also appear in numerous quantities in shallow depressions in the region of the neck, back and shoulder blades, which had lain furthest up. The iron could not have reached these areas via the ground. A much more plausible explanation is that it originated from material washed by melt water into the pit in which the Iceman lay, where it collected in those depressions in the body surface which now show the radio-opaque skin inclusions.

As neither the anterior surface nor the other parts situated lower down in the rocky recess show any radio-opaque particles, it is safe to assume that the rock pit, in which the Iceman was discovered lying face-down, only thawed superficially now and again, causing the uppermost body parts to come into contact with water, whilst the greater part of the body itself remained frozen within the ice. This hypothesis is supported by the observation that the legs and front side of the mummy, which had at the point of discovery been completely encapsulated within the ice, were mostly covered with clothes, the feet still in well-preserved shoes.

Fig. 7. Three-dimensional reconstruction of the right shoulder: fracture of the right humerus.

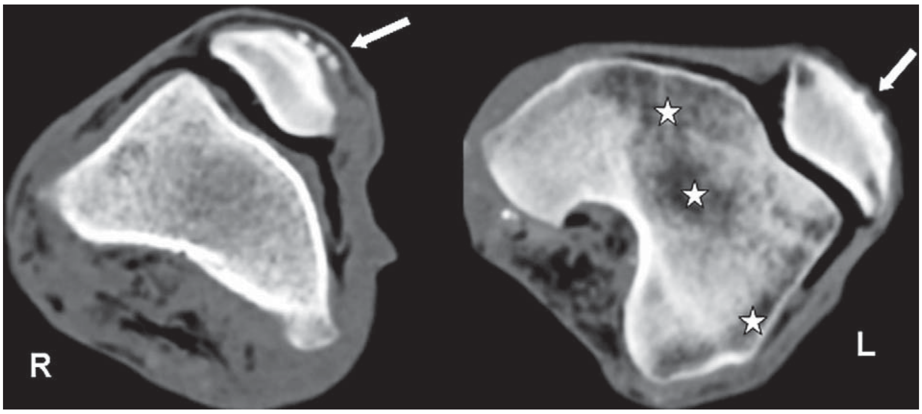

Fig. 8. CT section image through both patellae: along the anterior margin, the cortical bone appears bilaterally thickened and roughened with calcium deposits upon the right patella (arrows), constituting an enthesopathy. Several points of decomposition are visible within the bone substance, as shown by irregular translucent areas (asterisks).

The back and shoulders, on the other hand, were bare (Rastbichler Zissernig, 2006). These parts, which had lain farthest up, had thawed from time to time, causing the clothes to decay and to be dispersed by the wind.

As the pit and therefore the Iceman apparently only ever thawed superficially rather than completely, the body was preserved for thousands of years.

3.2. Skeleton

As the archaeological value was not recognised until some time after the discovery, heavy equipment was employed in the recovery of the body, causing extensive damage to bones and soft tissue. During the recovery of the corpse, it was realised that the left humerus had been broken through careless handling. The fracture of the right humerus, on the other hand, was only recently discovered through 3D-reconstructions derived from the latest CT scan examination. Retrospectively, this injury was verified in all axial CT images in Bolzano and Innsbruck, it had simply gone unnoticed in earlier evaluations. The soft tissue and skin in the region of the fracture is intact. This indicates that the fracture of the right humerus occurred during recovery, as was the case with the left humerus.

The knee joint shows only slight degenerative, osteoarthritic changes. The calcifications of tendons and their entheses constitute an enthesopathy (Resnick and Niwayama, 1983). The most common cause of this condition is a repeated, heavy strain placed on the joint in question. It usually causes pain and swelling of the knee joint during (weight-bearing) activities that dies down after relaxing of the joints. Enthesopathies are indicators of the affected person's habits and activities (Stirland, 1998). The knee disorder in the Iceman presents the image of a man accustomed to strenuous walks in high altitude terrains, rather than that of a valley dweller who rarely wandered into the mountains. Therefore, the Iceman's frequent mountain walks are the most likely contributory factor. It can be further speculated that the Iceman suffered from knee pain caused by the enthesopathy during his walking activities.

With regard to the carpal joints, both ulnae appear shorter than the radii, constituting a bilateral ulna-minus variant according to Hultèn (Hulten, 1928) (Fig. 10), which occurs frequently and is occasionally connected to pathological conditions of the lunate and scaphoid bones of the wrist. However, several authors draw attention to the potential distortion caused by the position of the lower arm: A supine position of the forearm may cause a normal ulna to appear as a minus variant, whereas a prone forearm reduces the optical extent of a minus variant, therefore necessitating a standard position for relevant imaging diagnosis (Epner et al., 1982; Yeh et al., 2001; Jung et al., 2001). As the mummy could not be thawed for the examination, such positioning was not possible: The Iceman's right forearm is supine, whereas the left forearm is in a prone position (Fig. 1). Even when this factor is taken into account, the radiological images still indicate a bilateral ulna-minus variant, more pronounced in the right side than in the left. In the right wrist the ulna is 2 mm shorter compared to the radius. No pathological conditions of the lunate or scaphoid bones are visible.

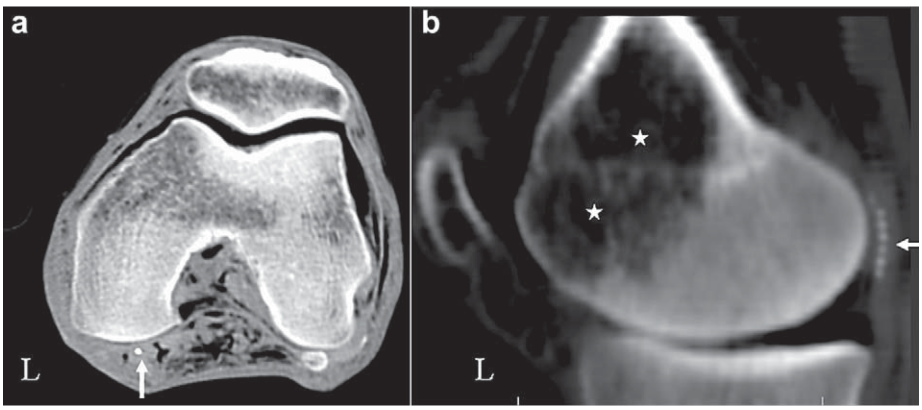

Fig. 9. Axial section image (a) and sagittal CT reconstruction (b) of the left knee joint: a bead-string shaped calcification (arrows) is visible within the tendon on the musculus semimembranosus. Decompositional lesions are visible in both the femur and the patella.

Fig. 10. X-ray image of both hands and carpal joints: ulna-minus variant bilaterally present, more pronounced on right side.

3.3. Stomach

Within the upper abdomen, an organ is visible which, due to its shape and topographical site, can be identified as the stomach. It is full of a meal of which the Iceman must have partaken shortly before death, possibly near to or at the spot in which he was killed. The fact that the stomach could not be located radiologically, and the failure of an attempt (carried out at Innsbruck University) to recover stomach contents per laparoscope, led to the previous assumption that the stomach was empty (Spindler, 2000).

It seems, however, that the laparoscopy was unsuccessful due to the stomach being situated relatively high up, in a transverse position behind the ribcage. It soon became clear that the obtained material came from the colon. It contained bone fragments from ibex and deer (Rollo et al., 2002), which are also radiologically visible within the colon. No bone particles are to be found in the stomach. Up to now, the colon contents were presumed to contain the Iceman's last meal (Oeggl, 1999). The full stomach could provide further insight into the last hours of the Iceman's life. In previously reconstructed scenarios the Iceman was fleeing from his pursuers after the first skirmish, which caused the cut wound to the hand (Nerlich et al., 2003). The new finding of a completely filled stomach make these scenarios unlikely, as the Iceman wouldn't have been able to have a large meal under the heavy stress of a chase. It much more appears that he considered the situation safe enough to rest and eat a heavy meal after the strenuous ascent. Shortly afterwards, he could have moved a short distance away from his place of rest and was killed by a surprise ambush from behind.

In November 2010, the Iceman's stomach contents were sampled through an incision which had been made in the abdominal wall several years before. The sampled material, which presented a homogenous, earth-like macroscopic appearance, are currently undergoing microscopical, microbiological and genetic analyses to determine (amongst other aspects) the exact nature on the Iceman's last meal.

3.4. Gallstones

Although the conservational status of the valuable mummy did not permit an extraction of one of the gallstones, previous studies have shown that the composition can be accurately evaluated through CT density measurements (Brakel et al., 1990; Brink et al., 1994). The values obtained for the stones in question indicate a mixed calcium-cholesterol-pigment composition. The combination of gallstones and the previously identified atherosclerosis (Murphy et al, 2003) in a man aged 40–50 years could indicate a predisposition towards early vascular calcification, for example due to a high cholesterol level in the blood. The man's diet could also have played a certain role, especially as the enthesopathic findings show that he did not lack sufficient exercise. On the basis of stable carbon and nitrogen isotopes from the Iceman's hair, as well as the high degree of dental abrasion (typical of a high level of plant fibre in the food), Macko et al. (1999) drew the conclusion that the Iceman maintained a predominantly vegetarian (or even vegan) diet. However, the colon contents were shown to contain meat remnants (Dickson et al., 2000), providing the first contradiction to the vegetarian hypothesis. It could be argued that the alimentary tract contents represent only a momentary image and not the long-term nutritional habits. However, the presumption that a high cholesterol level may have been a potential cause of the atherosclerosis and gallstones, point towards a higher long-term level of animal product intake than assumed on the basis of the aforementioned isotopic analyses (Lecerf and de Lorgeril, 2011). One popular hypothesis states that the Iceman many have been a semi-nomadic herdsman (Spindler, 1994), supervising animals on high alpine pastures, perhaps in the course of transhumance. This theory is supported by recent mass spectrometric analyses of the Iceman's fur clothing, which were apparently derived from domesticated rather than from wild animals (Hollemeyer et al., 2008). In this case, one would expect a substantial amount of dairy, and possibly meat, foodstuffs in the diet which would in all probability lead to high cholesterol levels in the blood.

To ascertain which role the diet played in the development of the Iceman's atherosclerosis and gallstones, genomic analyses of the Iceman's nuclear DNA are currently addressing the question of a potential genetic predisposition.

The findings presented in this paper illustrate the potential benefit of repeated evaluation of existing image material, especially in the light of new interdisciplinary knowledge. In this case, several new insights into the Iceman's life habits, last hours and subsequent preservation were obtained.

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