# Corresponding non-invasive 1H and 23Na MRI of ancient mummified human tissue

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## Introduction

Ancient mummies are well-perceived objects of scientific research. Yet, successful visualization of historic mummified tissue by non-clinical $^{1}$H-MRI was reported hitherto only after invasive rehydration [1], or preliminarily for the naturally mummified Neolithic "Iceman" [2]. While natural glacier mummies contain large amount of epi- and intracorporal hydrogen, freely movable particularly during defreezing, artificial mummies from ancient Egypt are completely dried out by natron (a blend of NaCl, $Na_2CO_3$, $NaHCO_3$ and $NaP_2SO_4$) resulting in a very solid nature of the mummified tissue. Thus, due to the mummification process one expects $^{23}$Na to be found abundantly in such tissues. The aim of this study was to show the feasibility of non-clinical MRI for the non-invasive investigation of the spatial distribution of $^{1}$H and $^{23}$Na in artificially mummified ancient human tissues.

## Material and Methods

An isolated mummified right first digit of a human adult (Fig. 1; Egypt; New Kingdom or later; # K1201, Rätisches Museum, Chur, Switzerland) has been investigated by MRI using a 7 Tesla Bruker DMX 300 MRI tomograph with a horizontal-bore magnet. The experiments were performed with a 25 mm doubly tuned resonator for $^{1}$H (300 MHz) and $^{23}$Na (79 MHz). For the $^{23}$Na imaging experiments an imaging sequence based on a solid echo was chosen in which the read and phase encoding gradients were implemented similar to conventional spin-echo imaging [3]. The proton images were acquired with a standard spin echo pulse sequence. The echo times were chosen quite short, i. e. 2.7 ms for $^{1}$H and 0.8 ms for $^{23}$Na, in order to avoid signal loss from rapid $T_2$ relaxation due to the solid nature of the tissue. For anatomical comparison, a computed tomography scan (petrous bone protocol, ultra high resolution, 140 kV, 300 mAs; Brilliance 16-slice, Philipps AG Medical Systems, Zurich Switzerland) has been performed at the very same location. As reference for $^{23}$Na MRI in historic dry bone, a right first digit of another human adult was visualized too (# 296, Dahlheim skeletal series, Germany, 11$^{th}$ cent. A.D.).

## Results

A three dimensional $^{1}$H surface-rendered image of the part of the mummified finger which was inside the sensitive volume of the resonator (Fig. 1) could be acquired. This demonstrates clearly that it is possible to measure mummified tissue with non-clinical MRI scanners. The $^{1}$H image shows some holes, which originate from very rigorous parts of the finger with very short $T_2$ that cannot be detected with the chosen echo time.

In order to address the question if and where sodium accumulates in mummified tissue, two-dimensional $^{1}$H and $^{23}$Na projections (Fig. 2) were acquired of the same part of the finger which is shown in the 3D-$^{1}$H-image in Fig. 1 (Fig. 2). The proton projections are shown in Figs. 2 a - c and the corresponding sodium images in Figs. 2 d - f. It can clearly be seen that $^{23}$Na accumulates inside the bone of the finger. This is confirmed anatomically by the corresponding CT images (Figs. 2 g - i; anatomical assignment: proximal phalanx:*, tendon of the flexor pollicis longus muscle with its attachment: °, dorsal aponeurosis with tendons of extensor pollicis longus and brevis muscles: arrows). The protons seem to be distributed primarily in the skin and soft tissue of the digit. Finally, as a reference, NMR experiments of a historic dry bone - without ancient attempts of artificial mummification - showed no sodium signal at all.

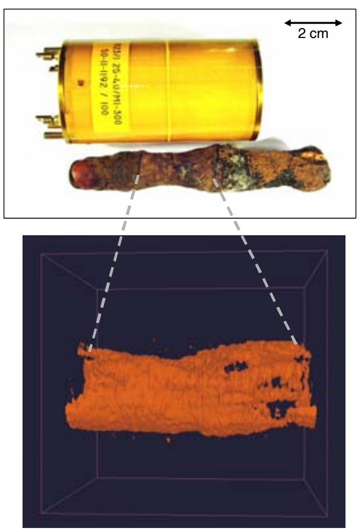


**Fig. 1**: Top: Photograph of the mummy finger and its position inside the NMR resonator. Bottom: 3D $^{1}$H spin echo image of the finger with a FOV of 30 mm$^3$, and a resolution of 469 µm in *x* and *y* directions, and 117 µm in *z* direction. The acquisition time was 15 hours.

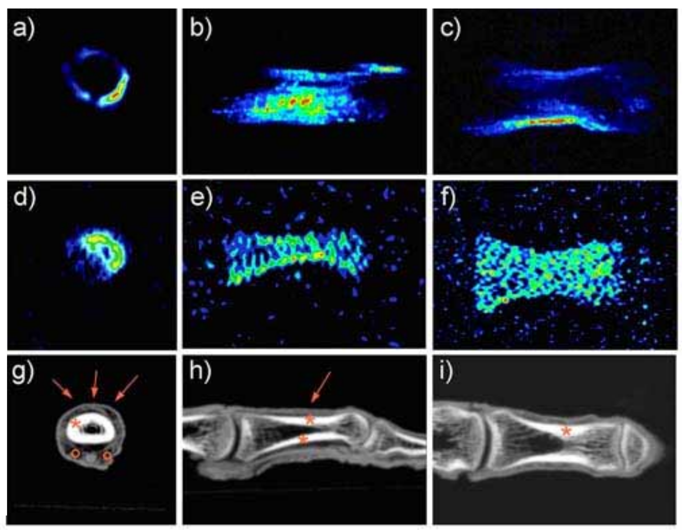


**Fig. 2**: Radiological comparison of $^{1}$H (a-c), $^{23}$Na (d-f) MRI, and of CT images (g-i) of the mummy finger a) $^{1}$H spin echo xy projection (117 × 234 µm resolution), 1.5 h acquisition time (at). b), c) $^{1}$H spin echo zy and zx projections (176 × 234 µm resolution, 1.5 h at). d) $^{23}$Na solid echo xy projection (469 × 469 µm resolution, 16.4 h at). e), f) $^{23}$Na solid echo zy and zx projections (703 × 469 µm resolution, 16.4 h at). g, h, i) CT maximum intensity projection recon-structions in the xy, zy, and zx planes.

## Discussion

Unlike in the hitherto most similar successful MR imaging study of dry mummified tissue [1], we were able to visualize the spatial distribution of $^{1}$H and also of $^{23}$Na in a completely non-invasive manner without rehydration of the precious sample. Piepenbrink *et al.* [1] acknowledge that only a minor contribution of their $^{1}$H-MR images were due to confined water, with the vast majority being due to the water absorbed during the modern re-hydration process. But in this study, we were able to detect the protons of the solid tissue directly and found them primarily in the close-to-the-surface regions. Due to the large line-width of the $^{1}$H NMR signal of about 3 kHz, we believe, that most the signal is due to the skin and tissue and not to modern external passive humidity.

We were also able to perceive signals for sodium ubiquitous in the bone of this digit. This must be a result of the mummification process by natron, especially, since in the historic reference bone, which was never exposed to ancient artificial mummification, no sodium signal could be detected at all by NMR. *In vivo* $^{23}$Na can be mainly found in kidneys, intervertebral discs and spinal canal [4] and its content e.g. correlates with proteoglycan content in cartilage. Contrary, the hereby found ubiquitous content of sodium within the bone of the mummified digit most likely represents a post mortem incorporation of $^{23}$Na-based natron. Additional research is needed to gain further insight into the complex impact of artificial mummification on the human body. Yet, the statement by Hunt and Hopper [5, p. 16] that NMR "… *is inapplicable in mummy investigations due to the lack of active hydrogen* …" is no longer true for non-clinical MRI settings as explored hereby.

## References

**[1]** H. Piepenbrink et al., *Am J Phys Anthropol* **70**, 27 (1986); **[2]** F. J. Rühli et al., *Am J Phys Anthropol* **S42**, 156 (2006); **[3]** B. Blümich, *NMR Imaging of Materials* Clarendon Press, Oxford (2000); **[4]** G. Steidle et al., *Magn Reson Imag*, **22**(2), 171 (2004); **[5]** D. R. Hunt and L. M. Hopper, *Non-invasive investigations of human mummified remains by radiographic techniques*, in *Human Mummies. A Global Survey of their Status and the Techniques of Conservation*, K. Spindler et al., Editors, Springer: Wien, New York. p. 15-31 (1996).