Nondestructive Insights into Composition of the Sculpture of Egyptian Queen Nefertiti with CT and the dependence of object surface from image processing

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Abstract
Precautions in the generation of surfaces from CT images should be the rule.
Two different data sets of the bust of Nefertiti and additional data from an industrial CT scanner will show the conflicts that arise when defining a surface.
The recent trend in CT is to extract surfaces from CT measurements which can compete with the accuracy of tactile measurements. As CT is complicated by artefacts, a lot of precautions need to be taken in order to get exact results. More errors are introduced, if the surface of an object made from different dense materials is calculated. A publication in April 2009 of "Radiology"[9] dealt with the surface of the stone behind the stucco layer of the famous bust of the Egyptian Queen Nefertiti in the Ägytische Museum Berlin. Using this data, we will show the different problems that arise from inadequate image processing. Furthermore, a detailed comparison of the two CT measurements made 14 years apart is given.
Conclusions: Respect the traps in virtual imaging.
Keywords: image processing (computer-assisted), computed X ray tomography, artifacts, implants

1. Introduction

Computed tomography (CT) has been used for more than 30 years in medical and industrial applications [1]. Current trend is to establish CT as dimensional control system [2], for whitch image processing and image correction is an important tool [3],[4]. Nevertheless the "truth" of the calculated image has to be verified, as it is influenced by artefacts and imperfectness of reconstruction algorithms. A severe example of misinterpretation from CT images is the "second face of Nefertiti", as widely published in the newspapers.
BAM has published on CT investigation since the beginning of the 1980s [5],[6]. The range of CT systems and instruments are applicable for objects of 1mm size with an accuracy of 0.5µm, to samples of 1m diameter and 2m height. The spectrum of investigated materials ranges from dust to uranium. BAM has a long-standing tradition of cooperation with museums, in the case that the objects of art to be investigated are suitable for the development of tomography. BAM is involved in projects to promote the use of CT in the industry i.e. car industry, as well as in projects that enable CT as a measuring tool. BAM is co-initiator of standards. It is therefore a vital interest of BAM to assist towards correct interpretations of CT results. Once a mistake has been spread, the whole system can be registered as non-reliable and non-authoritative.
The bust of Nefertiti is one of the most popular cultural highlights in Berlin; more than 600000 people visit the Egyptian Museum per year. Additionally the bust has evoked a hundred years of discussion between science, politics and the public. Much of what was known about Nefertiti was collected by R. Kraus [7]. Nevertheless there are still many remaining questions. A first CT investigation was done in 1992[8], which was followed by a second in 2006 [9], both intending to clarify the technology of fabrication as well as to detect areas with risk of possible damage.

An assignment to evaluate a possible progression of damage brought these two data sets to BAM. The 1992 data set was regained with a high resolution X-ray film laser scanner *Array 2905HD* at BAM [12], from the CT printouts on X-ray films, which are owned by the Ägyptische Museum Berlin[1]. The 2006 data set was reconstructed by Imaging Science Institute[2] for Rathgen-Forschungslabor[3] (RF). All data owners as well as the Staatliche Museen Preußischer Kulturbesitz[4] (SMPK) consented to the comparative analysis of these data by BAM Bundesanstalt für Materialforschung und –prüfung

2. Materials and Methods

We compared the CT data set of the bust of Nefertiti generated in 1992 by a Siemens Somatom Plus [8], to the 2006 data set by a Siemens Somatom Sensation 64 [9]. As the original data from 1992 was available only as a print out version on X-ray film, these were re-digitized by a special film scanner. The images shown here were generated with the aid of VGStudio MAX 2.0 by VolumeGraphics GmbH [11]. Additionally a drilled core from a concrete sample, investigated with µCT, is used to show the dependence of surface generation on parameters.

A three dimensional data set allows the virtual generation of surfaces for different material densities. This is a well known technique in medicine i.e. for exactly fitting bone replacements. The case is a bit more complicated with industrial CT, because the possible materials are wide spread and often unknown prior to measurement. It is a prevailing and demanding task to define the surface within a CT, in order to get a result, which is exact to the definition of length measuring devices and useable in any point of the object [10].

3. Results

3.1 Where is the point of the "real" surface seen in the CT slice?

Even for the finest measured resolution, the surface in the CT image can not be regarded as a sharp edge, jumping from zero to the value of bulk material. There is always a ramp, due to discrete sampling. For highly absorbing materials, this ramp can be stretched over several pixels, depending on filtering and reconstruction algorithms.

The true surface is regarded either as the point of half-way between zero and maximum or as a local operator, like the turning point of the ramp curve. Thus the HU (Hounsfield Units, normalized grey level values) value where the surface should occur is locally dependent on the maximal density of the material. If there are two or more materials involved or the one material has a locally different density, a global value for the surface threshold is not applicable. In the 2006 measurement with Siemens Somatom

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Sensation 64 [9] the limestone has an average density that lies between 1001 and 1600 HU and respectively a stucco[5] density between 400 and 1000 HU. Both materials thus have a broad range of densities. In the case of lime stone, figure 2b of Huppertz et al. [9] shows that there are inclusions of higher *and* lower densities (density being taken linear proportional to the measured linear attenuation coefficient). Depending on the height of the slice within the bust and the deferring material thickness, the image noise may deteriorate the ability to distinguish both materials.
Two materials, each having inclusions and weak areas, make the surface hard to define.

3.2 Is it possible to detect the stone surface below the stucco?

What you have to do is to virtually remove the layer of a certain lower density. This can be done by using a ray tracing program and setting the lower density as transparent. To get a smoother image, you would set a transparency ramp from zero to 100% for the material which should remain visible. This has to be done with respect to the value found i.e. the above mentioned turning point.
From the published images [9] it is not possible to deduce which method and which levels were used to generate the published surface. Two years before, the author Huppertz first broadcasted his results of the Nefertiti CT in the television report "ZDF Expedition, Jäger der verlorenen Schätze, Die Odyssee der Nofretete", ZDF, D2007. At this report the computer screen was shown while the surface was generated. Not only the resulting image, but also the defining parameters for density distribution and the chosen non-transparent region were visible. Unfortunately, single images from this TV production, even a digital snapshot from the video recorded movie, cannot be reproduced, due to complicate copyright protection rulings. We have therefore re-set this scenario with our own image processing system. The image closest to the broadcasted one is shown here in figure 1.

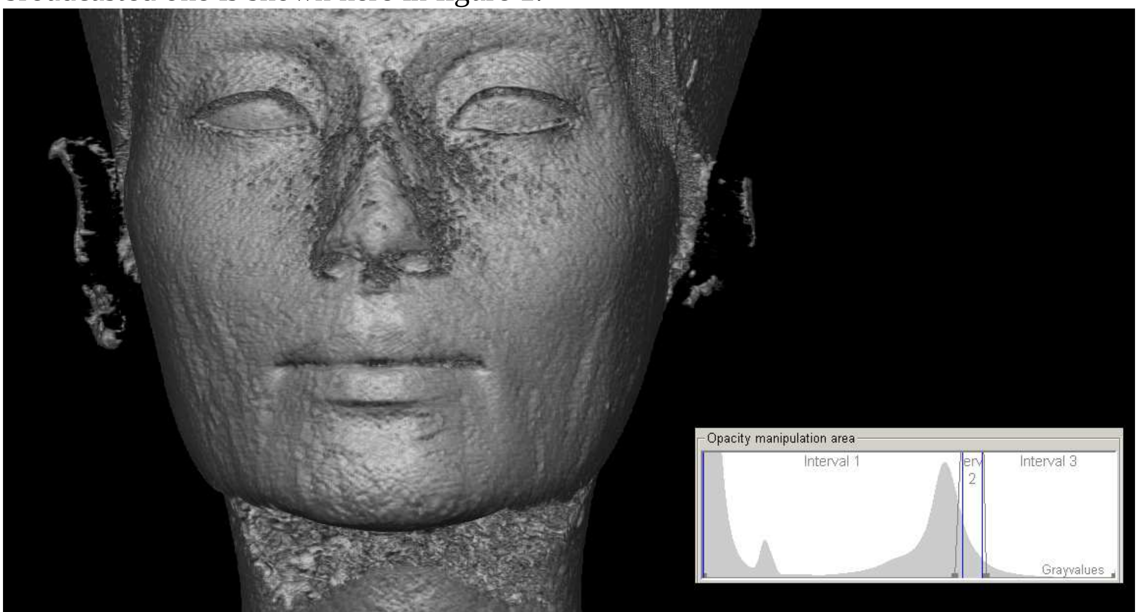

Fig. 1 Generating a second face with a VolumeGraphics[6] ray tracer, opacity given in small window.

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[5] The term stucco is used here for all materials of lower density which were added to the stone. The term stone is used without claiming a chemical composition.
[6] VolumeGraphics see http://www.volumegraphics.de/

Figure 1 shows a 3D representation and also, on the right side, the parameters that were used to generate this surface. A ray tracer software was used. The included graph in the lower right corner shows the HU distribution and an in-written trapeze which gives the range and value of transparency. The important point is, that the ramp for visibility starts *after* the maximum of HU values and ramps to the highest densities included in the distribution. This means, the shown surface is well inside the stone! The so-called “second face of Nefertiti” is definitely a virtual object, which is there because the human brain wants it to be there. The logical retesting is missing.
For every material there is always only one level to set as surface point, if the problem is solved globally. Nevertheless, you can create a second surface at any other level by setting the imaging parameters: a surface at a lower HU value will always appear on top of the true surface.

3.3 Comparison to a concrete sample

To show how important the parameter setting is, we will use the CT of a concrete sample, core-drilled from a bigger part. In this case the surface is visible; it is smooth except for some rings originating from the drilling. The concrete is made of stones and cement, which both have densities close yet distinguishable from each other. Figs 2 and 3 show the rendered surface with different parameter settings, to be seen within the images at lower right. Fig. 2 shows the surface as it looks from the outside. A measurement of the diameter of the concrete cylinder from these data would give a slightly larger value than exact. The level was set too low. Many pixels that do not fulfil the above rule are part of the surface. When shifting the region of interest to the declining side of the density distribution (fig. 3), the concrete object assumes a deeply scratched surface. But we know it is even.

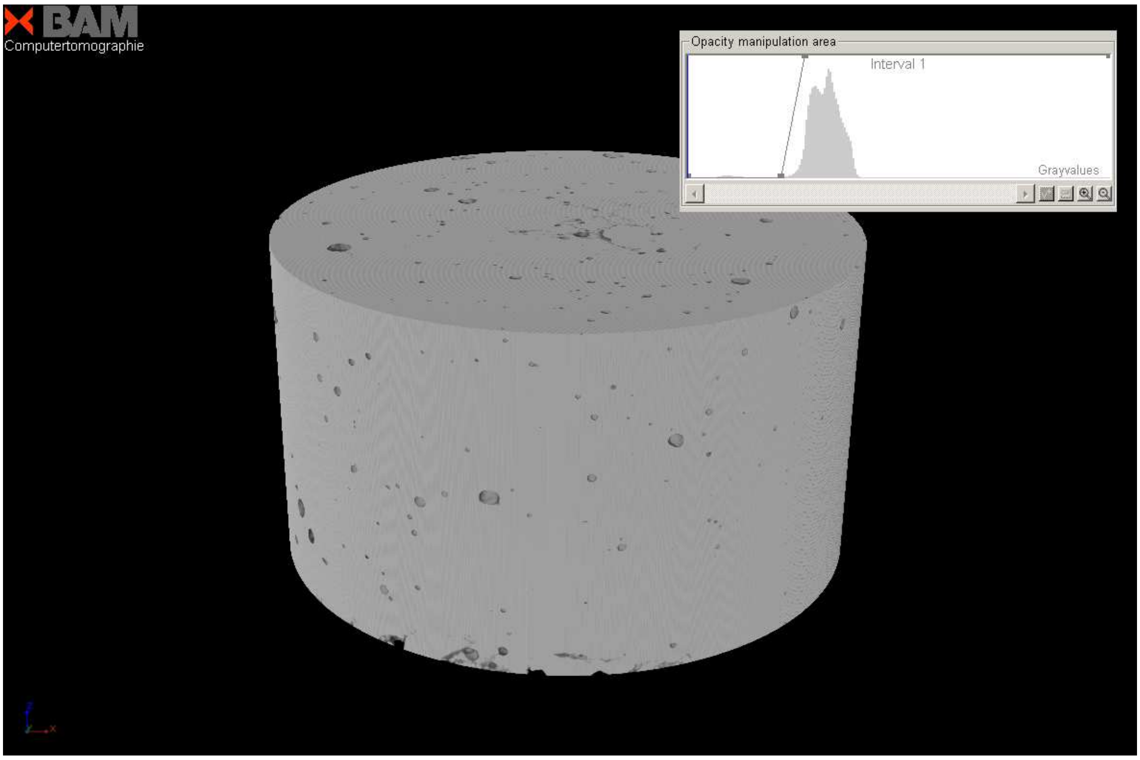

Fig. 2 Surface of a cylindrical drilled concrete sample note the parameter settings.

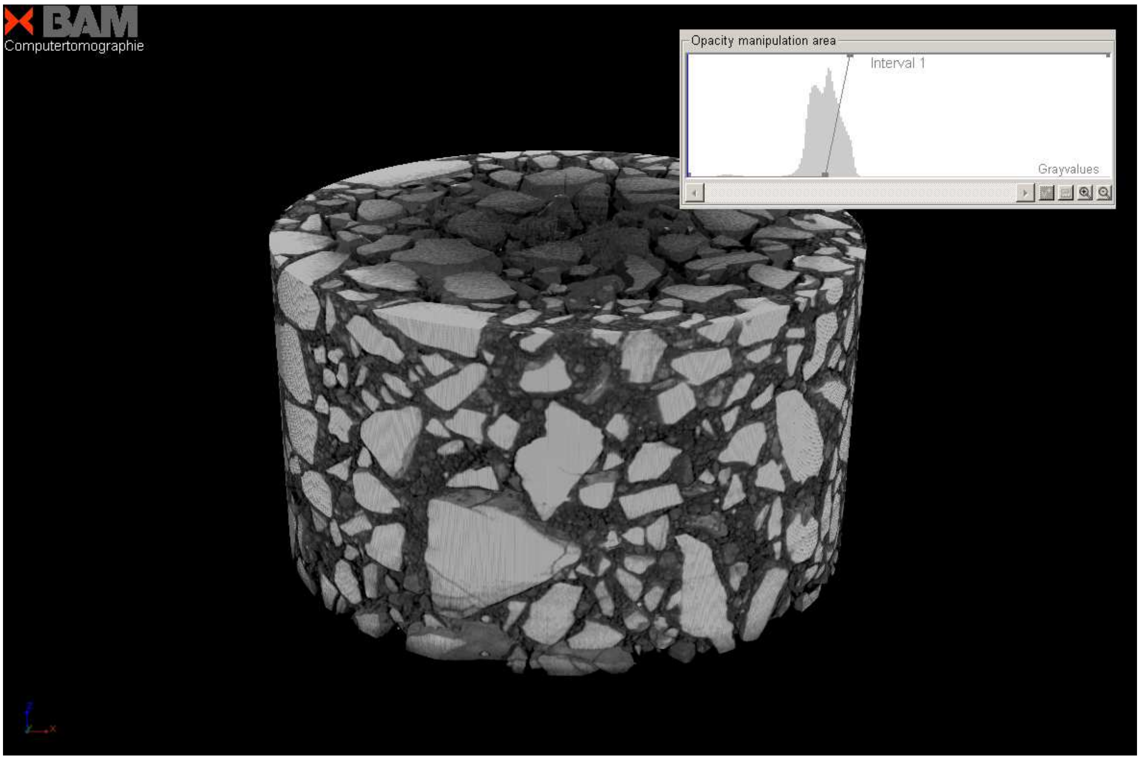

Fig. 3 Surfaces of the same cylindrical drilled concrete sample note the parameter settings

3.4 More investigations

Why do the lines, recognized as wrinkles [9], seem to be symmetric to the nose of Nefertiti, leading to the explanation of a scary face? The answer is given in a vertical data cross section in figure 4. Here the HU levels have been stretched to show small differences in the values. The veining of the stone is now clearly visible as bright and darker streaks. These veins are layered in planes parallel to the face (as is in fact mentioned in [9]). Their distribution on the surface is relatively symmetric in the left and right parts of the face.

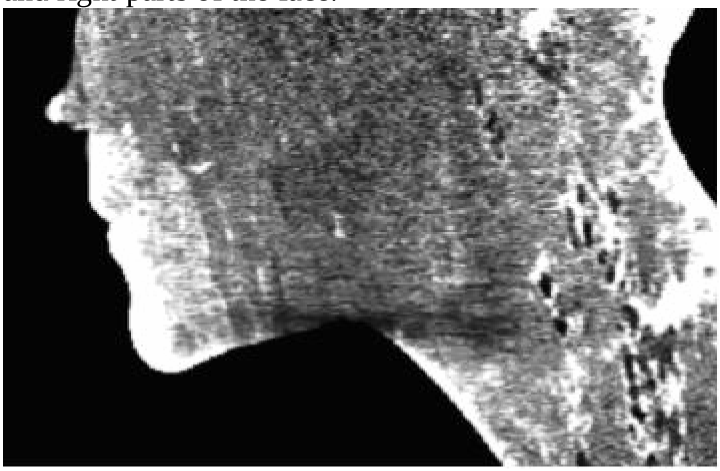

Fig 4: Veining of the stone in the area of the face, data set of 2006.

If there is a second face behind the painted surface, this layer would be visible in a single tomographic slice, see for instance fig 2e in [9]. We know that the density of plaster is lower than that of stone. Thus the plaster layer should be darker in the images. This is not the case; there is no measured darker outer layer, not even with a slice thickness of 2mm. In contrast, the outermost area of the stone is slightly brighter than the bulk material (fig. 5 and fig. 6). Not even the primer is detectable (although it is present). Again, image 2f of Huppertz et al. is good to clarify this point. The right ear is connected to the head without a disruption in the material; it is continuous at this point. Nevertheless the area of ear outside the head is darker than the bulk of the head. This is due to an effect (artefact) known as beam hardening, which describes the changing of X-ray spectra while passing through any object. The same artefact produces a brightening of the outmost layer of the bulk material, which is also visible in the mentioned image. In fact, beam hardening is a major problem in technical CT, if more than one material is involved. In the medical case beam hardening correction is “hard wired” and optimized to biological material with bones as highest density.

Another known artefact (disturbing surface generation) is visible in image 2b of Huppertz et al. Long material edges produce streak artefacts of lower density in the direction of the edge: the right shoulder being the long edge, the streak goes into the throat.

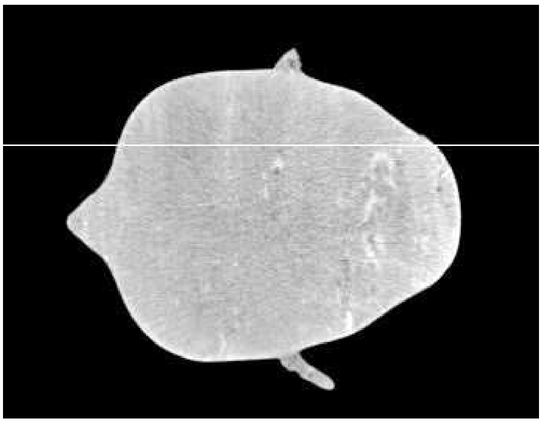

Fig. 5 slice (K390, 2006) at mid face height, density profile along the white line is given in figure 6.

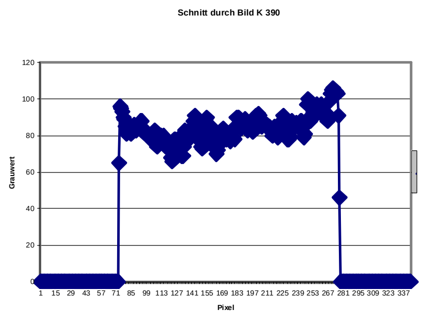

Fig. 6 Grey value distribution along a line from front to back in slice of fig. 5. Beam hardening is visible at first and last object points. The stucco layer is not detected.

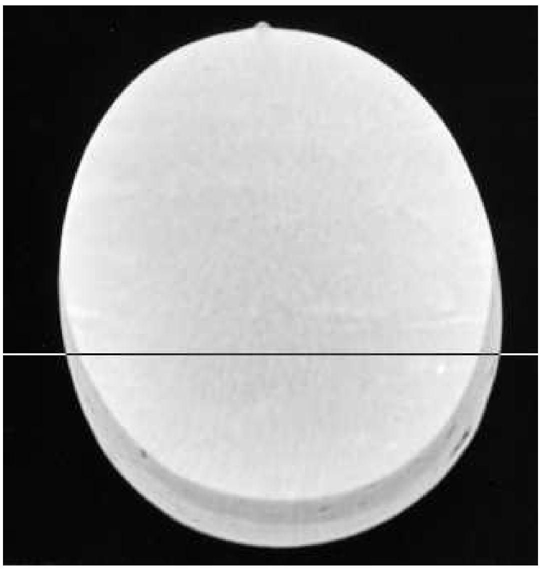

Fig. 7 slice (scan 20, 1992) at height of helmet, density profile along the white line is given in figure 8.

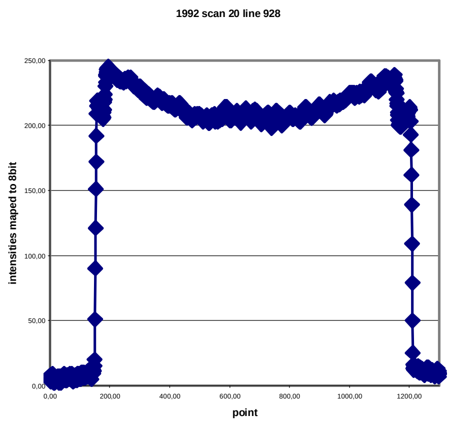

Fig. 8 Grey value distribution along a line from front to back in slice of fig. 7. Beam hardening is visible at first and last object points. Two stucco layers are detectable.

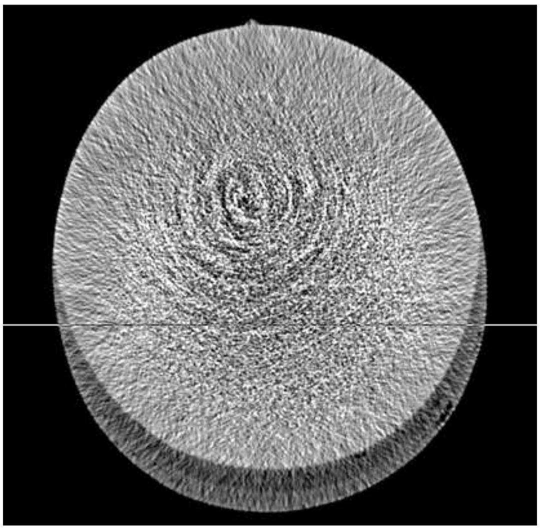

Fig. 9 slice (2006, roughly same height) through helmet, density profile along the white line is given in figure 10.

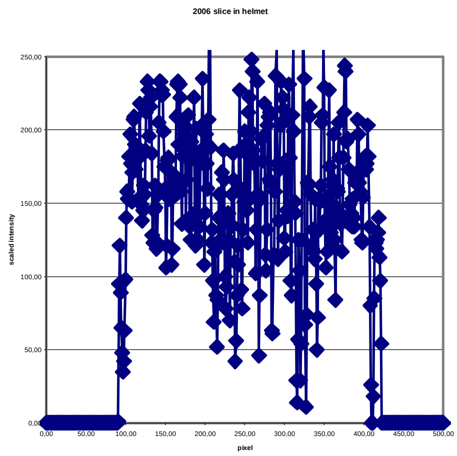

Fig. 10 Grey value distribution along a line from front to back in slice of fig. 9. One stucco layer is detectable.

3.5 Comparing the Nefertiti CTs

The cross-sectional slices shown in Huppertz et al. [9] are averaged to a thickness of 2mm or 2.5mm, stated in the caption of image 2 of Huppertz et al., thus are far away from the possible thickness of 0.6mm and closer to the one used in 1992. In comparison, the measurements of 1992 have a great advantage: as they are single slices the total runtime of the CT tube could be used for one slice; the voltage is slightly higher. Additionally the slice height from 1992 multiplies the number of used photons by a factor of 8.4. Thus much more photons were collected and the density resolution in these tomograms is much higher. In the case of the spiral machine (2006), the total scan was completed within one minute, thus limiting the measurement time and density resolution. On the other hand, both tomograms have the same number of pixels in the horizontal direction; this means spatial resolution is gained mainly in the vertical direction. (1992: Siemens Somatom Plus, 137kV, 580mAs, slice height 5mm, 6.4min total exposure time. 2006: Siemens Somatom Sensation 64, 120kV, 400mAs, slice height 0.6mm, ~1min total exposure time).

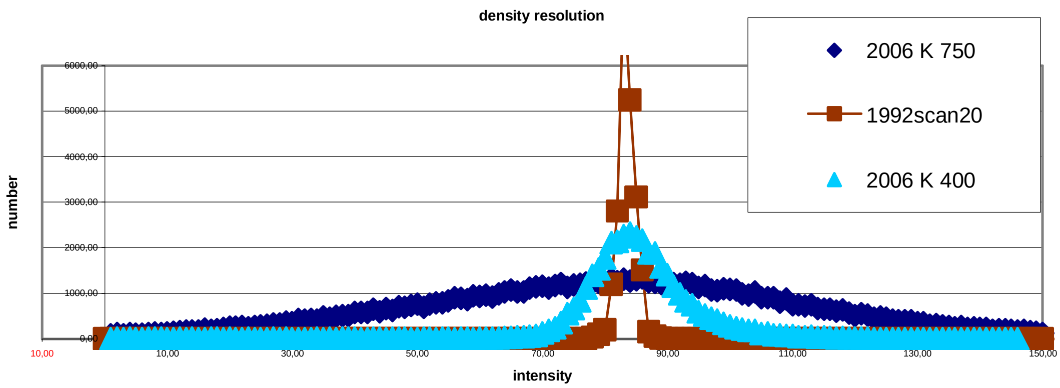

Figure 11: Density resolution for different slices, (see text) graph of the normalized intensities for pixels within the stone.

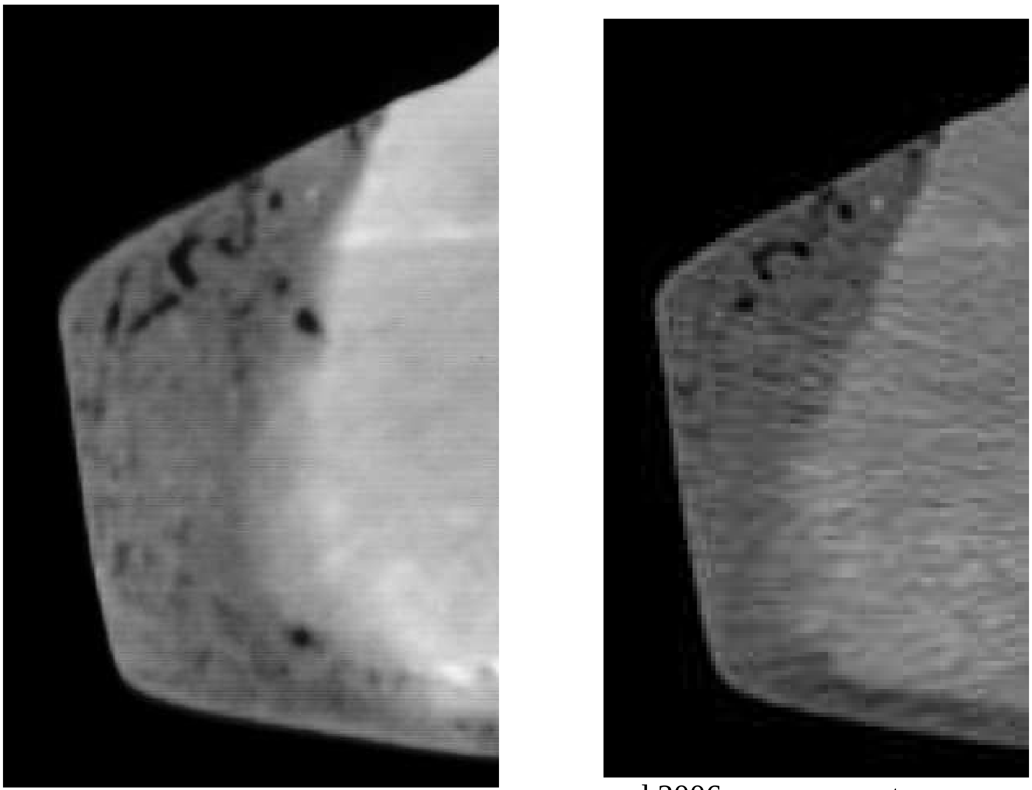

Fig 12 Detailed comparison between 1992 and 2006 measurement..

We have generated two similar slices from each data set at approximately mid height of the helmet, see figure 7 and 9. The data statistic can best be seen in the grey level distribution given for the white line in figure 8 and 10. From figure 10 (2006), it can be deduced, that the chosen X-ray energy was too low, the penetration of the object is not complete, resulting in a 100% noise. Figure 11, gives the noise distribution in nearly the same horizontal slice within the helmet (2006: 2006 K 750; 1992: 1992scan20). For comparison a distribution in mid face height from 2006 is given (2006 K 400). Due to the longer measurement time per pixel, the higher voltage and current, and the greater pixel size, the difference is blatantly obvious. The visibility of a feature, like a crack or an inclusion, is equally dependent on the spatial as well as on the density resolution. (See ASTM “Standard Guide for Computed Tomography (CT) Imaging, E-1441): The better the density resolution, the smaller the difference which can be detected as a feature, even if it is much below the spatial resolution. This is true as long as the features are separated by more than one pixel.
This can be illustrated by two similar slices from both measurements. Figure 12 left shows a slice from 1992 through the shoulder with a curious curved long pore (or low density inclusion). The slice on the right image is from nearly the same height. In the right image, the HU values have been stretched by a factor of two. As the slice height in 1992 was much thicker, more indications are summed up to one slice. Non-vertical borders, like the stone inside, become blurred. (Both measurements are slightly tilted in all directions to each other.)

Because Nefertiti has a fragile surface, any handling should be planned carefully. It would surely have been more prudent to undertake a test measurement with a similar stone prior to the CT of the original. Comparing the results from the 1992 CT scan with the test measurements could also have allowed a careful planning of a further CT. With two good scans obtained 14 years apart, the deduction of a possible crack development would have actually been feasible. In addition, both scans were done with a different orientation of the statue. Therefore it is necessary to regain the full three-dimensionality of the 1992 data set to be able to get a registration between both sets. As all three possible angles are tilted, it is hardly possible to do this precisely enough by hand.
Image 2d of Huppertz shows a cracked and repaired area. The article states that this part was repaired with a different material. From Nefertitis documentation, we know the occasion of the accident and have the statement of the restorer to have re-attached the original part with glue. It may be that the glue has infiltrated the stucco, thus augmenting the density. This example illustrates the caution that is advised, when drawing conclusions from generated images

Fig 13 Stretched view of the stone in the area of the shoulder, see text

3.5 Many interesting questions

There are a lot of interesting questions which could be asked about the bust of Nefertiti. The one which arises from the visible stucco add-on is to clarify the reason why it was applied. Up to now this has not been answered. We simply accept the stucco that is added onto the back of the helmet as the ancient master's correction to a work. Another interesting application is the stucco to the shoulders: This was done onto a defined limited area. In the neck the plaster is sharply limited by the stone which forms a step at this point. Yet the outer surface in the painted area of the braid is stone, not stucco. So the cut-out might have been planned. Figure 13 shows two views of the area of the neck and shoulders with removed stucco, generated from the 2006 data set. Due to the growing of noise caused by the thickness of material in this area, some of the stucco has

a similar HU value as the stone. This material was removed by hand in each slice. The shown surface is an isosurface. The rough surface behind the chin is an artefact due to beam hardening. The rough surface below the stucco may partially be generated by the increased noise.
One last point of interest that arises from the 2006 data: The mean density of the stone in each slice in a square which is totally inside the stone was calculated (Fig. 14). The density of the stone is lowered by 10% with increasing height.

4. Discussion

The zeroth fundamental theorem of computed tomography is: what ever you do to your data, there will always be an image. In other words: There is definitely no second face. There are three possible surfaces, the painted face as we see it, a painting ground and the stone. The given spatial and density resolution does not allow to distinguish between these.
Tomograms should be taken with the appropriate scanner. If non-biological materials are involved, specialized systems should be taken into account.
Nevertheless, the radiation reduction of Siemens Somatom Sensation 64 and the spatial enhancement of the helical scanner is an obvious major improvement for better healthcare.

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