Digital X-ray examination: archaeology and paleontology

In the previous article from «Digital X-ray examination» cycle we appealed to all those interested in microtomographic researches. It bore fruit, we had some meetings with both tech-savvy colleagues and members of the academic community.

Today we would like to tell you about our experience of cooperation with Maria Borisovna Mednikova, a famous anthropologist, Doctor of Historical Sciences of the Institute of Archaeology of the Russian Academy of Sciences.

The text contains a lot of pictures of close-up human skulls and bones so in case it makes you feel uncomfortable, you are still able to switch over to another article. Enjoy!

This article is a brainchild of several minds, we use the following legend to maintain co-authorship:

Italics: Maria Borisovna Mednikova, the academic advisor of the Institute of Archaeology

Underlining: Artem Avakyan, our researcher and «dab hand» in the field of tomography

All the rest – your faithful servant Artem Ustinov.

Well, in case you would like to dig a little deeper in physics of X-ray visualization and make small talk – come to our lab on ResearchGate. There aren't very many things at the moment but the Artems are working at it now;)

Intro

Archaeology studies material culture of the past, physical anthropology – human remains of Antiquity and the Middle Ages found during archaeological excavations.
Computer tomography and microtomography allow to obtain digital three-dimensional copies of unique artifacts and anthropological finds, explore their internal structure without destroying it. Thus rare objects of cultural heritage are preserved for further study by means of other methods and further storage in a museum.
Use of microtomography became an integral part of research in the field of paleopathology describing the illnesses and injuries of ancient people.

What is the difference between microtomography and tomography? First, it's the size of the object. Microtomography works with objects with diameter 1-200 mm, tomography – with big medical (whole human body, skull-jaw) or industrial objects (from an engine to a whole car).

Second, it's image resolution, it concerns the difference between medical CT, micro-CT and industrial CT. Generally voxel resolution of medical CT is 512^3 or 1024^3, rather a low value. It is due to minimizing of the dose for the patient and increase of projections capture speed.

There are no firm resolution limits for micro-CT, usually its range is from 2k^3 up to 5k^3. The object can be given any dose, acquisition time is from 30 minutes to 12 hours, even several days in especially severe cases. The larger diameter of the object is, the higher resolution the applied detector is to have – otherwise the voxel size can hide the defect.

Subject of research

We applied microtomography studying a series of samples obtained during the archaeological excavations concerning archaeological cultures of different ancient periods – from the Bronze Age (4000 BCE to 3000 BCE) to the Late Middle Ages. The results of scanning are very promising. It is thanks to radiological examination we managed to detect oncological diseases the population of the steppe belt of Eurasia (Orenburg region, Voronezh region) had already 6-5 thousand years ago. After all oncology is considered to be «a disease of civilization». In the long run it allows to study the negative factors the people faced in ancient times, the factors seemingly related to the early metallurgists way of life. Among the objects we studied there are representatives of the era of the great migration of peoples that changed the political and the ethnical map of Europe and Asia in the first millennium BC. And the data on injury rate during *combats is very important here. Microtomograhpy that allowed to «delete» virtually the consequences of restoration influence helped to research the three-dimensional reconstruction of skulls in the area of injury caused by a shot, a battleax and a battle hammer. Now we can reconstruct the battle scheme and effectiveness of different weapons in this or that era. And finally – we managed to get conclusive radiologic proof of effectiveness of therapeutic action in the early Middle Ages. Traumas and craniotomies of that period often bear the traces of curing of people living for a long time after they got them. The method of microtomography is quite irreplaceable for diagnosing degree of healing of such wounds.*

A research sample – a human skull found during the archaeological excavation. The aim is to get a full size digital copy of a sample with resolution ≤ 150 µm for analysis of structural features and cranial deformations. Search for some areas of interest is carried out on the basis of tomography results already. The main technical difficulty on both stages of getting and processing of tomographic projections is volume of reconstruction. Skull dimensions: diameter – 150..250 mm, height – 250..350 mm. Estimate of the volume of reconstruction at depth of grayscale 16 bit and voxel size 200 µm is $V = (\pi d^2 h/4)(1/v^3)16 \geq 15$ GB of data. While choosing X-ray parameters one should also take rather high X-ray density of bone tissue, possible radiation scattering and beam hardening effect into consideration.

Some words about hardware

We carried out tomography on our first CT scanner, to be more precise, on a tomography test stand. It's not much to look at, doesn't have an X-ray protection cabinet (it's located in an X-ray protection room) but it works hard enough for two.
Technical characteristics:

Parameter	Value
Detector	Mark 2430CG
Pixel size, µm	49,5
Frame size, mm	228 * 290
Frame size, pixel	4610 * 5890
X-ray source	RAP-150, ZAO "Eltech-Med"
Voltage, kW	110
Projections capture	Complete turn, at equal intervals
Pitch angle, angle degree	0,4
Number of projections	900

Parameter	Value
Time of projections acquisition, min	90
Projections data size, GB	45,5
Reconstruction software	Siemens CERA
Voxel size, µm	125
Reconstruction data size, GB	8..15 depending on the object /cropping
Reconstruction time, min	3
Operator's time at reconstruction preparation, min	45

The main «shtick» of this tomography stand is that we can use any our detector changing (in)significantly what we need. We chose Mark 2430 with the 27 megapixel matrix , a top-class detector, for this research. It's really cool, take my word for it. A couple of comments on the X-ray apparatus — I've told before that microtomography uses a specific class of apparatuses referred to as microfocus ones.

To put it simply, the X-ray beam comes from a micron sized spot. It improves image quality significantly and allows to «physically» magnify the image. The Russian apparatus made by our friends from Saint-Petersburg - ZAO "Eltech-Med" – was used on the stand. We also use some imported apparatuses (Spellman, Hamamatsu) but for other tasks where voxel size 2-5 µm is required.

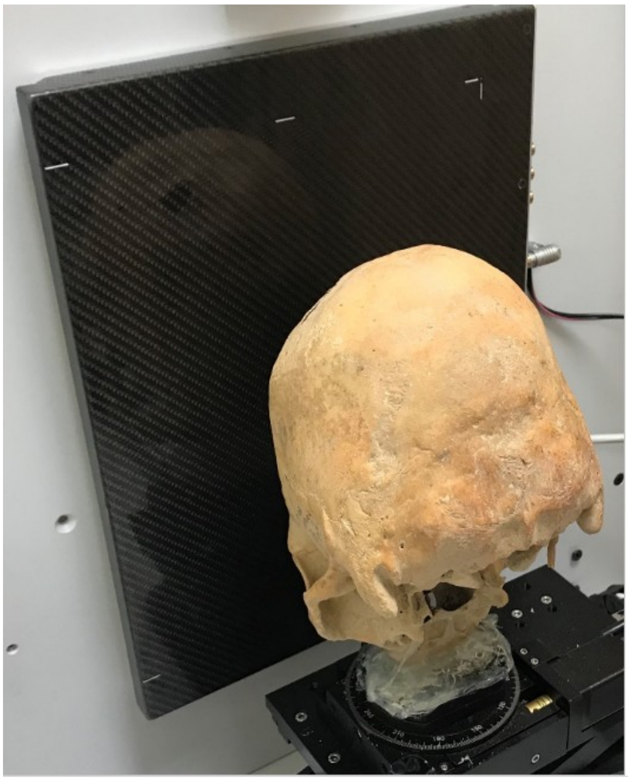
Some words about software

For tomographic reconstruction and analysis we use different software packages depending on the task: VolumeGraphics VGS, Siemens CERA, ThermoFisher Avizo + some Russian packages. In this example all the images were made in Siemens CERA.

We found empirically that both time of projections loading into the reconstructor (every object is 900 projections, 50 MB each, 45 GB totally) and of results saving and inability to work properly on analysis in the visualizer at reconstruction volume exceeding 15 GB cause the greatest difficulties. The main task was maximum decrease of data size while retaining spatial resolution and diagnostic characteristics of the tomogram. The following solutions were used:
• positioning of the object so that the projection could get into the detector plane at all angles of CT;
• geometric magnification at CT of about 1,3 times;
• orientation of zero projection corresponds to anatomical orientation of the skull (face/back of the head to the X-ray source);
• tight restriction on volume of reconstruction imposed by the overall dimensions of the object (minimization of non-diagnostic volume of «air»);
• median 3x3 filtering of projections being priority over hardware binning;
• software suppression of the beam hardening artifacts, ring artifacts.

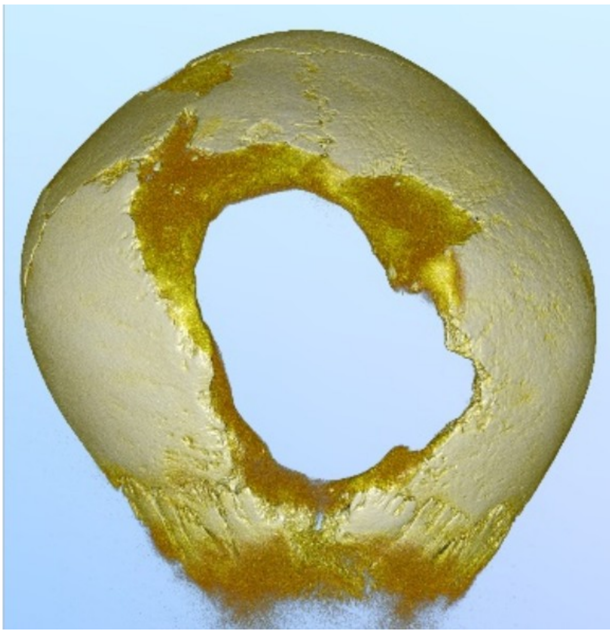
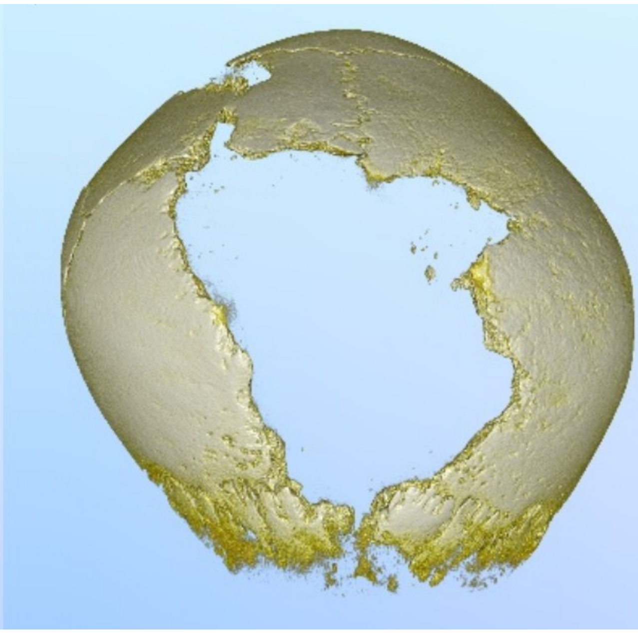
Yes, you'd better have a very powerful PC for tomography. We had consumer assembly: Core i7, 128 Gb RAM, GTX 2060 6 Gb, SSD disc. The part of the software is CUDA-optimized and renders objects in the visualizer rather fast, as for the volume analysis in VG, for instance, it is implemented on CPU, and it's about painful 15-60 minutes on the average dataset. We have high expectations of AMD Threadripper (coming soon).

The filming process looked something like this:

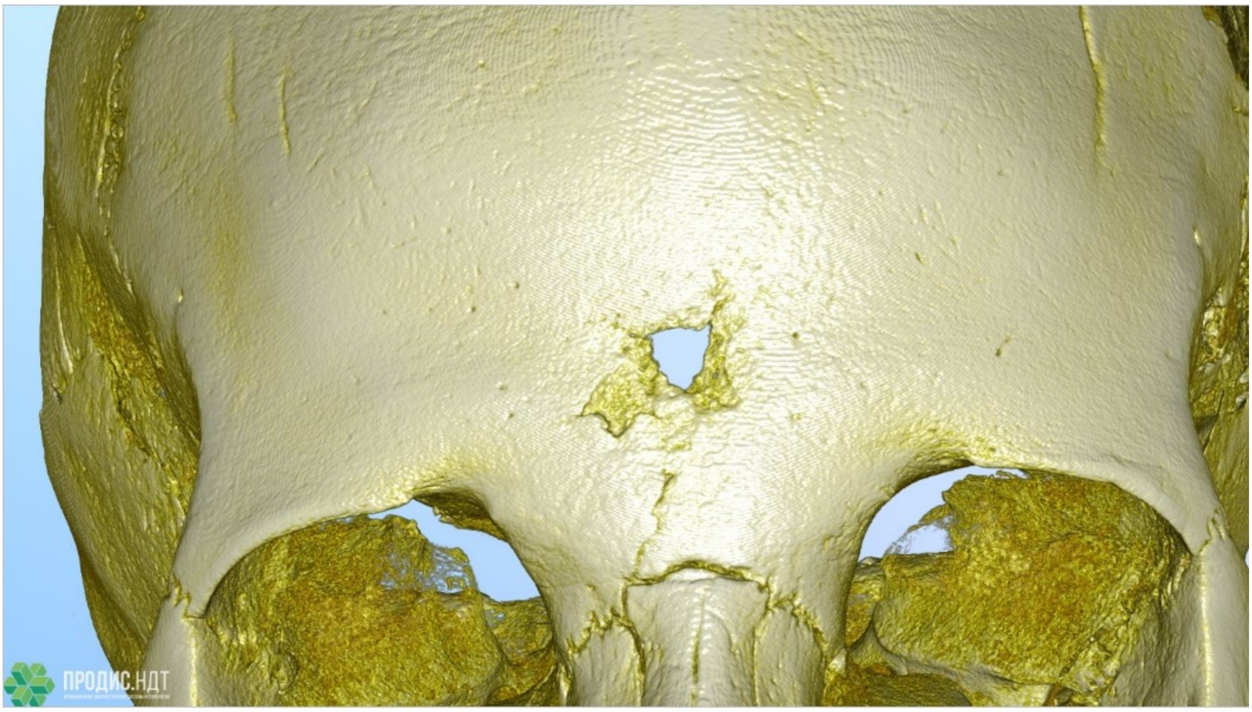
What we saw

Anthropological materials from museums and scientific laboratories are often covered with a thick layer of restoration mastic. Microtomography allows to virtually «delete» these surface layers and describe the area required for the specific research».
Mastic is a polymer with weak absorption of X-ray radiation so it's not that difficult to divide it programmatically in the reconstructed data, it differs greatly from the bone tissue. Below you can see the pictures before and after.

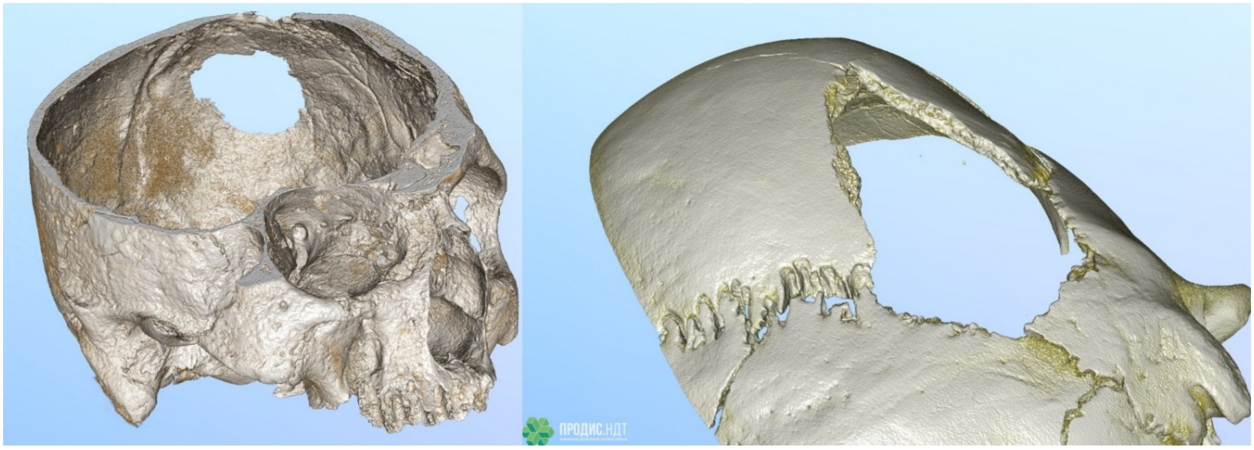
Social environment of the past was often aggressive, and the method of microtomography allows to estimate the consequences of battle wounds and home accidents on people's skeletons and skulls found during archaeological excavations. Three-dimensional digital visualization of these *injuries helps the experts determine the type of the weapon applied and sometimes, after centuries or even millennia, investigate the circumstances leading to people's death.*

Below you can see a lucky arrow hitting, a headshot of the Copper Age.



Another field of application of microtomography is studying impact of activity of the ancient surgeons some of which were very skillful and performed complex surgical procedures, for example, craniotomies. It's microtomography that allows to get magnified and high resolution images, identify the healing traces and draw conclusions on successfulness of surgical interference.

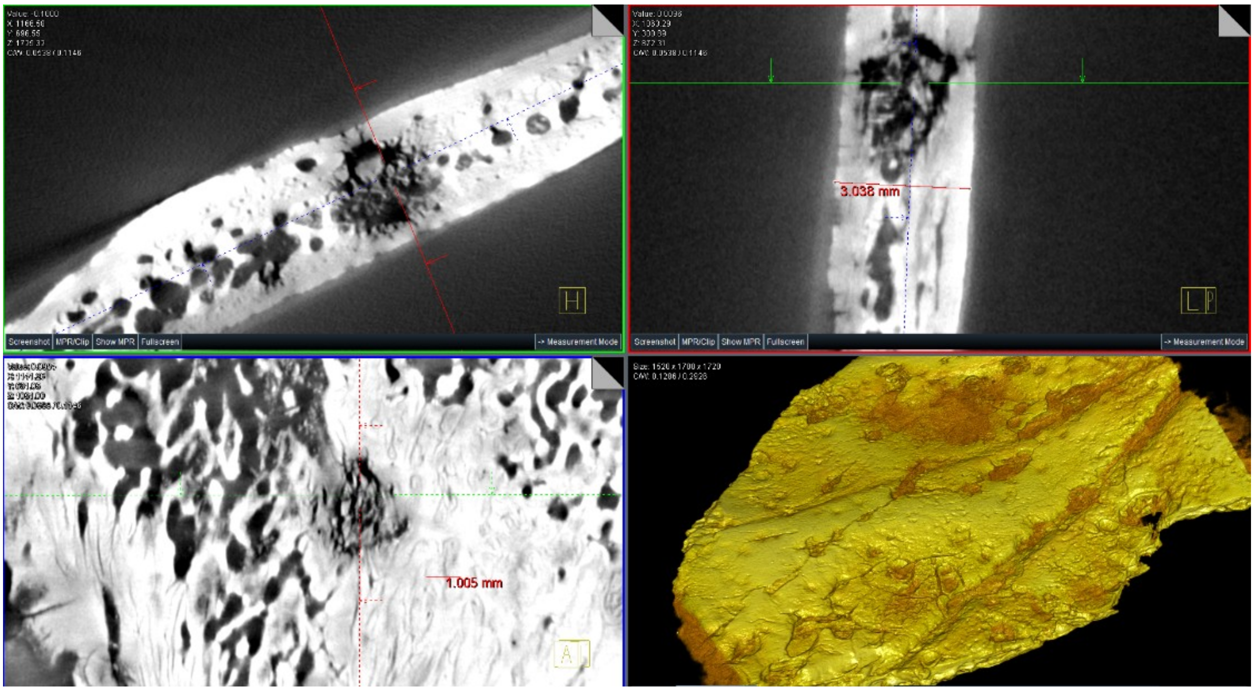
In case you didn't get – the picture below shows a craniotomy. People could even survive after that. Iron people of the copper age – no antibiotics, only natural forces of the organism.



Microtomography allows to carry out differential diagnosis of many diseases of ancient people. For example, thanks to the method we can detect metastatic lesions of the bone tissue and therefore draw a conclusion on ancientness of spread of oncological diseases.
The ancient people can be diagnosed with oncological diseases thanks to traces of metastatic lesions (secondary tumor nidi) in the bone tissue. Depending on the disease they are localized in

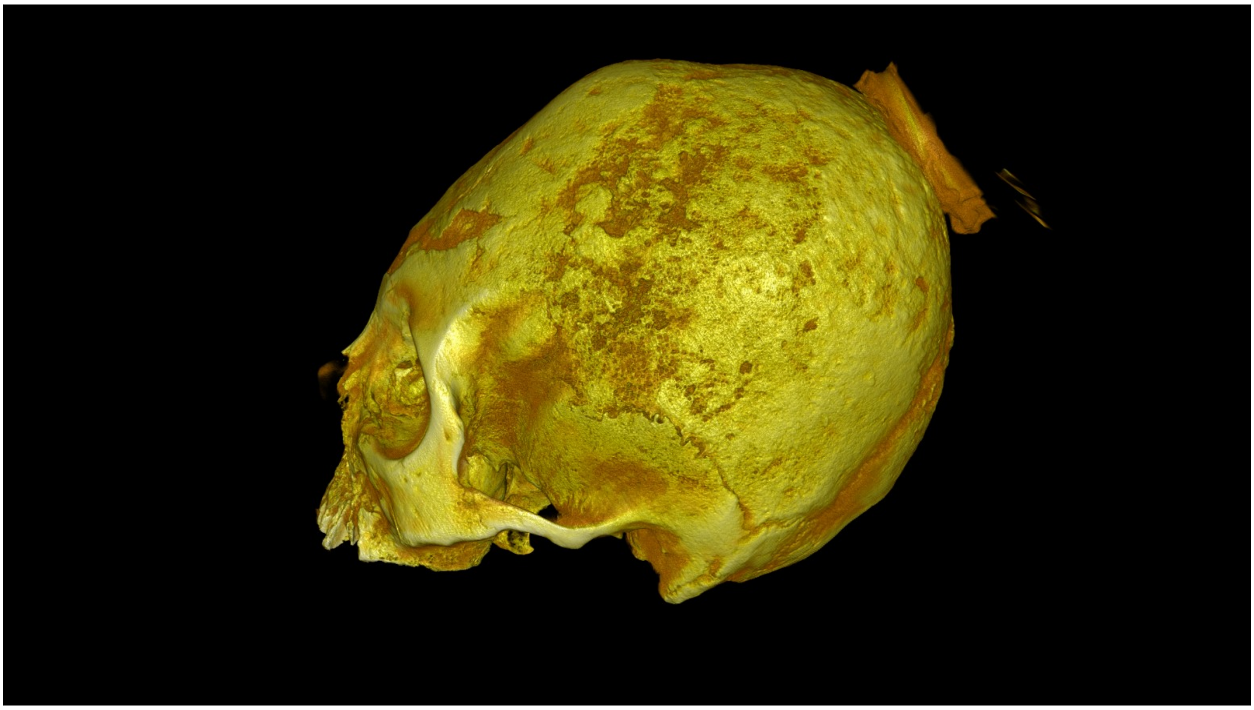
the cranial vault and certain parts of the skeleton penetrated by vasculature. Microtomography allows to detect active invasion of the vessels feeding the tumors and specific resorptive lesions (destruction).

It looks like this:



Another field is studying the consequences of inflammatory processes, infection processes in the bone tissue before using antibiotics, in the long run it can be useful for both goals of historical reconstructions and modern clinical practice.
The infection evidence can look quite different on a tomogram – from insignificant surface changes to major osteomyelitis (suppurative necrosis) resulting in total destruction of joints and central parts of large tubular bones. Chronic bacterial infections (tuberculosis, syphilis) led to serious destruction of the skeletal system.

That's the way the infection looks like:



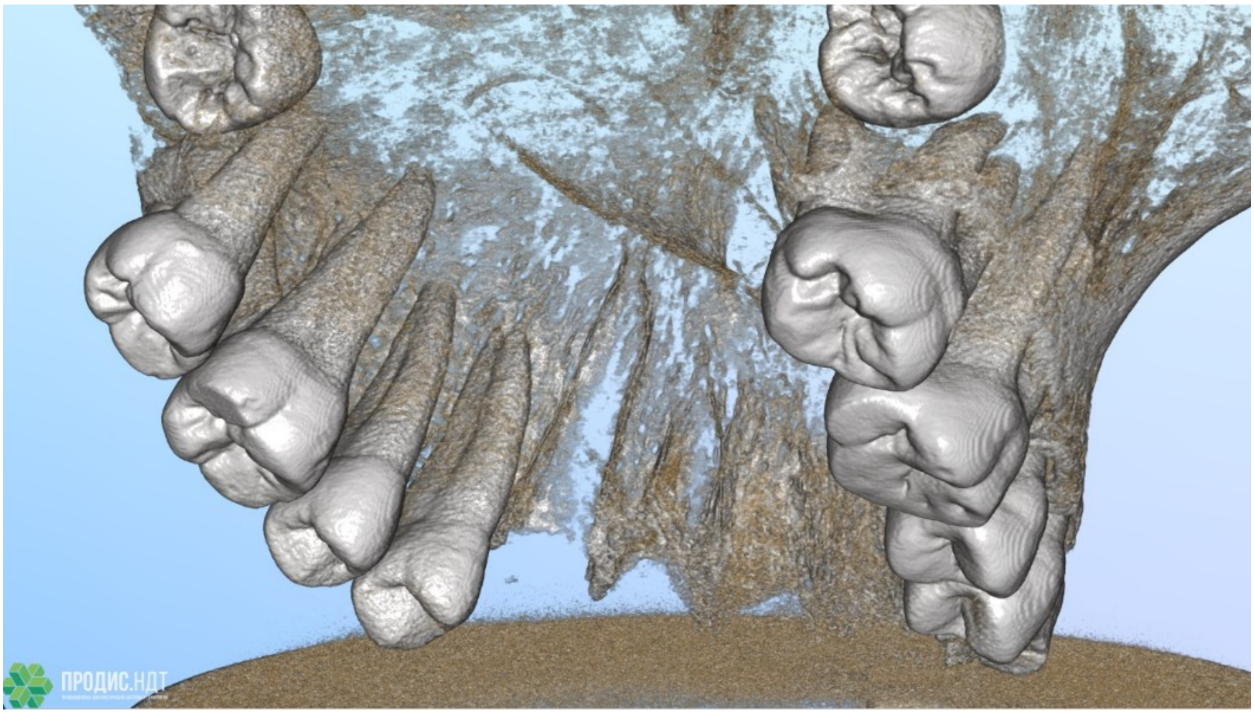
Conclusions

It was an interesting experience for us. To hold the 4000-year-old remains of the ancestors — an indescribable feeling. It's also a good answer to all sorts of fans of lizard people and aliens – if you only knew what ancient people had done with their bodies searching for beauty: change of the skull shape, craniotomy, sharpened teeth and other delights.

Technically work with big data size is the most difficult thing. Ordinary, medical CT is expressed as a cube with sides 1000 digits, it takes 12 bit for every digit at the best. And we have 3000...5000 and 16 bit. With such data software optimization for reconstruction and visualization alone is a headache, let alone analysis and data processing (segmentation, filtration, structure).

P.S. Books by Maria Borisovna can be looked at and bought in a virtual store Labirint

P.P.S. In prospect we would like to work with dentists and implantologists. In case you have interesting tasks don't hesitate to write;) And don't forget about dental hygiene:



P.P.P.S. Thanks to Sveta for the art-cover!