APPLICATIONS OF INDUSTRIAL X-RAY COMPUTED TOMOGRAPHY IN PALAEONTOLOGY

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Abstract
X-ray computed tomography (CT) as a non-destructive and powerful method for examination of a great variety of palaeontological materials and specimens with sizes from a few millimetres up to several decimetres in diameter has expanded in many scientific and industry branches. It reveals the internal structure of objects with higher sensitivity than other non-destructive methods, determined by variations in density and atomic composition. A large series of 2D cross-sections of adjustable thicknesses could be obtained, which allows reconstructing a 3D image of a certain feature. The nature of many fossils makes them ideal candidates for examination by this method. X-ray CT enables to visualize and discover features hidden from an external view. Thus the determination of precise forms and dimensions of fossils has achieved the promotion for the latest scientific investigations. Moreover, the collection of variously rare exhibits should be protected from damages or even losses. All the efforts lead up to creation of replicas of their origin by substitutes as mass objects or digitalization process. And just the X-ray CT is intended for digitalization, which solves many issues for the future.
The experiments of palaeontological specimens from collections of National Museum in Prague carried out on two industrial x-ray tomographs in the Prague Centre of Industrial X-ray tomography at the Faculty of Nuclear Sciences and Physical Engineering, the Czech Technical University (FNSPE CTU) in Prague bring novel scientific results and give way for broader applications of this technique. Also limitations of industrial X-ray CT as well as their accuracy are discussed and techniques to handle such problems are suggested.

Keywords: X-Ray tomography, palaeontology

1. INTRODUCTION

Many palaeontological findings hidden from the external view require non-destructively examination and measurement. X-ray CT may be the only practical means of gaining information on internal materials and geometries. One of the best advantages of CT is its ability to image the interior of opaque solid objects in three dimensions.
The digital character of a CT data supports computer visualization enabling user to interact with the data and to better understand the features and interrelationships among elements of dataset. Further the digitalization process provides quantitative measurements of diameters, angles, volumes etc., and it is an unrivalled means of archiving and exchanging information.

The exhibits from the Palaeontological Department of the National Museum in Prague represent the ideal objects for examination using X-ray CT.
The 90 million-year-old (age of Late Cretaceous) fossilized vertebra of a marine reptile from the group of Pliosauria has become the object of examination. In older publications it was described as a reptile species "Hunosaurus fasseli". This is an original (syntype) described by A. Frič in 1905 [1]. Such a rare exhibit was found in a few pieces in Hudcov at Teplice, Czech Republic.

Figure 1. Fossilized vertebra of a marine reptile

The purpose of this examination was to non-destructively extract the bone part from the surrounded background of rock. The digital form of individual tomographic cross-section images in axial plane allows us to reconstruct the 3D model. The means of CT facilitates the difficult work of natural scientists in the course of chemical preparation. The chemical process is represented by etching with the help of low concentrated acetic acid (2 %). The specimen would have to be frequently put out from the acid, it would have to be purified from undiluted remains. The exposed (uncovered) parts of bones would have to be dry-cured and preserved by polyvinyl acetal. After the conservation becomes dry the specimen must be again soaked in the acid. This whole cycle is several times repeated; totally it could last about two years.

2. THEORY

The principle of computed tomography consists in measuring of attenuated X-rays passed through a tested object along the set of defined paths followed by the reconstruction of an acquired dataset with the aid of mathematical reconstruction algorithms. The result represents the distribution of the attenuation coefficient $\mu(x, y)$ for individual pixels in each cross-section.
The linear attenuation coefficient is a function of the bulk density, ρ, effective atomic number, Z, and energy, E in the following form [2]:

$$\mu = \rho\left(a + b\left(Z^{3.8} / E^{3.2}\right)\right) \tag{1}$$

where 'a' is the Klein-Nishina coefficient and 'b' is a constant. For energies above 100 keV, X-rays interact with matter mainly by Compton scattering, which depends on electron density whereas for energies less than 100 keV, the interaction is dominated by photoelectric absorption, which depends on atomic number.

For analysis of the elemental composition of the investigated object the energy dispersive X-ray fluorescence analysis (XRFA) was successfully used. X-ray fluorescence (XRF) is based on photon excitation of the electron shells of atoms and subsequent qualitative and quantitative spectrometry of the emitted characteristic X-rays. In a laboratory of FNSPE CTU in Prague XRFA was carried out with a miniaturized X-ray tube. The tube employs a Mo anode and can operate with a maximum current of 0,1 mA at a maximum voltage of 30 kV. The detection module consists of the AMPTEK Si-PIN detector, cooled by a 2-stage thermoelectric cooler and sealed with a Be window [3]. The sample was placed 2 cm from 13 mm^2 Si-PIN detector. The incident and emergent angles were set to 45°.

Due to recognized elemental occurrence the linear attenuation coefficient behavior could be defined for an appropriate energy range reflecting the operating parameters of 420 kV X-ray tube. Then it is generally known that the basic quantity measured in each element (pixel) of a CT image is the linear attenuation coefficient as defined by the Beer's law:

$$\frac{I}{I_0} = e^{-\mu \cdot h} \tag{2}$$

where I_0 is the incident X-ray intensity, I is the intensity remaining after the X-ray passes through a thickness h of a homogenous sample, and μ is the linear attenuation coefficient. Likewise for a heterogeneous medium in the integral form:

$$\ln\left(\frac{I}{I_0}\right) = \int_0^L \mu(h(x,y))dh \tag{3}$$

where h(x,y) are the coordinates of the attenuation coefficient in two dimensions, L is the path from a source to a detector and dh is a distance along this path length.

The Beer's law considers a narrow X-ray beam and monochromatic radiation. In case of X-ray tube the beam is polychromatic. The true situation also with respects to the efficiency of detectors can be interpreted by [4]:

$$I = \int_{e_l}^{e_h} \frac{dI_0}{dE} \varepsilon(E) \exp\left(-\int_0^h \mu(h(x,y,E))dL\right) dE \tag{4}$$

where dI_0/dE represents the spectral distribution of the incident radiation, ε(E) is the efficiency of the detector at a particular energy E and e_l and e_h limits the relevant spectrum of energy.

In practice, Eq. (3) is used to reconstruct images and is discretized into n elements (pixels) each with unknown attenuation coefficients. Measurements of multiple ray projections provide sufficient data to solve multiple equations for the attenuation coefficient. Images are reconstructed with a filtered back projection. The measured attenuation corresponds to the sum of attenuations over each ray path. Each pixel receives a proportional contribution from ray passing through it. Images obtained are blurred because of the assumption of the back projection that attenuation is uniformly distributed over the entire length of the ray. A convolution or filtering process is then used to modify the ray sum data and improve images.

Finally the values of the linear attenuation coefficient are converted into corresponding numerical values, called CT numbers.
The polychromatic spectrum of X-ray tube has an enormous effect on the ray distribution through the object. The lower energy portions of the X-ray spectrum are absorbed preferentially at the sample edges.
To partially avoid this phenomenon the filtration method should be suggested that produces a narrower band of X-ray spectrum with a shift to 'harder' beam of radiation.

3. EXPERIMENTS AND ANALYSIS

The examined specimen consists of two visually detachable parts according to their coloring. The gray-colored one represents bone remains of vertebra, whereas the rest is formed by rock. The color ordering is to a large extent assigned to elemental composition.
Using XRFA the elemental composition was precisely determined. The sample was put on the lifting platform, the focal spots on the sample were chosen so that both bone parts and the rock parts were examined (see Figure 2).

Figure 2. Focal spots of X-ray on the sample
(a spot on vertebra on the left image, on the right side a spot on rock)

The detected spectrum of vertebra indicates what elements dominate to the bone composition. Without any doubt the K_α and K_β peaks of calcium protrude above all. Iron and strontium contribute also considerably to the general composition of bones. In this case we consider the elements deposited on a surface. If an element is presented in some depth of specimen, its characteristic X-ray fluxes are significantly changed. Nevertheless the element surface concentration is satisfactory for the principal analysis of the specimen. The energy-dispersive spectrum of bone is shown in Figure 3.
The other measurements were concentrated on a structure discovery of rock. Measurements proved that the structure of these two parts is similar, except calcium, iron and strontium, the K_α and K_β peaks of zinc are additionally detected (see Figure 4) and considerably participate in the total attenuation coefficient.
The XRFA outlined what elements composition is present in the specimen. On the basis of this knowledge the adjustment of adjusting parameters such as voltage and current could be derived.

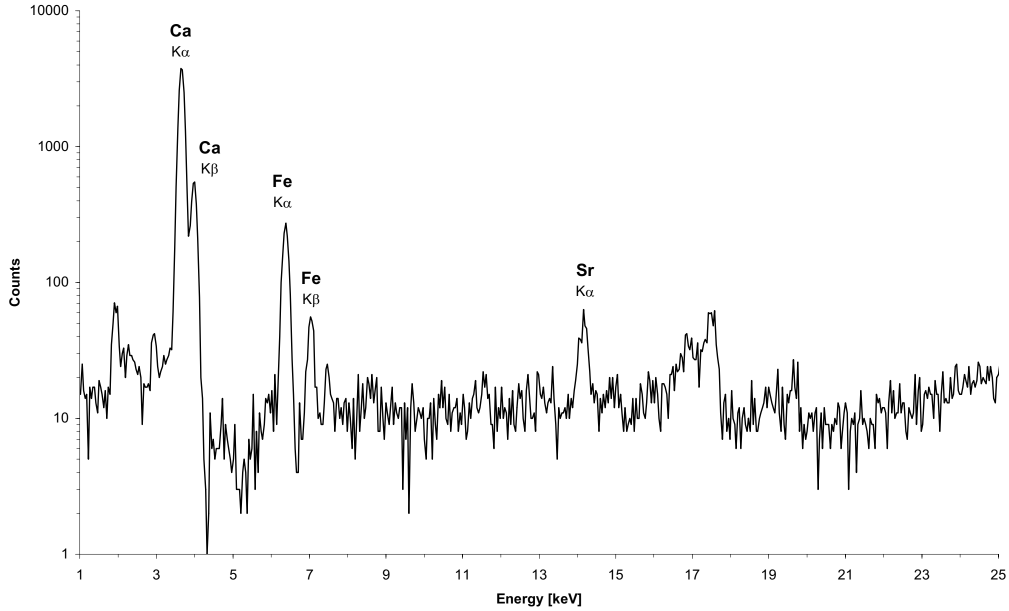

Figure 3. Spectrum of characteristic X-rays of reptile vertebra

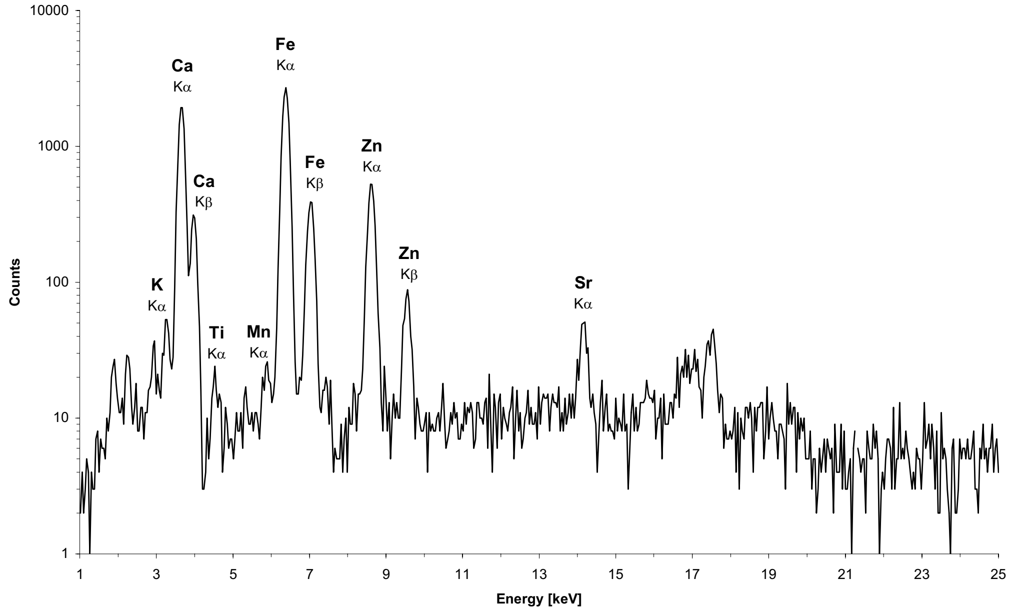

Figure 4. Spectrum of characteristic X-rays of rock surrounding bone

The measured ratio of the X-ray intensity passed through the sample and the incident X-ray intensity is dependent on the linear attenuation coefficient as well as on the width of polychromatic spectrum of the X-ray tube. The influence of the linear attenuation coefficient on the increasing energy is depicted in Fig 5. Curves for the three most represented elements are illustrated. From that, it is obvious that calcium attenuates the X-rays much less in the whole energy range for a 420 kV X-ray source than the other two elements. On the other hand the course of Fe and Zn curves did not vary much and in addition, the ambiguities about element concentration induce that the accurate determination of these elements is hardly defined.

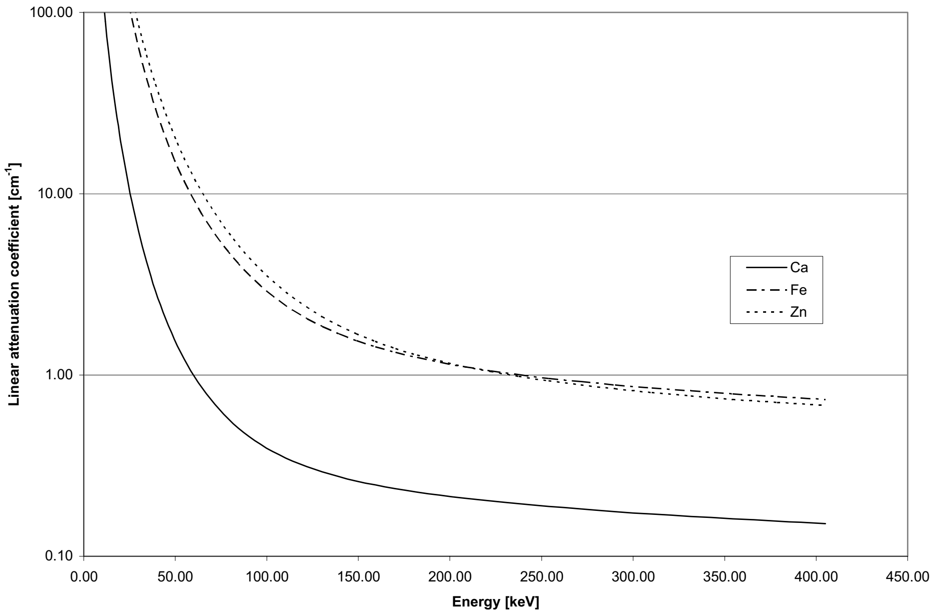

Figure 5. Plots of the total linear attenuation coefficient of Ca, Fe and Zn

The theoretical background was fully combined with the practical examination. A few setting-up parameters were tried out with the emphasis on as distinguishable as possible features. Further the method of dual energy was taken into account, but due to the character of the tested sample it did not prove as the convenient way for better visualization.

Regarding the sample thickness and the element composition a tube voltage of 300 kV and a current of 2mA with 1,5mm Cu filter were taken as the scanning parameters for the whole sample. Under these conditions the fossilized vertebra was the best distinguishable from the surrounding rock. The medium in which the bones are hidden makes difficult to easily determine the compact borders of bone. The chemical processes in such old specimen cause the diffusion of some small parts at the edge of bone into the surroundings. Thus the supplementary adjustments regarding software filtration and visualization are required to improve the image in the term of clearness.

To cover the whole object the series of 98 slices were carried out with 1 mm thickness of each slice. Figure 6 shows the cross section through the specimen.

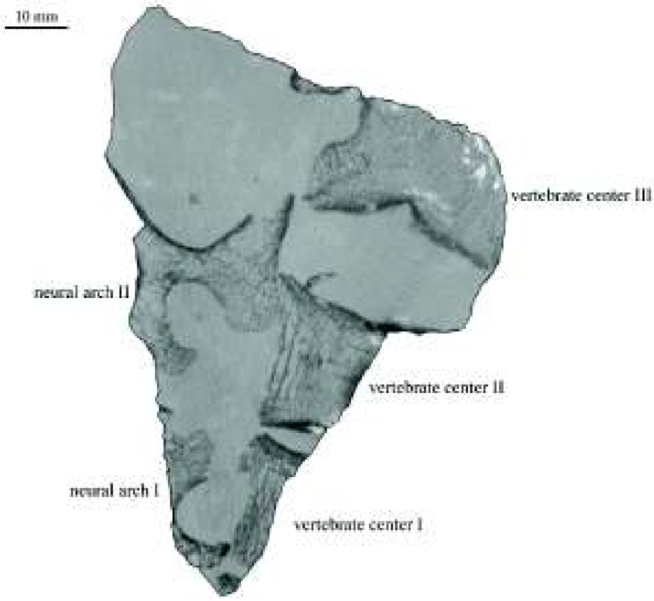

Figure 6. The composition of separated parts of fossilized reptile vertebra

The vertebra consists of several apart bone splitters which must be compounded together in order to give the compact shape. The 98 slices were put together so that the 3D model of vertebra was reconstructed. The 3D model shown in the following figure requires a piece of imagination. The above standard solution would claim for a separation of individual parts, its little shape readjustment and final image compilation.


Figure 7. 3D model of reptile vertebra

4. CONCLUSIONS

By using X-ray CT the shape of the fossilized reptile vertebra was revealed. The XRFA was the additional method for close investigation of the specimen. The general principal was derived from the digital non-destructive separation of the vertebrate part from the rest of sample. In the “Prague Center for industrial X-ray tomography” at FNSPE CTU the results came from the combination of theoretical background with practical proofs. The results were obtained on the industrial tomograph VT 400 with the image quality defined by the pixel size of 0,2 mm and spatial resolution of 1 LP/mm.
The photons impinged into material have different kinetic energy due to the conventional X-ray source. As discussed above the narrow bandwidth of spectrum has a positive effect on imaging quality. In spite of the fact that the hardware filter was introduced, the new spectrum did not embody the quasimonochromatic aspect. The possibility of tuning polychromatic spectrum to monochromatic is limited by the increasing voltage. The last research made in this field was focused on the K-edge filters and reflective (mirror type) filters. The narrow bandwidth (1-3 keV) over a range of 10-80 keV makes a very attractive improvement over current X-ray technologies. For the higher values of energy the quasimonochromatic state is inaccessible by the filtration method.
The disadvantage of used CT seems to be acquiring a series of many cross-sections. The scanning process is adjusted for using linear detectors. The thickness of individual slices is optional. For height objects the scanning with respect to time and machine load could be demanding, but once the data are acquired the large dataset would be satisfactory for a rigorous three-dimensional model. Such the non-destructive examination led to answering issues concerning the new information about the form and the size of the vertebra.

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