

RÖNTGEN AND ARCHAEOLOGY: PAST, PRESENT, FUTURE*

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History

November 8, 1895, is an important day in the history of mankind. The night of that day, Wilhelm Conrad Röntgen discovered the radiation named after him.

W.C. Röntgen was born to a German father (a clothes manufacturer) and a Dutch mother on March 27, 1845. In 1848, the family moved to the Netherlands, where Wilhelm attended primary school and, in Utrecht, a polytechnic school. He wanted to continue his studies at university, but failed his entrance examination. Even so, he studied at the Utrecht university, but was not allowed to take the examinations. After three years, he left for Zurich, where, after three more years, he became a mechanical engineer. The next year, he took his doctor's degree writing a dissertation on gas properties. Zurich is also where he met Bertha, the woman to be his wife.

Having wandered through various universities and research institutes, he became a professor at the Würzburg University in 1888. There, in his laboratory, the night of November 8, 1895, he experimented with a so-called cathode-tube. The negative electrode of the tube, the cathode, emits an electron current into the tube. To screen the concomitant fluorescence in the tube, he had glued black paper on it. Having switched on the tube, stray barium-platinum-cyanide crystals flared up brightly. Röntgen realized that a radiation must have come about which could penetrate the paper. At the time, this was an unknown phenomenon. Röntgen referred to it as 'X-rays'. Experimenting with the penetrative power of the radiation, he developed the first X-ray photograph of part of a human body, namely his wife's hand (Fig. 1). The exposure time was 15 minutes.

Röntgen published his findings in three volumes, entitled "Über eine

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Fig. 1. X-ray photograph of Bertha Röntgen's hand, 1895.

neue Art von Strahlen." On account of his pioneering merits, he was awarded the first Nobel price for physics in 1901.

Röntgen was not the first to have witnessed a phenomenon caused by X-rays. Already before their discovery by Röntgen, Sir William Crookes was one of several scientists facing their effects. Crookes designed and constructed vacuum cathode tubes. He complained about the photographic plates delivered by the Ilford company. The untouched plates from the boxes in his laboratory appeared to be veiled or black even before exposure. Ilford promised to replace the plates, even though the exposure must have been in Crookes' laboratory, considering no other institutes had complained. Here, it is useful to know that one of the properties of X-rays is its capacity to expose photographic material.



Fig. 2. X-ray photograph of two coins of William Jennings, 1890 (after Eisenberg 1992,62).

In 1890, experimenting with a Crookes tube, Prof. Goodspeed found silhouettes on a photographic plate which he could not account for. The photographic plates were the property of William Jennings, a photographer who witnessed the experiments. Jennings had placed the plates in the laboratory, inadvertently leaving two coins on one of them (Fig. 2). This coincidence yielded the very first X-ray photograph, resulting from air and metals having different absorptive powers with respect to X-rays. Actually, the use of X-rays is based on the fact that each material has its specific absorptive power. In 1890, also Ludwig Zehnder, Prof. Röntgen's assistant, witnessed a phenomenon caused by X-rays. Switching on a cathode-tube, he saw a screen flare up due to X-rays, be it only for a split second, as the tube broke down point-blank. However, all these people apparently lacked the phantasy or keenness of observation shown by Röntgen.

Particulars

Just like light, radio waves, infrared, ultra-violet and gamma rays, X-rays are a manifestation of electro-magnetic radiation. This radiation is thought of as energy quanta travelling like waves. In contrast to radioactivity, it contains no particles. In other words, X-rays are not radioactive. X-rays result from a current of high-energy electrons interacting with bound electrons in elements or with the nuclei of such elements. This happens when the electrons discharged from the filament in the cathode part of a modern X-ray tube collide with the tungsten anode. The high energy required to produce X-rays is transmitted to the free electrons by creating a wide potential difference between the anode (+ pole) and cathode (- pole). The potential difference should be between 28.000 Volt and 120.000 Volt. Despite the high energy transmitted to the free electrons, the generated amount of X-rays is relatively low.

Only about 1 % of the energy added is transformed into X-rays, the rest escapes as heat.

X-rays develop in two ways, each of which is an interaction of the free electrons from the filament and the bound electrons in the tungsten of the anode.

In the first way, so-called general radiation develops. The attractive power of the tungsten nuclei of the anode either deflects a high-energy electron from its original path or causes it to collide with one of these nuclei. In either process, generally repeated a number of times, an electron loses energy, which is emitted as X-ray photons or as heat. As an electron's initial energies and the energies it loses vary from process to process, X-ray beams are never homogeneously structured. In X-ray beams, there are always different intensities of radiation.

The second way yields the so-called characteristic radiation. The bound electrons are found in various shells (K, L, M etc.) around the tungsten nuclei. The binding force of these electrons depends on the attractive power of the nucleus. This attractive power of the nucleus varies with the elements. When a free electron expels a bound electron from the K (= innermost) shell, an electron from another shell will take its place. The electrons in the K-shell having greater negative energies than the electrons of the other shells, energy will disengage when the vacancy in the K-shell is occupied. This energy will transform into an X-ray photon or into heat. Owing to the differences between the binding forces of the electrons in the K-shells of the various elements, each element has its specific value determining the above phenomenon. With tungsten, it takes 70 KeV¹ energy for a free electron to expel a bound electron from the K shell. The result is an X-ray photon of 59 KeV energy, 59 KeV being the difference between the binding force of a K-shell electron (70 KeV) and one in the L-shell (11 KeV). The amount of radiation thus generated ranges from 0 % - 28 % of the X-ray beam from the tube. The actual percentage depends on the height of the potential difference chosen.

X-rays and archaeology. Conventional techniques

Even in the year of the discovery of X-rays, the German Egyptologist Georg Ebers had two X-ray photographs taken of a mummy. The photographs show the mummy's entire body. In 1899, the famous Egyptologist Flinders Petrie had X-ray photographs made of mummies

¹ KeV = Kilo electron Volt: the amount of kinetic energy received by a free-moving electron while exposed to a potential difference of one thousand Volt.

in the British Museum. The apparatus used, however, was either inappropriate or used so inappropriately as to merely reproduce the mummies' feet and legs. It would seem to me that he might have done better to have turned around either the mummy or the apparatus, feet hardly ever yielding the most interesting photographs. Two years after Röntgen's discovery, physicist Walter König made X-ray photographs of mummies in order to test the usefulness of the radiation. X-rays were soon found to be a useful, 'non-destructive' tool of research of human and animal remains. X-ray photographs can reveal what is inside a mummy, for instance embalmed intestines, amulets, artificial eyes, etc. Also, they generally allow us to ascertain a mummy's state of preservation and to investigate bone fractures, congenital defects and diseases once suffered from. The largest collection of mummies in the Netherlands, in the possession of the Rijksmuseum van Oudheden in Leiden, was first methodically examined in 1965.

In other branches of archaeology, X-rays were less warmly received. Even today, there are probably many questions to be answered by means of an X-ray technique that have not been put to the right persons or institutes.

X-rays are not only useful to the highly interesting research of mummies but also to that of production methods of metals. This will be clear from J.F.W. Koens and the present author's (R.J.J.) research of a pair of tweezers from c. 700-675 B.C., excavated in the archaic settlement of Carthage (Tunisia; Fig. 3a-d).² The X-ray photographs of the tweezers reveal one of its legs to be brighter and have an old fracture. Furthermore, the tweezers are shown to consist of two kinds of iron: 1. Iron with a low carbon content, tough but not very flexible. 2. Iron with a high carbon content (steel), flexible and hard but brittle.

A reliable pair of tweezers has typical properties. To prevent fractures, it is elastic, not too hard and brittle. The tweezers under discussion are made of the above two kinds of iron. This appears from the X-ray photographs, on which each leg has its own degree of unequally spread corrosion. Iron with a low carbon content is known to corrode much sooner than iron with a high carbon content. On the photographs, the corroded material appears as dark spots. The ancient blacksmith bent the part of the tweezers made of iron with a low carbon content. As on the photographs, this is the central and most corroded part of the tweezers. To

² Inv. no. Musée de Carthage: KA 93/551-77; Docter/Koens 1994, 24-25, fig. 5. The object was found in stratum IIIa1 of house 8 (room U), in the Phoenician urban quarter below the Roman Decumanus Maximus. On these excavations, see Niemeyer/Docter/Rindelaub 1995 and Niemeyer *et alii* in preparation, where the object will be published by J.F.W. Koens in full detail.

Fig. 3a-d.
Pair of tweezers
from Carthage.



Fig. 3a. Normal photograph.



Fig. 3b. X-ray photograph.



Fig. 3c. Section.



Fig. 3d. Metallurgical
section.

render them hard and flexible enough and to ensure the development of a layer of steel on the outside, the tweezers were put in a fire for some time amidst e.g. bones. Carbon atoms from the bones penetrating the iron would bring about the layer of steel. Judging from the corrosion pattern, the process proves to have been successful with the darker leg. Its outer layer is steel, its inner layer common iron. The leg is quite flexible, supple and hard. The brighter leg, however, entirely turned into steel. Thus, lacking flexibility, it was broken with use in antiquity. The smith mending it did a Monday-morning job.

Conclusions to be drawn from the above: the ancient smith deliberately tried to produce steel. The process involved, however, was partly beyond control. Thus, there was an element of gambling to it, not invariably yielding the effect intended.

Subsequent metallurgical research confirmed the conclusions drawn from the X-ray photographs. Furthermore, the tweezers were found to be the oldest known artefact subjected to the process of producing steel in antiquity. All this can be inferred from just a few X-ray photographs.

Digital X-ray techniques

In the late 1960's, G.N. Housfield managed to translate the theoretical principles of reconstructing X-ray images into a useful machine, the computed-tomography (CT) scanner (Fig. 4). A CT-scanner consists of three main parts: an X-ray tube, a radiation detector and a computer.

After an object of examination is placed in the CT-scanner, the radiation detector and X-ray tube start turning around it. While turning, the tube sends its rays through thin slices of the object in all directions. The object absorbs part of the radiation. The detector records the radiation transmitted. This done, the slice is divided into small volume units, the so-called voxels. The voxels each have a fixed place in the slice and a specific dose of radiation absorbed. Next, upon a reconstruction calculation, the computer puts the voxels in place (Fig. 5). Then, the slice is stored in the computer as a collection of figures. To visualize it, 256 different shades of grey are attached to the H.U. values (Hounsfield Units = doses absorbed) of the voxels. The voxels by far outnumbering the 256 shades of grey, a useful area to be coloured must be selected. This is done with the so-called 'level' and 'window' function of the scanner. The 'level function' indicates the density of the material examined, the 'window function' the range involved. According to their values, the voxels outside the selected area are rendered either black or white. Once the grey values are attached to the voxels, the scanned slice can be visualised on a monitor and printed on a film.

CT scanning has two major advantages over conventional X-ray tech-



Fig. 4. Computed-tomography (CT) scanner.

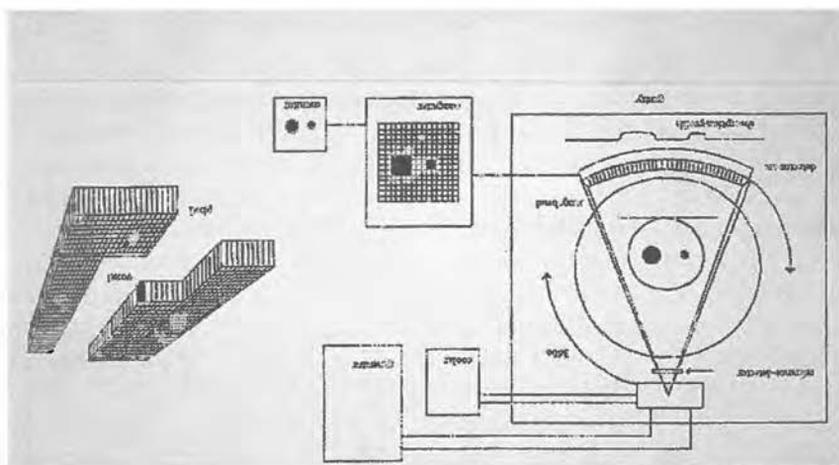


Fig. 5. Working scheme of the CT scanner.

niques. First, the use of a reconstruction technique rules out superimposed structures. Then, the specific way of colouring voxels enhances perception of absorption differences, which leads to eliciting more information. The technique is quite suited to research of mummies. All parts of a mummy can be represented in full detail. Its bones, contents and positions of e.g. amulets are open to inspection.



Fig. 6. Three-dimensional reconstruction of mummy head (Allard Pierson Museum inv. no. 10.842).

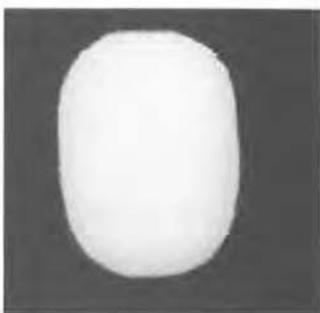


Fig. 7 a-d.
Three-dimensional reconstruction of scarab in Egyptian mummy (Allard Pierson Museum inv. no. B 12.983 = Leiden RMO L.XII.1).

As the so-called 'raw data', the data on which the computer composes its representations, are digital, they allow of a number of special operations built in the software of the CT-scanner.

One such operation is the three-dimensional reconstruction. It will give a three-dimensional representation of any selected part of a mummy, clearly showing the spatial relations of its structures (Fig. 6).



Fig. 8. Three-dimensional reconstruction of a loose scarab (showing backside).

Another special operation is MPR (Multi Planer Reconstruction). This is a technique to select and visualize sections of the slices. It is the technique we used to visualize the back of the scarab in a mummy (Fig. 7a-d).³ The hieroglyphic texts or other images often inscribed in the backs of scarabs may shed light on the times in which a mummy lived and even mention its name. The scanning of a loose scarab yielded fine results, the engravings in its back coming out nicely (Fig. 8). By means of the technique, also the back of the scarab between the bandages of the mummy in the Allard Pierson Museum (Amsterdam) came out clearly. Unfortunately, there were no engravings or hieroglyphs on the scarab's underside. Developed to elicit information on mummies without damaging them, MPR is an addition to existing 'non-destructive' methods.

CT scanning is not only suited to research of mortal remains. In various

³ Scarab inside Egyptian mummy (Allard Pierson Museum inv. no. B 12.983, on loan from the Rijksmuseum van Oudheden, Leiden, inv. no. RMO L.XII.1). See also the contributions in this volume of J.F.W. Koens, Fig. 14, and of P.F. Dijkstra *et alii*, Figs. 13-15.



Fig. 9a.



Fig. 9b.



Fig. 9c.



Fig. 9d.

Fig. 9a-d. CT scans of Greek vases in the Allard Pierson Museum, showing exact profiles:
 a-b. Black Figure kothon inv. no. 605;
 c-d. Red Figure 'miracle vase' inv. no.721.

ways it furthers the study of ceramics (Fig. 9a-b).⁴ It is common practice for profile drawings to be presented in publications on ceramics. Traditionally, these drawings depend on measuring the thickness of the walls with callipers and rendering the results to the best of one's ability.

⁴ The Black Figure kothon inv. no. APM 605 will be published in short by O.E. Borgers in a CVA volume on Black-Figure vases in the Allard Pierson Museum.



Fig. 10. X-ray of Egyptian mummy head of child (Allard Pierson Museum inv. no. 13.009).

ty. There are a few disadvantages here. First, the method is time-consuming and not very accurate. Then, it cannot be used with closed pot-shapes. In contrast, a CT-scanner can produce precise profiles of any pot-shape within 60 seconds (Fig. 9c-d). Moreover, the reconstruction technique permits of having a look inside the walls. Thus, inclusions, ways of attaching the various parts, restorations and turning marks can be clearly perceived. Also, production techniques can be studied more thoroughly.⁵

Phosphor technique

Regarding conventional X-ray techniques, phosphor screens more and more replace films. X-rays hitting such screens will shake the electrons in the phosphor, causing them to absorb energy. The amount of energy absorbed depends on the number of X-rays involved. In places hit by many X-rays, the energies absorbed are higher than in places hit by only a few. The differences between the amounts of absorbed energy on a screen constitute its latent image. Next, a special type of laser beam lights the phosphor screen. This restores the electrons to their initial sta-

⁵ Publication by Theodor/Jansen/Koens, in preparation.

tes, causing emissions of light with intensities directly proportional to the amounts of X-rays locally absorbed. Then, the light photons are caught in a so-called photo-multiplier-tube (an amplifier), which transmits the signals to an analogue-digital-converter. Finally, the digitalized signals are put in the computer to be processed beyond the limits of conventional technique.

The resultant phosphor photographs are richer in contrast and poorer in definition than those on film (Fig. 10).⁶ The phosphor technique widens the scope of archaeological research.

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⁶ Mummy head of child (Allard Pierson Museum inv. no. 13.009). See also the contributions in this volume of J.F.W. Koens, Fig. 7, and of P.F. Dijkstra *et alii*, Figs. 11-12.