A comparative and critical study of X-ray CT and neutron CT as non-destructive material evaluation techniques

Jelle Vlassenbroeck¹, Veerle Cnudde², Bert Masschaele¹, Manuel Dierick¹, Luc Van Hoorebeke¹, Patric Jacobs², Koen Pieters²

¹ Dept. of Subatomic and Radiation Physics, Ghent University, Proeftuinstraat 86, B-9000 Ghent, Belgium
² Dept. of Geology and Soil Science, Ghent University, Krijgslaan 281/S8, B-9000, Ghent, Belgium

Corresponding author: Jelle Vlassenbroeck
jelle.vlassenbroeck@ugent.be

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Abstract

For years computerized X-ray tomography has been widely used as a medical diagnostic tool. This non-destructive technique soon turned out to be an important research tool for a wide variety of scientific subjects. For material research medical CT, microCT, and since very recently nano- or sub-micro CT are being used as non-destructive material evaluation techniques for engineering and geology purposes. The fact that X-ray CT visualizes the internal structures of natural building stones and yields information on porosity values and pore-size distributions, is a major advantage for the study of their conservation. The penetration of fluids like water, consolidants or water repellents inside porous materials is a hot topic when dealing with conservation and restoration research. Only very recently high-speed neutron tomography has

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been introduced as visualization technique for fluids inside porous material. High-speed neutron tomography can be used as a complementary technique to X-ray tomography since elements like hydrogen, which have a weak attenuation for X-rays, are easy to detect with neutrons. In this article the basic principles of computer tomography and more specific X-ray and neutron tomography are discussed. Additionally application possibilities, advantages and limitations of medical CT, X-ray microCT and high-speed thermal neutron are outlined.

**Keywords: non-destructive technique, X-ray CT, neutron tomography**

Many research techniques, often destructive ones, are available to analyse stone samples. However, there is a need for non-destructive techniques that provide 3D visualization of the internal structure of stone structures. These non-destructive techniques should allow the monitoring of certain phenomena as a function of time, including fluid flow, conservation and restoration actions and artificial weathering.

A well known 3D visualization technique, originally used in medicine, is X-ray computed tomography. Due to the large potential of this technique, it was soon introduced in different geological fields, including palaeontology, sedimentology, petrology, soil science and fluid-flow research. By the middle of the 1990s X-ray microCT started to find its way into rock analysis and related research fields. Although X-ray microCT offered already a much higher spatial resolution, compared to the original medical X-ray CT systems, recently X-ray nanoCT (or better described by sub-microCT) is already slowly integrating in material research. Besides X-ray CT, recently neutron tomography was introduced to monitor fluid flow inside natural building stones (Masschaele et al. 2004, Dierick et al. 2005). X-ray CT and neutron tomography turn out to be complementary to each other, since they can provide different information about the same...
sample. Although the physics of X-ray and neutron interactions are quite different, the basic theories behind X-ray CT and neutron tomography are similar. In this article both these differences and similarities are being discussed.

**Basic principles**

Computerized tomography is a tool designed to visualize the internal structure of a sample. A number of projections – taken at different angles by means of a type of penetrating radiation – can be used to reconstruct the three-dimensional distribution of the different elements inside the sample. The two most important radiation probes are X-rays and neutrons.

In a projection image – recorded by a detector – every pixel value corresponds to the amount of attenuation of the radiation along a straight line through the sample between the source and the pixel position. This is mathematically represented by the line-integral of the attenuation coefficient (2D information) along this path. The relation between the original intensity of the source and the intensity at the detector position is known as the law of Lambert-Beer:

\[ I = I_0 e^{-\mu(s)\sigma(s)\mu(s)} \]  

(1)

Here \( \mu(s) \) is the mass attenuation value per unit mass (in cm²/g); \( \sigma(s) \) is the gravimetric density (in g/cm³), \( \mu(s)\sigma(s) \) is the linear attenuation coefficient (in 1/cm) and \( \mu\sigma \) is the length of the material along the radiation path (in cm).
From this set of projections the linear attenuation coefficient at each point of the sample can be derived (3D information). Since attenuation coefficients are dependent on the local density and chemical composition, the internal structure of a scanned material can be reconstructed.

It has to be taken into account that the law of Lambert-Beer makes the following assumptions, which are in most cases not valid and therefore complicate the measurements:

- The attenuation coefficients should be independent of the path length inside the sample. Since attenuation coefficients are generally energy-dependent this implies that the radiation should be monochromatic. Otherwise the spectral distribution of the radiation changes according to the penetration depth (beam hardening), and so do the attenuation coefficients.

- The intensity at a detector point should only be dependent on the absorption along a straight line between the source and the point.

Typically, these assumptions are not met. The beam is often not monochromatic, especially in microfocus X-ray tubes. Here, a beam hardener is used to remove the low-energy X-rays with the lowest energies. These X-rays are attenuated very easily and can not penetrate the whole sample, resulting in artefacts in the reconstruction. Only at synchrotrons, less accessible than microfocus X-ray tubes, monochromatic beams with a high flux can be produced. Beam hardening is less of a problem when using neutron beams.

The intensity at a detector point can be influenced by scattering. The amount of scattering depends on the type of radiation (neutrons or X-rays), the energy of the radiation and the
composition of the sample. Positioning the sample close to the detector reduces the influence of scattering, since the scattered particles hit the detector close to the point where they would be detected without scattering. Positioning the sample close to the source results in an almost homogeneous background, since the scattering occurs at a large distance from the detector. Positions in between can give corrupted projections and result in a degradation of image quality and loss of resolution.

Next to the complications regarding the possible violation of the law of Lambert-Beer, the tomographic reconstruction also requires some assumptions. Theoretically, every detector row should only contain the information of one cross section through the sample, perpendicular to the axis of rotation and the detector. This would imply the use of only a parallel or a fan beam.

Parallel beam geometry is typically used at neutron beam lines and X-ray synchrotron facilities. The radiation emerges from a relatively large opening and the rays are (approximately) parallel to each other. A two-dimensional detector is used to take projections. For each detector row, the data at different projections angles can be arranged in a two-dimensional array, called a sinogram. A sinogram contains all data necessary for the reconstruction of one cross-section.

Fan beam geometry is used at high power, high energy X-ray tubes and in some medical scanners. A point source is used and projections are registered by a detector consisting of one row. The use of a point source allows for a magnification of the sample. Since only a line detector is needed, more sensitive and advanced means of detection are possible. Also, the influence of scattering can be reduced, because collimation in front of the detector is possible. The main disadvantage is the scanning speed, since different scans should be taken for every cross-section.
that has to be visualized. This can be partially compensated by moving the sample while scanning, a technique often used in modern medical scanners (helical or spiral CT) (Crawford 1990). The combination of high power tubes and sensitive detector elements also reduces the exposure time, resulting in an acceptable scanning time.

In reality a third scanning geometry can be used, namely cone beam, where a point source is used and projections are taken with a two-dimensional detector. By means of the so-called FDK algorithm (Feldkamp et al. 1984), corrections necessary due to the use of the cone beam can be made to the reconstruction process. The reconstruction will no longer be mathematically exact, but for small opening angles of the cone beam the artefacts are small. The cone beam geometry combines the advantage of magnification with the speed of a two-dimensional scan. This allows for quick scans compared to fan beam geometry and is especially beneficial at radiation sources with a low flux. Cone beam geometry is typically used at X-ray microfocus tubes and can also be applied at X-ray synchrotron facilities.

**X-ray CT**

_In general_

Different methods are available to produce an X-ray probe for radiography and tomography. Most methods are based on one of two physical processes: bremsstrahlung and synchrotron radiation. In microCT and medical scanner tubes bremsstrahlung is responsible for the creation of X-rays. This paper will focus on these scanners since they are the most commonly used and most easily available. We refer to Materna et al. (1999) for an example of the application of synchrotron-based tomography to the field of geology. It should also be noted that high energy gamma rays
from radioactive sources can be used to visualize large samples, because of their large penetration depth.

In X-ray tubes a mono-energetic electron beam impinges on a solid target which results in the production of X-rays with an energy between 0 keV and the energy of the electrons. Superposed on this continuous spectrum are the so-called edges (peak features), which generally contribute little to the total X-ray flux.

A slab of a material with a relatively high atomic number can be put in front of the beam to attenuate the low-energy X-rays (beam hardener). The material and thickness can be chosen depending on the tube voltage.

The resolution $R$ of the CT system is a very important parameter for material research. It is defined by the resolution of the X-ray source and the detection system and expressed by equation 2 (Mouze, 1996):

$$ R \approx \frac{d}{M} \left(1 - \frac{1}{M} \right) \frac{d_s}{d} $$  \hspace{1cm} (2)

Here $d_s$ is the spot size of the X-ray source, $d$ is the resolution of the detector and $M$ is the magnification, which is determined by the position of the source-object distance $D_{so}$ and the source-detector distance $D_{sd}$:

$$ M \approx \frac{D_{sd}}{D_{so}} $$  \hspace{1cm} (3)
Consequently, the instrumental resolution plays an important role in the resolution that can be obtained in the object visualization. Since it is easier to minimize the size of the X-ray focal spot (Van Geet 2001), the spot size will often determine the optimal achievable resolution of the instrument. This optimal resolution is only relevant when the object can be placed very close to the X-ray source (large magnification) and is therefore limited to small objects. The focal spot size is mainly dependent on two parameters: the size of the impinging electron beam and the amount of scattering of the electron beam in the bremsstrahlung target. Larger spot sizes limit the resolution but allow higher electron beam currents, since the heat load can be spread over a larger surface. Higher electron (and by consequence higher X-ray) energies and thicker targets also worsen the resolution but provide a more efficient conversion from electrons to X-rays.

*Interaction processes*

X-rays primarily interact with materials through the photo-electric effect and Compton scattering. In both processes the incoming photon (X-ray) interacts with the electron cloud of the target atoms. The photo-electric effect is dominant at low energies (below 100-200 keV depending on the material). Here the X-rays are absorbed and the attenuation coefficients are strongly dependent on the atomic number. Compton scattering is dominant at higher energies (100-200 keV and above). Not only does it have a low dependency on the atomic number – the attenuation is essentially proportional to the density of the penetrated materials - but since it is not an absorption process it violates the law of Lambert-Beer.

To differentiate minerals with very similar mass density but dissimilar compositions, preferably low-energy X-rays are used. It has to be taken into account that these low energies will limit the
maximum object size that can be penetrated. For high absorbing materials and larger objects high energies are required. The disadvantage of working with high energies is that the transmission values will lower in sensitivity for different atomic compositions and scattering is predominant.

**Medical CT**

In a medical CT scanner, the patient (or sample) is stationary, while the source and detector rotate at a high speed in a large frame called a gantry. Typically, a high power X-ray tube with an electron beam energy lower than 150 keV and a focal spot size of the order of 1 mm is used. The target rotates at a high speed to spread the heat load over a larger area, which allows for a high electron beam current, together with a relatively large spot size. The detector – typically consisting of one or more (up to 32) curved linear arrays next to each other – has a very high sensitivity and takes projections with a large signal-to-noise ratio in short exposure times. The linear detector arrays can be composed of two different types of elements: Xenon filled gas ionization chambers or photodiodes covered with a scintillating material. A collimator in front of the detector reduces the contribution of scattered X-rays.

Medical scanners allow for obtaining images having a large contrast while keeping the total dose absorbed by the patient low. The need for a large focal spot (to allow large currents) results in a limitation of the resolution to about 250 µm in modern scanners. Because of the high power of the tube and the sensitivity of the detector, the scanning speed per slice is high (1 second or less) and the total scanning time for a large number of slices is still acceptable. By moving the patient or sample along the axis of rotation during the scan – which results in a helical scanning path – the waste of time due to the movement of the patient/sample between different scans (fan beam
CT) can be eliminated. Special reconstruction algorithms are developed for this helical or spiral CT. If more than one row is used, the partial cone beam geometry further complicates the reconstruction algorithm (cone-beam helical or spiral CT). The use of these multislice detectors however further increases the scanning speed.

**MicroCT**

In microCT (and nanoCT) the sample is rotated instead of the source-detector system. The electron beam in the X-ray tube is focused to a small spot by using coils. The target is very thin (~10 micrometers) to minimize the amount of scattering of the electron beam and by consequence the X-ray spot size. Because the electron beam power is focussed to a small spot, the current is much lower than in medical tubes, otherwise heat dissipation poses a problem. The combination of a low electron beam current and a thin target results in a low X-ray flux. This means that generally only two-dimensional detectors are used to save scanning time and every projection requires a relatively large exposure time (up to 30 seconds).

Typical detectors used are fiber optically coupled (intensified) CCD sensors and flat panel detectors. CCD based detectors always need a scintillator material to convert the X-ray energy to visible light, which can then be detected and possibly intensified. The most commonly used scintillator screens are gadolinium oxysulphide (GOS) and thallium-doped caesium iodide (CsI:Tl) screens. Flat panel detectors can be composed of amorphous selenium, which results in direct detection of the X-rays, or amorphous silicon, which requires a scintillator screen. Another kind of flat panels uses CMOS (complementary metal oxide semiconductor) technology to
convert the scintillation light to an electronic signal. CMOS technology has the disadvantage of being sensitive to radiation damage because of the crystalline structures used.

The resolution of microCT systems is an order of magnitude better than the resolution of medical scanners. Apart from the focal spot size of the tube, the pixels of the detector should be small enough. Smaller pixels require less magnification, which means the source and detector can be put closer to each other. This results in the same flux per pixel but makes the system more compact. If the detector pixels are smaller than the spot size, the resolution is determined by the detector (and not the X-ray tube) as described by eq. 2, but only if the sample is positioned close to the detector (M ~ 1).

The actual resolution is often larger than stated above because of the detection mechanism. A hit of an X-ray on the detector results in a so-called point-spread function, representing the distribution of the corresponding signal over the detector surface. This is normally not limited to one pixel, so the detector resolution is larger than a pixel. The modulation transfer function (MTF) – equal to the Fourier transform of the point spread function – can be used to quantitatively characterize the behaviour of the detector.

Special care has to be paid to the rotation of the sample. Two parameters are very important for the rotation motor: the wobble (random rocking motion) of the rotational axis and the radial eccentricity (displacement of the centre during the rotation). These should be very small so they do not distort the reconstruction.
The same considerations can be applied to nanoCT, where the focal spot size of the tubes can be as small as 200 nm. Accurate motor control and a good detector choice (due to the lower X-ray flux) becomes even more crucial.

Applications in geology

In the early 1970s CT was primarily used for palaeontological research, but soon soil researcher, petroleum engineers, sedimentologists, petrologists and many others discovered the wide range of possibilities when using X-ray CT. In the beginning only medical CT was being used, while in the 1990 microCT was introduced as a non-destructive evaluation technique.

X-ray CT is basically and most importantly a non-destructive visualization technique, providing 2D and 3D images of the internal structure (porosity, fractures, etc.) of natural building stones. When the X-ray attenuation difference for different materials is large, clear and high contrasting images can be made, like the location of pyrite inside natural slates (Fig. 1).

![Fig. 1. 3D reconstruction of pyrite in natural slates after scanning with micro-CT (samples from De Taeye R.)](image)

Since it is possible to calculate the theoretical attenuation of a certain mineral, it is possible to make some predictions concerning their visibility and detectability inside reconstructed CT images. Figure 2 illustrates the theoretical attenuation curves for the minerals calcite, quartz, and gypsum.
Gypsum turns out to have a theoretical attenuation lying in between the attenuation of quartz and calcite, meaning that its resulting grey value will also be situated between the grey values of quartz and calcite.

![Attenuation coefficients for different minerals](image)

Quartz and calcite, with a mass density of 2.65 g/cm$^3$ and 2.71 g/cm$^3$ respectively, have different attenuation coefficients, due to the difference in atomic number of the composed minerals. Only in a small area at low energy the attenuation coefficient of quartz is higher than the one of calcite (Fig. 2). With rising X-ray energy, their attenuation coefficients change-over, making the calcite more attenuating than the quartz and finally their attenuation coefficients converge at approximately 130 keV. Due to their difference in attenuation, it should be possible to distinguish the two minerals by microCT imaging.

Besides providing information on the internal structure of natural building stones, X-ray CT can be used for the visualization of conservation products, the monitoring of weathering phenomena and many more.
Based on the law of Lambert-Beer, products can be made visible by increasing their X-ray attenuation. Higher attenuation can be accomplished when the original products are doped with a material, containing elements with a high atomic number. Products containing iodide, with atomic number 53, or bromine, atomic number 35, will result in a higher attenuation than minerals like quartz and calcite. By mixing conservation products with a higher attenuating product, their visualization inside natural building stones is possible. Cnudde & Jacobs (2004) and Cnudde et al. (2004) already demonstrated that by mixing ethylorthosilicated based consolidants and siloxane based water repellents with a higher attenuating material like 3-bromopropyltrimethoxysilane, these products are detectable inside natural building stones.

Figure 3 demonstrates the theoretical attenuation of an oligomer siloxane (10 vol-% in white spirit) water repellent (Hydro 10), and its theoretical higher attenuation due to the mixing with different concentration 3-bromopropyltrimethoxysilane. On this curve it is immediately clear that...
to obtain a visual contrast between the water repellent and the quartz, mixing with 3-
bromopropyltrimethoxysilane is necessary.

Figure 4 demonstrates the localization of the water repellent product mixed with 20% 3-
bromopropyltrimethoxysilane inside the natural building stone, after scanning with X-ray microCT.

Salts, which often manifest themselves by efflorescence or subflorescence are some of the most
damaging agents to stone. Internal accumulating pressure due to salt crystallization, often
generates spalling and flaking phenomena in building stones. From previous study (Chudde &
Jacobs 2004) the accumulation of thenardite (Na$_2$SO$_4$) inside stone material turned out to be
visible, due to porosity reduction. Based on the attenuation coefficients of quartz, calcite and
thenardite, theoretically no contrast between quartz and thenardite will be present, while this
should be the case for calcite and thenardite. On the reconstructed images of salt containing
sandstones, salt accumulation can be detected by local porosity reductions.
The monitoring by microCT of biological weathering by bacteria on natural building stones and concrete, described by De Graef et al. (2005), indicates that although microCT is not able to detect the 0.5 to 1.5 µm large bacteria, their influence on the superficial surfaces is noticeable.

4. Neutron tomography

In general

Neutron beams can be produced by a number of methods. For radiographic and especially tomographic purposes, two kinds of sources are the most common. First, there are nuclear reactors, where uranium or plutonium fission is used to produce a controlled chain reaction that frees energy and produces neutrons. Secondly, in spallation sources high energy particles hit a solid or liquid target and knock neutrons out of the nuclei of the target.

In both cases, the neutrons are slowed down by passing through a ‘moderator’, consisting of cells of water at room temperature (thermal neutrons) or containers of hydrogen (or deuteron) cooled to 20-30 Kelvin (cold neutrons) to produce a thermal or cold neutron beam, respectively. Once moderated, the neutron beam is led to the tomography set-up. Cold neutrons are led through neutron guides, where the neutrons are reflected at the inner surface of the guide and emerge from an opening near the set-up. Thermal neutrons pass through a collimator window with a certain width or length (noted as $D$) and propagate to the set-up at a large distance $L$.

The degree to which extent the thermal neutron beam is parallel is characterized by the L/D-ratio, which is an indication of the divergence of the beam. This ratio is mostly between 50 and 800. The neutron flux is lower for larger L/D-ratios. The L/D-ratio defines which resolution can be
obtain by the system if the detector is not the limiting factor. For cold neutrons, the divergence (in degrees) of the beam exiting from the neutron guide defines the resolution under these circumstances. As in X-ray CT, positioning the sample close to the detector increases the influence of the detector resolution on the image resolution.

The neutron beam has a continuous spectrum, but beam hardening can be corrected more easily during reconstruction than in X-ray CT.

**Interaction processes**

In contrast to X-rays, neutrons interact primarily with the nuclei of a material. The most important processes for cold and thermal neutrons are nuclear absorption reactions and elastic scattering (meaning without energy loss). High energy neutrons will not be considered, since they are less suited for applications in geology.

Because of the complex gamma of nuclear reactions, the (absorption) attenuation coefficients for neutrons have no simple relation to the atomic number of the material of interaction. Light elements like hydrogen, lithium and boron show high cross-sections, but so do some heavy elements like cadmium and gadolinium. On the other hand both light elements like aluminium and heavy elements like lead are almost transparent for neutrons. As a consequence neighbouring elements in the periodic system or even isotopes of the same element can show big differences in neutron attenuation.

Scattering can degrade the image quality as described previously. However, scattering is the primary process of interaction for hydrogen. Since the scattering occurs over large angles, the
sample should be positioned at a large distance from the detector. This means the majority of the scattered neutrons do not hit the detector and those who do, give rise to a homogenous background.

For geological samples, thermal neutrons are more interesting than cold neutrons. The latter have a much lower energy which results in very large absorption cross sections. This means only small samples (typically smaller than one centimeter) can be scanned.

*Neutron detectors*

The limited resolution of neutron tomography is not only due to the divergence of the neutron beam, but also to the detection process. Because neutrons are electrically neutral, they can not interact directly with a detection material. Therefore neutron detectors are often doped with elements who have a large cross section for a specific fission, capture or collision reaction. These reactions produce secondary charged particles which can then be detected. This indirect mechanism of detection gives rise to a rather large point spread function.

The most commonly used detector for neutron tomography is the combination of a scintillating screen with a cooled CCD camera, with a mirror and lens in between to guide the light from the scintillator to the camera. The resolution is determined by the thickness and composition of the scintillator. Scintillator screens are composed of the same phosphors as in X-ray detection, but are sometimes doped with Lithium to increase the light production. The main disadvantage of this detection system is the small throughput of light from the scintillator to the CCD sensor. However, it is very flexible and prevents high energy gamma rays from the source to hit the CCD sensor (because of the mirrored path of the light).
Flat panels can also be used for neutron detection. The use of amorphous silicon or selenium is preferred to CMOS flat panels since radiation damage can pose a major problem. Again the scintillators can be doped to be able to detect the particles better.

Applications in geology

The way neutrons interact with materials makes them complementary to X-rays. Whereas materials such as water only result in low absorption and low contrast when using X-rays, they can easily be visualized with neutrons. Dense materials such as metals on the other hand are highly attenuating for X-rays but almost transparent to neutrons. Also, the high neutron fluxes make it possible to follow processes such as water penetration dynamically and in three dimensions. As demonstrated by Masschaele et al. (2004) and Dierick et al. (2005) water and conservation products can be easily located and monitored inside natural building stones. Figure 5 shows a Maastricht-limestone, where the top was treated with Hydro8. Water was applied on the top, but some drops fell and infiltrated the stone from the bottom. This is one of a number of preliminary tests and further research is needed to come to a better interpretation of the results.

Fig. 5. Visualization of water infiltration inside a Maastricht-limestone, treated with Hydro8

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If the water content of the sample under investigation is too large, it is possible to use so-called heavy water, where the hydrogen atoms are replaced by deuteron atoms, which have a lower thermal neutron cross-section.

**Conclusion/discussion**

The non-destructive techniques X-ray tomography and neutron tomography were discussed. Both techniques are complementary and provide important 3D information of the internal structure of materials. Depending on the used X-ray CT system, different resolutions can be reached for samples of different size. While medical CT is used for large samples, microCT and nanoCT are more suitable for small samples. X-ray CT is a very powerful visualization technique for the internal structures of natural building stones and contributes to the identification of minerals, or at least gives an indication of possible elements. Since it can locate doped water repellents and consolidants inside the stone samples, a wide range of experiments can be performed in order to obtain more detailed information on the capabilities of these products. An important link between the internal structure of a natural building stone and the localization of the conservation products is possible. Additionally, microCT imaging allows the localization of salts and the effects of bacterial weathering. Since microCT is a non-destructive technique, samples can be monitored during natural and artificial weathering experiments, providing besides visual data, also data on the porosity changes and the changes of the internal structure of the samples, during the experiments. For neutron tomography, the obtainable resolution and the more practical fact that neutron sources are less accessible offer some limitations, but the fact that water, water repellents and consolidants can be visualized inside larger samples, without any doping, is of high importance in the research domain of fluid flow inside natural building stones. For both X-ray and neutron tomography a
promising future lays ahead as material research techniques that can act complementary to the more traditional destructive research techniques.

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