

Lung Imaging with Synchrotron Radiation

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1 Introduction

The difficulty of x-ray imaging using radiation from traditional x-ray tubes, and traditional methods is that signals are reduced by absorption of anatomic structures along the long beam path. This sets limits for observable details. K-edge subtraction (KES) imaging is a method that makes small anatomic structures visible due the contrast agent while supressing all other anatomic structures.

2 K-edge subtraction imaging (KES)

The experiments are carried out at the Medical Beamline in European Synchrotron Radiation Facility (ESRF), because sufficient flux for KES imaging in narrow energy bands is available only at the high-energy synchrotron radiation sources. The flux of synchrotron radiation exceeds the flux from a traditional x-ray tube by 5 orders of magnitude.

The attenuation coefficient of Xe increases by a factor of 5.4 when the absorption edge (K-edge) at 34.56 keV is crossed, while the attenuation coefficients of cortical bone and lung tissue change by 1.8% and 0.9% per 250 eV, respectively (Figure 1). In KES imaging method, two narrow energy bands bracketing the K-edge are used for simultaneous recording of two images. When the image taken by the lower energy is subtracted from that taken by the upper energy only the distribution of the contrast agent is seen, because absorption in other anatomic structures is the same for both energies.

The monochromatic beams are focused to 0.7 mm high lines at the patient position where they cross, and afterwards they diverge and are recorded by a dual-line Ge detector, where the horizontal pixel width is 0.35 mm, and there are 432 pixels in each line (Figure 2). The beams are fixed in space, so that patient or other subject moves vertically through the beams at constant speed (typically 250 mm/s), and the charge integrated at each detector element is read out and digitized every 1.4 ms. In this way, two-dimensional radiographs are acquired with both beams, and the vertical pixel size is the same as the horizontal one, 0.35 mm. In tomography the subject is rotated about an axis perpendicular to the plane of the beams [1].

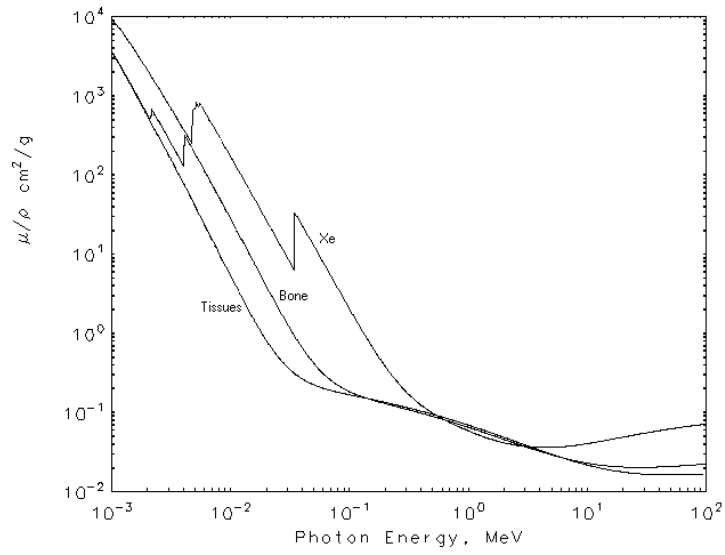


Figure 1: Attenuation coefficients for xenon, bone and tissues

There is no local blurring in the subtraction image, because the two images are recorded simultaneously. The resolution is determined by the pixel size and vertical width of the beam, and studies with phantoms have shown that the resolution is better than 0.5 mm.

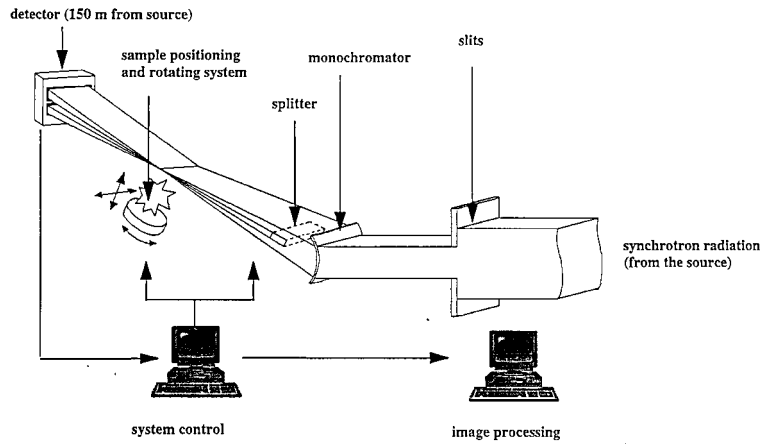


Figure 2: Set-up for KES imaging at the Medical Beamline of the ESRF

3 Experiments and Results

The experiments were performed on anesthetized rabbits. The animals were ventilating by either an air/oxygen or Xe/oxygen mixture.

A series of KES radiographs is shown in Figure 3. The actual size of the image field is 52.5 mm (hor.) by 84 mm (vert.). The image sequence begins at the moment when the gas mixture is switched from air/oxygen to Xe/oxygen, and the repeat time is 1.3 sec. The contrast agent appears first in the upper bronchi, and after that it starts to fill the alveoli. The imaging sequence was not synchronized with the respiration cycle, respiration had 1 sec period.

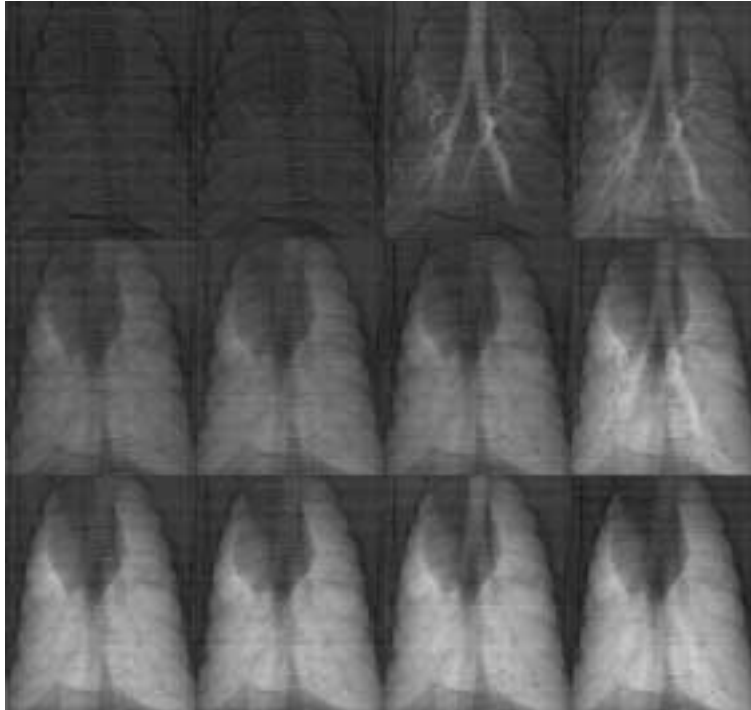


Figure 3: KES radiographs of rabbit lung

The bronchial tree is visible in frames 3 and 4, and the larger bronchi are seen also in some of the later frames. The alveoli start filling already in frame 3, and the bronchi become more and more shadowed in the following frames. However, the evolution of gas convection and diffusion can be followed by taking the differences between images taken at different times. Such a subtraction image is shown in Figure 4. The "fog" due to the contrast agent in the alveoli is largely removed, and the bronchial tree is visible in great detail. Perhaps the most important feature of the subtraction images is that the actual size of the bronchi can be evaluated.

Only the regional filling of alveoli can be estimated from the radiographs, and the absolute concentrations cannot be calculated. For this reason, CT was



Figure 4: Subtraction of two images

performed on the rabbits. In the sequence where cumulation of Xe was observed the rabbit was first ventilated by air, and then by Xe/O₂ mixture. For calibration, the gas inlet tube was included in the CT images. After 4-8 inspiration/expiration cycles of 1 s, ventilation was stopped, and an image was taken during the apnea. Then ventilation was resumed, and the next image was taken again during the apnea. The time interval between two images was 3.6 s. This was repeated several times for determination of the time constants of ventilation. A series of images are shown in Figure 5. These show the distribution of the Xe gas in a horizontal section in the upper part of the lungs, near the lower end of the heart. Blood vessels and bronchi are visible in the pictures, and the diameters of bronchi are easy to calculate. Also absolute concentration of xenon in bronchi and alveoli can be calculated.

4 Discussion

The results of this study demonstrate that the use of stable xenon gas as contrast agent allows serial high resolution imaging of the airways, when dual-energy x-ray synchrotron radiation is used. The advantages of KES imaging of lungs with stable Xe as the contrast agent are the excellent spatial resolution and precise knowledge of the physical parameters. The absolute concentration of the contrast gas can be mapped, and the fast imaging sequence makes functional studies possible. Although the present experiments were not optimized, the results show that diffusion and bulk flow (convection) of the gas can be measured by temporal subtraction of images. It is obvious that quantitative measurements of Xe concentration and its changes as a function of time along the bronchial tree and in the alveoli would allow for the quantification of regional ventilation, and the ventilation inhomogeneity in normal and pathological lung. Promising perspective of this technique is to correlate the 3-dimensional structure of the bronchial tree with the distribution of Xe concentration within the airways. The 3-dimensional reconstruction can be made from many 2-dimensional CT images, but also from stereo images acquired in the radiography mode.

Further animal studies will be needed for establishing optimum conditions for

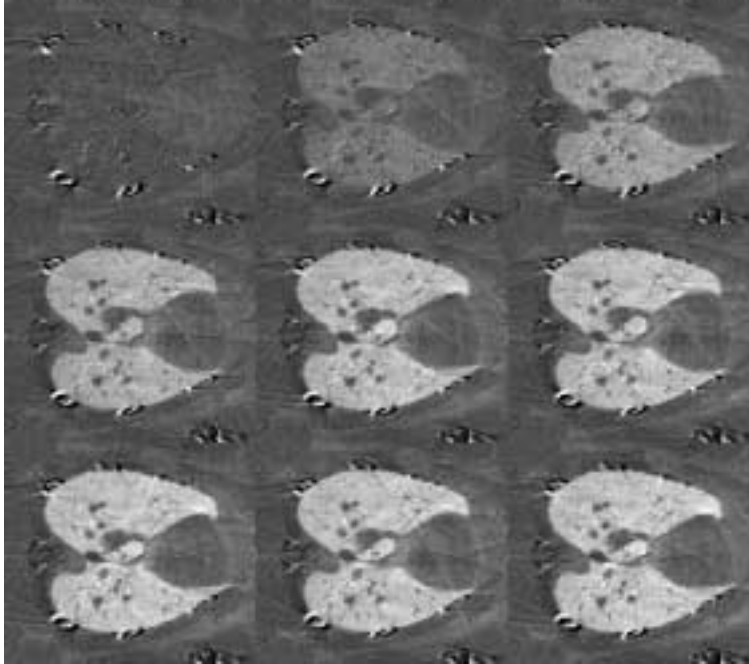


Figure 5: Reconstructed images of the Xe distribution

KES imaging, both in the radiography and CT modes. The method is seen as a research tool for better understanding of ventilation of normal lungs and lungs affected by a disease. The possibility to image the bronchial tree, and functionally active small airways in particular, offers an important new tool for the study of structure-function correlation, and airway pathophysiology.

This paper is based on article by S. Bayat, G. Le Duc, F. Grimbert et al. *Quantitative Imaging of Small Airways with Synchrotron Radiation Using Stable Xenon Gas As Contrast Agent*. To be submitted to *Radiology*.

References

- [1] Elleaume H, Charvet AM, Berkvens P, et al. *Instrumentation of the ESRF Medical Imaging Facility*. Nucl Instrum Methods A428,513 (1999).