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CT imaging of the internal human ear: Test of a high resolution scanner

M. Bettuzzi [a,*], R. Brancaccio [a], M.P. Morigi [a], A. Gallo [b], S. Strolin [a], F. Casali [a], Ernesto Lamanna [b], Marilù Ariù [c]

[a] *Department of Physics, University of Bologna and National Institute of Nuclear Physics Section of Bologna, Italy*
[b] *Medicine Faculty, Magna Graecia University, Catanzaro and INFN Cosenza, Italy*
[c] *CEFLA Dental Group, Imola, Italy*

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ABSTRACT

During the course of 2009, in the framework of a project supported by the National Institute of Nuclear Physics, a number of tests were carried out at the Department of Physics of the University of Bologna in order to achieve a good quality CT scan of the internal human ear. The work was carried out in collaboration with the local "S. Orsola" Hospital in Bologna and a company (CEFLA) already involved in the production and commercialization of a CT scanner dedicated to dentistry. A laboratory scanner with a simple concept detector (CCD camera-lens-mirror-scintillator) was used to see to what extent it was possible to enhance the quality of a conventional CT scanner when examining the internal human ear. To test the system, some conventional measurements were made, such as the spatial resolution calculation with the MTF and dynamic range evaluation. Different scintillators were compared to select the most suitable for the purpose. With 0.5 mm thick structured cesium iodide and a field of view of 120×120 mm^2, a spatial resolution of 6.5l p/mm at 5% MTF was obtained. The CT of a pair of human head phantoms was performed at an energy of 120 kVp. The first phantom was a rough representation of the human head shape, with soft tissue made of coarse slabs of Lucite. Some inserts, like small aluminum cylinders and cubes, with 1 mm diameter drilled holes, were used to simulate the channels that one finds inside the human inner ear. The second phantom is a plastic PVC fused head with a real human cranium inside. The bones in the cranium are well conserved and the inner ear features, such as the cochlea and semicircular channels, are clearly detectable. After a number of CT tests we obtained good results as far as structural representation and channel detection are concerned. Some images of the 3D rendering of the CT volume are shown below. The doctors of the local hospital who followed our experimentation expressed their satisfaction. The CT was compared to a virtual endoscopy and judged particularly useful for clinical pre-surgery diagnostics. The experimentation proceeds with a faster scanner now under development in our laboratories. We believe this work could be of a certain interest for the medical imaging world.

1. Introduction

The problem of imaging the internal human ear for pre-operative planning, post-operative assessment, prosthesis check or disease diagnosis is a challenging and very fascinating subject. Studies employing nuclear magnetic resonance imaging have also been performed [1]. As is well known, however, the spatial resolution cannot be pushed forward too much by this technique. On the other hand, conventional multi-slice CT has proven to be a standard clinical tool for internal ear diagnosis [2,3]. But it is somewhat limited if one wants to look more deeply into the complex structure of the organ since the vestibular conducts, cochlea spiral and semicircular canals are barely detected and thus are difficult to visualize [4]. Most high resolution imaging studies on the internal ear have been done by means of micro-CT systems on specimens [5–7]. But imaging a small sample, usually the temporal bone, is quite far from a real case. While the results could certainly be important for studying and understanding the anatomy of this organ in a quasi non-destructive way, they cannot effectively provide useful clinical diagnostic information for a living patient. On the other hand, CT volume navigation software is now widely used by surgeons and one wonders why it is not possible to have the same astonishing computer aided operative planning tools for the inner ear too. The answer is linked both to the state of the art of existing technology and the physical limits imposed on imaging by dose requirements of X-ray in-vivo scanning. Our work is an attempt to investigate the above question, choosing a mostly experimental approach.

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[*] Corresponding author. Tel.: +39 051 209 5098; fax: +39 051 209 5047.
E-mail address: matteo.bettuzzi@unibo.it (M. Bettuzzi).

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We first explored the opportunity and modality of high resolution X-ray CT imaging of the temporal bone without extracting it from its anatomic context. This involved using artificial or semi-organic phantoms with features as close as possible to a real human head. The results were shown to specialists for a subjective quality judgment. In the framework of a three-year project called RITOR, supported by the National Institute of Nuclear Physics, the present work represents the first, albeit experimental, explorative phase of the problem. The second phase will be the choice of the most suitable components of a "close to clinical" device and reproduction of the results obtained in the first phase correlated to dose measurements, in order to verify how far from the discussed limits it is possible to go with the present commercial technology. The principal aim, however, is to provide a laboratory prototype of a device useful for specialists of the inner ear, which can enhance the quality of the present conventional X-ray CT scanners. To give some numbers, a possible goal could be to achieve a reconstruction voxel of less than 100 μm in the CT volume. This would mean having one fifth of the linear size of the voxel of a conventional scanner, or, thinking in 3D, a voxel 125 times smaller. In principle, this factor is somewhat related to an increase in the absorbed dose, depending on X-ray flux and detection statistics, if we intend to maintain exactly the same signal-to-noise ratio. Thus a significant part of the work will be to find out if a detector exists and a system layout could be designed that has enough efficiency to keep the dose acceptable while increasing the spatial resolution to such an extent.

2. Materials and methods

A key point for our test was the opportunity to use a human head phantom, which contains a skull with all the anatomic features of interest to us: cranium with temporal bone, cochlea, and semicircular canals. A simpler head phantom made of a base of plastic material was designed and built for calibration purposes. The second head is divided into different horizontal slabs. One of the slabs was carved and filled with a layer of hydroxyapatite to simulate the cranium bone. The two heads are shown in Fig. 1.

2.1. Microtomography test

A first attempt to obtain a high resolution CT of the temporal bone was made with the existing micro-CT system of our laboratory at the Department of Physics in Bologna. The system is composed of a Photonic Science CCD camera, a system of axis (vertical, horizontal, double tip-tilt and rotation) and a microfocus X-ray tube (Figs. 2 and 3). The camera has a 1:1 fiber optics plate coupled with a gadolinium oxysulfide scintillator layer deposited on it at the X-ray beam input end. The camera is cooled with a Peltier stage and a liquid circuit. It mounts a Kodak KAI-1100 sensor with 4008 × 2572 active pixels, $9\times9\ \mu m^2$ and 60,000 electrons well capacity. The maximum quantum efficiency of the sensor is 50% at 500 nm.

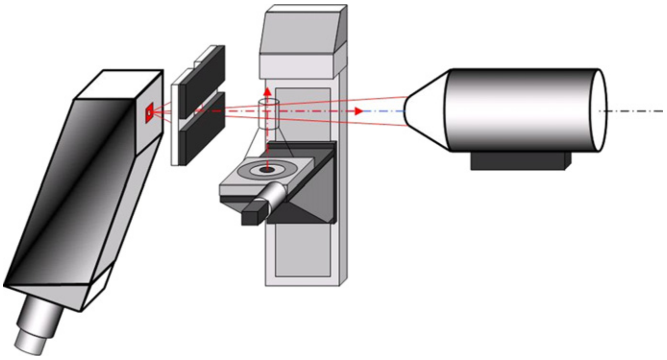

Fig. 2. Sketch of the micro-CT system.

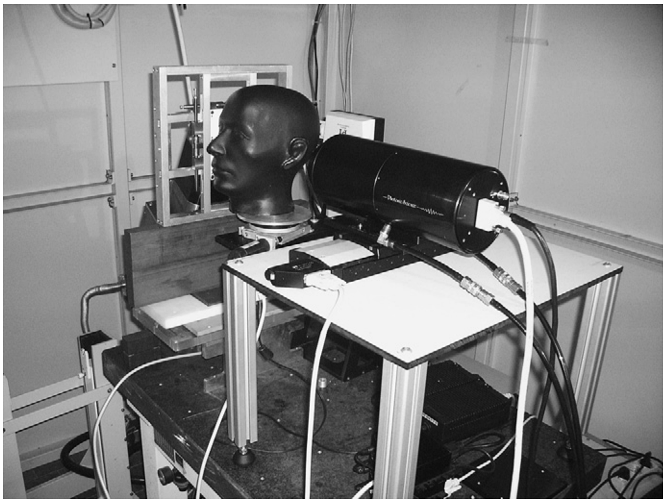

Fig. 3. The micro-CT experimental set-up.

Fig. 1. Left: human head with anatomy inserts; right: calibration phantom.

The microfocus tube is a Feinfocus FXE200.20 with minimum focal spot of 5 μm, 200 kVp maximum and 3 mA, current 900 W power. The sample manipulator system including rotary table is based on Physik Instrumente micropositioning M-038rotary, M-511linear and M-415linear devices. A custom made control software combines rotation and radiography grabbing in the scanning process according to the input parameters. The parameters used for the scanning of the human head phantom are reported in Table 1. The result of the CT reconstruction is a cylinder containing the internal ear area (Figs. 4 and 5). Despite the high resolution (with a 32 μm voxel), we obtained poor contrast and it was thus very difficult to separate bone from soft tissue. Another problem is the very small field of view that makes it very difficult to focus on the area of interest. We did, however, succeed in demonstrating that a reconstruction of the internal ear is possible using a micro-CT device as it is. The long scanning time is due to the very low current of the X-ray tube (0.2 mA).

Table 1
Scanning parameters for human head micro-CT.

Micro-CT parameters	
Voltage (kV)	**120**
Current (μA)	**200**
Exposure time (s)	**3**
Frames per projection	**4**
Pre/post collimation	**Yes**
Angle range (deg.)	**360**
Number of projections	**720**
Binning	**8 × 8**
Projection size (pixels)	**500 × 325**
Detector pixel size (μm)	**72**
Object pixel size (μm)	**32**
Total scanning time (min)	**144**
Source detector distance (mm)	**345**
Object detector distance (mm)	**191**
Source object distance (mm)	**155**
Magnification factor	**2.22**

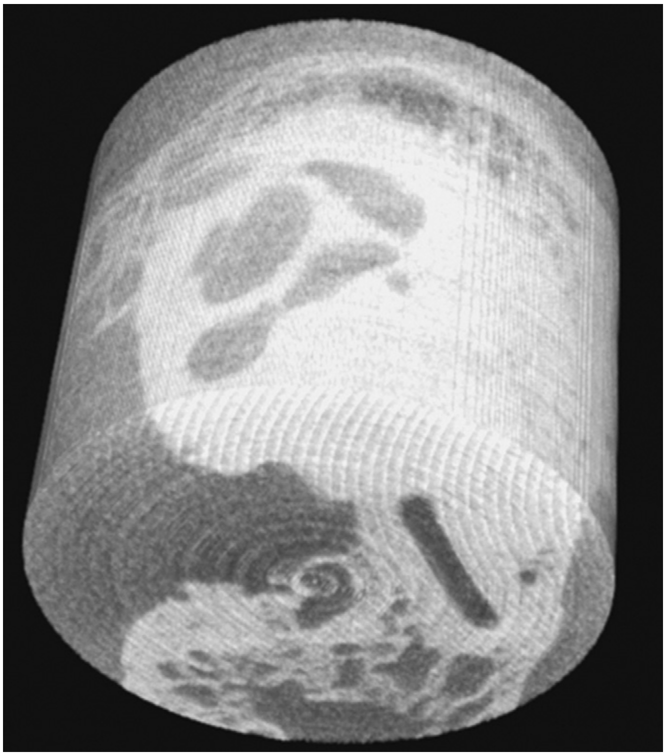

Fig. 4. 3D volume relative to the micro-CT scanning test.

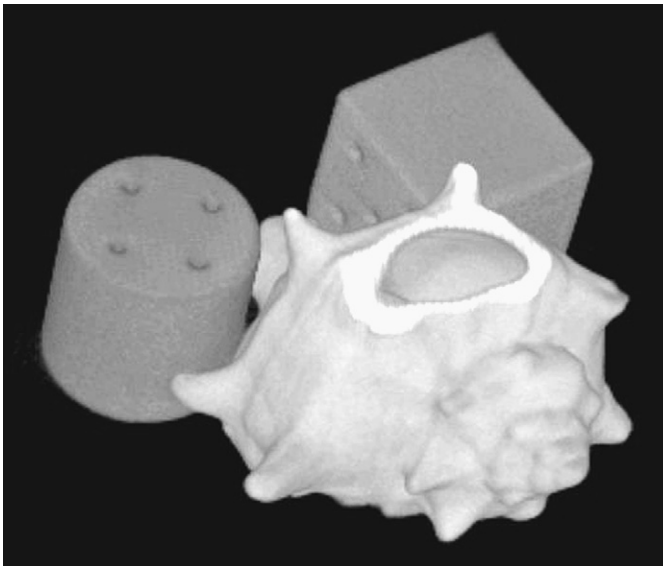

Fig. 5. Calibration scan 3D rendering on artificial phantom.

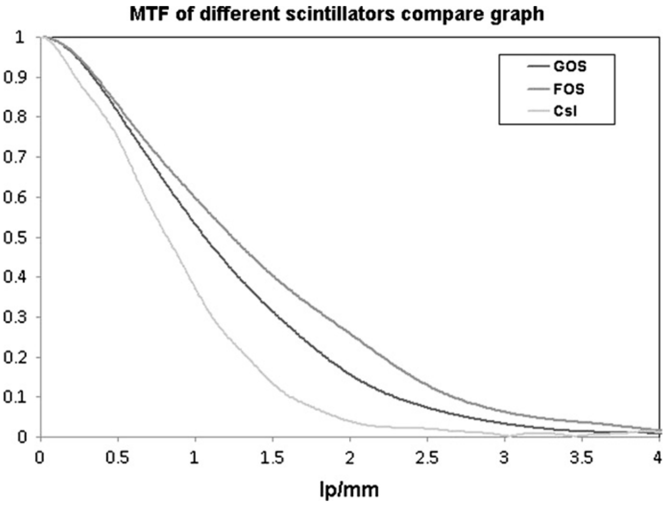

Fig. 6. MTF of three scintillators compared.

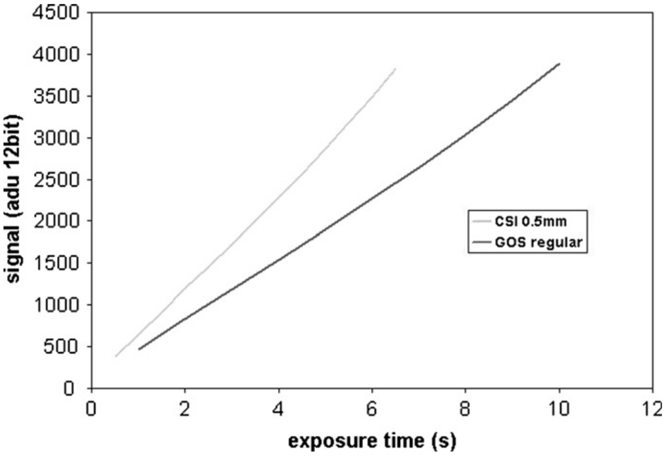

Fig. 7. Light output of CsI and GOS.

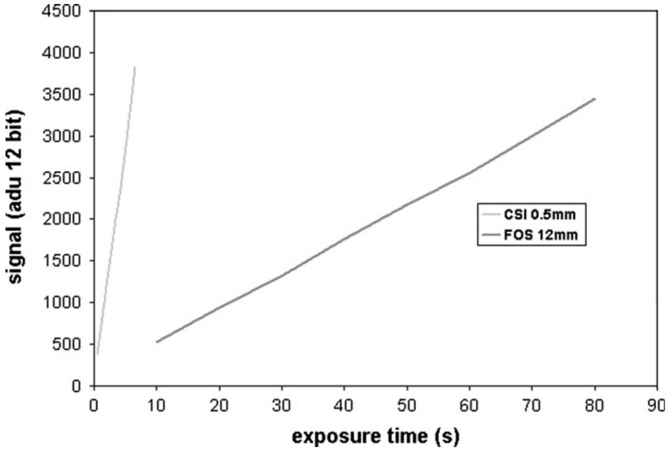

Fig. 8. Light output of CsI and FOS.

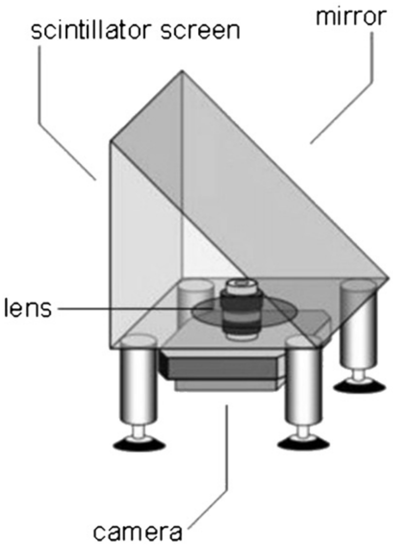

Fig. 9. Sketch of the detector structure.

Fig. 10. Photo of the wide field laboratory CT system.

2.2. Dedicated CT test

A dedicated CT system was set-up in order to enlarge the field of view, enhance the contrast and work with parameters somewhat closer to a prototype CT (Fig. 10). The detector of this new system is based on a CCD camera made by Apogee (AltaU9000 model). This camera was lens coupled with a scintillator of area 120 mm × 120 mm (Fig. 9). This field of view appears the most suitable for scanning the head in the area of the internal ear. The camera mounts a Kodak KAF-09000 sensor with 3056 × 3056 pixels, 12 μm and 120,000 electrons well capacity. The sensor quantum efficiency curve has a maximum of 65% for 560 nm. The X-ray tube is a Bosello XRG120IT.50 model, capable of 120 kVp maximum voltage and 8 mA current and limited to 500 W. The rotary table is a Physik Instrumente M-038 stage. We first compared the performances of different scintillators (Figs. 6–8). The final choice was the cesium iodide for its much higher light output, which is very important in order to have a good signal-to-noise ratio and a good final contrast. The head calibration phantom was placed at a distance of 1.4 m from the source spot, while the source-detector distance was 1.7 m giving a very low magnification value of 0.83. This helps in preserving

Table 2
Scanning parameters.

CT parameters	
Voltage (kV)	120
Current (mA)	4
Exposure time (s)	24
Frames per projection	1
Pre/post collimation	Yes
Angle range (deg.)	360
Number of projections	900
Binning	3 × 3
Projection size (pixels)	1018 × 1018
Detector pixel size (μm)	132
Object pixel size (μm)	110
Total scanning time (min)	360
Source detector distance (mm)	1736
Object detector distance (mm)	290
Source object distance (mm)	1446
Magnification factor	0.83

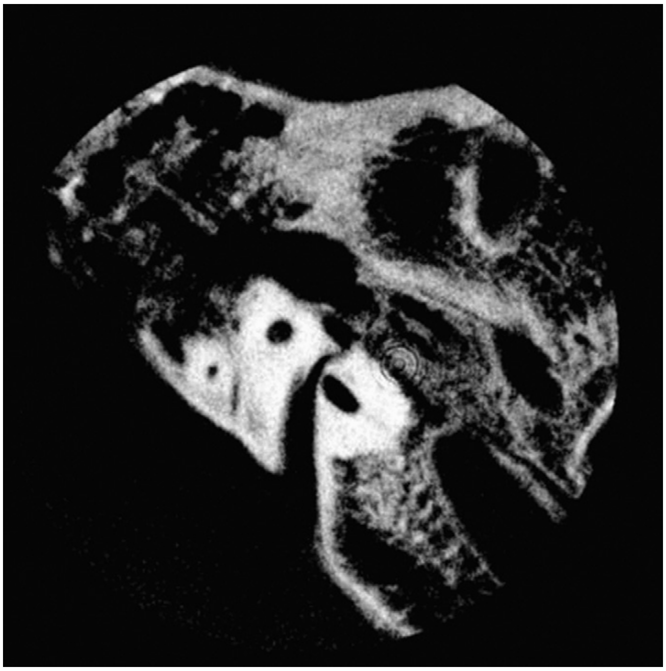

Fig. 11. Section of canals.

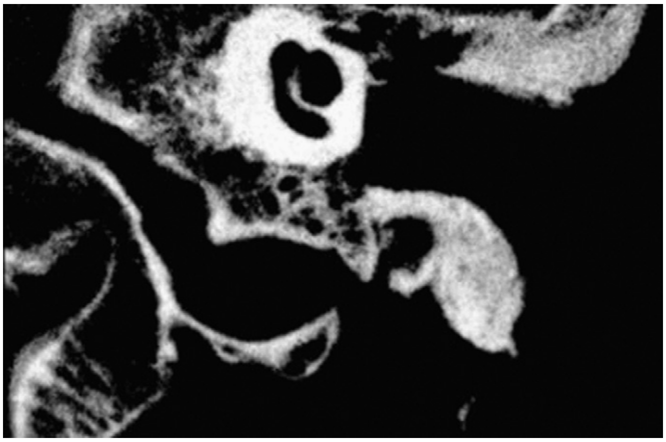

Fig. 12. Axial section of cochlea.

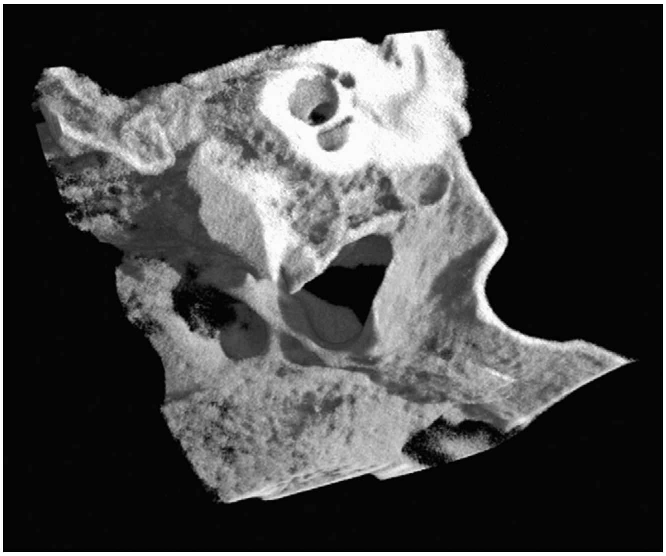

Fig. 13. 3D rendering of the temporal bone.

the spatial resolution when working with the relatively large focal spot of our tube (0.8 mm). The scanning parameters are reported in Table 2. Objects inside the calibration phantom and simulating cochlea and canals are clearly well resolved. After this first calibration scan, the human head phantom was mounted on the rotary table and focused. The parameters of the CT are reported in Table 2. A few CT slices of this last scan are reported in Figs. 11 and 12, while in Fig. 13 a 3D rendering of the temporal bone is shown. The segmentation of the bone from soft tissue is effectively and easily performed due to the very good contrast. The trabecular structure of the bone is also partly visible.

3. Conclusions

A very clear image of the internal ear was obtained, which was greatly appreciated by the specialists, who actually compared it to a virtual endoscopy. The scanning time reported in Table 2 is very long as we tried to obtain a good quality CT regardless of clinical time requirements and absorbed dose value in this phase of the project. The scan obtained will form a reference for further developments of the system in a more suitable way for a real application. A fast detector (17 fps flat panel) and a pulsed high power X-ray tube will be tested in the next year and dose measurements will be performed in order to relate the image quality level to the admissible dose values. These constraints will allow us to assess if current commercial technology is adequate for the clinical scanning of the internal ear.

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