NON-COMPUTERIZED OFF-AXIAL TOMOGRAPHY WITH 580 MeV PROTONS

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Abstract

Tomography so far has used a "passive" property of radiation absorbtion, i.e., variation of the transmission rate. Computerized tomography reconstructs (Fourier analyses) a 2D picture out of a sequence of 1D transmission profiles. The resulting image is therefore axially oriented. The use of the stereoscopic effect of two views of the same object (slice), taken at two slightly different angles, is, in such a case, not feasible.

"Protoscopy" is based on an "active" property of radiation absorption, i.e., large angle nuclear scattering. The vertices of the large angle scattered protons are individually measured. The spatial resolution of the detectors and the Coulomb multiple scattering are responsible for the existance of an "elementary volume". Stereo display is under study. Despite the fact that "protoscopy" requires a (still) expensive proton source of 600 MeV, a scanning system, the "protoscope", is proposed to challenge all the excellent performances of the most advanced X-ray tomography techniques, such as the automatic computerized transverse axial (ACTA)-scanner.

1. Transmission Tomography

The digital CAT (Computerized Axial Tomography) systems attempt to reconstruct a 2-D picture by computer analysis of a large number (up to 180) of 1-D profiles, each composed from a great deal (160 to 80 000) of the individual transmission data points.

A transmission tomogram is a set of pels (picture elements) containing n bits of information each, representing the computed value of the absorption of each individual vel (volume element) in a slice of a tissue. A more detailed description can be found in ref. 1.

There are several scanning modes according to the particular preference of the originators, e.g. parallel and narrow X-ray beams have been used in the EMI-[2], Siemens- and ACTA[1]-scanners while fan beams are prefered for fast whole body scanners[3,4]. The use of ^{68}Ga, which is a β^+ emitter, also gives promising results despite its invasive character.

A non-conventional approach to CT has been proposed by K. Crowe[3]. Instead of using X or γ rays, he took advantage of the availability of 940 MeV α-particles from the 184" LBL cyclotron. Helions have absorption properties differing from that of X-rays and offering a different radiological sensitivity. In fact alpha transmission tomography is a logical outcome of all research in the field of digital marginal range radiography[6] which, after the spectacular demonstration by Alvarez et al. in the Chephren's pyramid , was finally recognized of interest for biomedical applications by Dr. V.W. Steward. Let us just mention the extensive work of R. Martin et al. at the A.N.L.,of K. Crowe et al. at the L.B.L. and our own work with the Philips injector at S.I.N.

The α-tomogram of an head presented in Stanford by K. Crowe[3] nearly reaches the quality of an EMI-tomogram although the quoted dose delivered[5] might have been quite underestimated.

Despite its advantages α-CT systems requiring the exclusive use of 940 MeV α-accelerators can hardly become economically competitive.

2. Scattering Tomography

Instead of using transmission measurements requiring complex mathematical analysis, one is tempted to use large angle scattering in order to measure directly the absorption value of a specific vel;i.e. by the precise reconstruction of the vertex of interaction of each individual scattered particle. The purely geometrical vertex reconstruction can be done by hardwired logic instead computer but large angle scattering occurs only with hadrons!

By projecting a pencil beam of hadrons on a target one obtains the density profile of the target along the beam line by measuring the flight direction of the scattered particles. We will call such a cylindrical radiogram a "cylogram".

In 1967 we measured[7] cylograms of a liquid hydrogen target (full, empty and accidentally with frozen air) by using a 6 GeV π^- beam from the CERN PS. At this time we believed that the small cross sections involved deny any future for biomedical application of this technique.

Fortunately J. Sandinos et al.[8] proved this assumption to be wrong. The 600 MeV protons have indeed all the requested properties for diagnosis of tumours in soft tissus:

1) a sizable fraction of the quasi elastically scattered particles is scattered between 20° and 40°, thus allowing a precise vertex reconstruction. The rate

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of absorption is of the order of 1 % per gramme of tissue[9], and the angular dependance is weak, varying over the used angular range by a factor 2 only.

2) The measured 600 MeV proton absorption rate is closely related to mass-density, offering a so far unexplored radiological sensibility. This rate shows a very weak energy dependance.

3) The multiple Coulomb scattering is sufficiently small to allow the precise reconstruction of vertices.

4) A good mass-resolution can be achieved without a prohibitive dose of radiation.

5) Synthesis of a 3-D array by successive measurements of the adjacent cylograms allows free choice of the tomograms axis, hence Off-Axial Tomography.

6) The selection of coplanar events makes possible the display of the Hydrogen content of a tissue. The selective sensitivity to Hydrogen has been so far the greatest merit of neutron radiography!

The decisive experiment of Sandinos et al. at the CERN PS consisted of 2 phases:

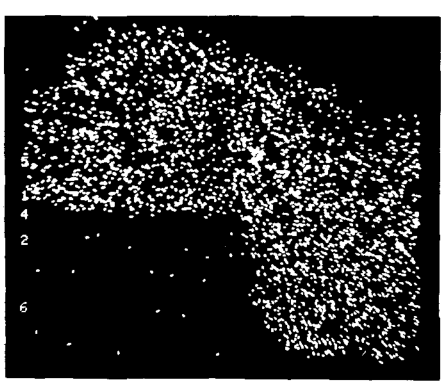
i) An already published[8,10] study of an egg.

ii) An unpublished study of a dead rabbit[11] and of a living mouse with tumour.

Summary of the CERN "Proton-Bunny" Scattering Experiment

Exposure time: 24 hours
Sensitivity to density variations: ± 2 % per gramme.
Necessary dose/effective dose: 1 %

Fig. 1 shows a 1-bit scattering-tomogram of a rabbit head, 1 mm thick. It is a lateral view containing the right side of the jaw.



With an average of 3 events/mm^3 one can only distinguish between bone, teeth or tissues and air. The styrofoam in which the body of the rabbit was embedded appears as an ideal low background support.

The data acquisition rate and the detectors system's efficiency were far too low to allow a complete evaluation of the potential of the method.

3. Protoscopy

In order to judge of the future of proton large angle scattering tomography or "protoscopy" as a useful diagnosis tool one has to compare the density resolution achieved with its associated dose.

For 600 MeV protons in a tissue slab over 10 cm thick the ICRP report (vol. 21) gives the dose equivalent per unit proton fluence as 10^{-7} rem • cm^2, of this 55 % is due to nuclear interaction and 45 % from the dE/dx losses of the beam.

If we consider a dose of 1 rem as tolerable we see that one can inject up to 10^7 protons/cm^2, i.e. 10^5 events/gramme of tissue. This will give a sensitivity to density variation of ± 2 % for a sphere of 3 mm in diameter. Dr. V.W. Stewards, on the other hand, quotes a typical mass density increase of 3 % in a tumour.

The remaining problems to be solved before an actual patient protoscopy is attempted are as follows:

1) Realisation of a pencil beam with very low off-beam radiation.

2) Need for high speed data acquisition rate.

3) Need for high detectors efficiency.

4) The detectors should cover most of the solid angle of the elastically scattered protons ($\theta_{max.}$ = 42^0).

A protoscopic system is at present under design at SIN[12]. It aims at the following characteristics:

beam: "parasitic" scattered proton beam (pM1)
proton energy: 580 MeV
beam size: 1 mm^2 with small divergence
beam rate: 1 MHz
events rate: 100 kHz
elementary volume
(due to limited spatial resolution): 10 mm^3
scan time/1 mm slice: 10 sec
scan time/litre: 15 min
horizontal scanning speed: 1 cm/sec
vertical scanning speed: 1 mm/10 sec
sensitivity to density variations: ± 0.3 % per gramme/cc
equivalent dose: 1 rem
energy released in tissue: 10^{-2} Joule/litre.

References

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