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Proton Scanner

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I. Introduction

The scanner is based on the nuclear scattering of high energy protons by the nucleons (protons and neutrons) included in the atomic nuclei. It has been described elsewhere (1,2,3) and we just recall here the main properties :

a) Due to the large value of the scattering angle, one may compute the three coordinates in space of the interaction point and obtain directly three dimensional radiographs. Volumic resolution is about a few cubic-millimeters.

b) Because the basis interaction is the strong nuclear force, the atomic dependence of the obtained information is different from the one of the X-ray scanner for which the basis interaction is the electro-magnetic force. For a volume element (vel) ΔV expressed in cubic centimeter, with density d and atomic composition $\sum_i a_i A_i$ the number of scattered protons is :

$$N_S = 0.6\ N_I \times \Delta V \times d\ \frac{\Sigma\ a_i\ \sigma_i\ A_i}{\Sigma\ a_i\ A_i}. \qquad (1)$$

There N_I is the intensity of the incident proton beam (particles/cm^2) and σ_i are the nuclear scattering cross-section of the elements A_i expressed in barns (10^{-24} cm^2). Because the localisation of only one scattered particle is involved, the radiographs obtained from the variations of N_S are called simple or S radiographs in the following. To illustrate the difference between the proton scanner and the X-ray scanner, we recall that calcium (d = 1.53) gives within 10 % the same N_S as water. In case of 60 keV-X ray, the absorption is about a factor 5 higher for calcium compared to water.

c) If one detects not only the scattered proton but also the recoil nucleon (2) one is able to separate simultaneously the nuclear scattering by the hydrogen contained in objects. The number of protons scattered by hydrogen is :

$$N_H = 0.6 \times N_I \times \Delta V \times d \times \frac{a_H\ \sigma_H}{\Sigma\ a_i\ A_i} \qquad (2)$$

with the same units as in formula 1.

This property gives us a second independent information on the objects. The radiographs obtained from the variations of N_H are called hydrogen or H radiographs.

Moreover one may do the ratio H/S and obtain radiographs dependent on the value $a_H\sigma_H/\sum_i a_i\sigma_i A_i$ and not on the density or one may do the product H × S and obtain radiographs dependent on the square of the density.

Despite these properties, the proton scanner has not been yet of practical use because the time of irradiation of the order of several days is much too long. Before to speak about the future improvements, we would like to show you the results already obtained.

1. Experimental results

The radiographs of a human head conserved in formalin has been done last year at CERN. It was placed in a low density styrofoam cradle (d = 0.03) inside a lucite box. In that way we simulate as closely as possible the conditions of an *in vivo* radiograph. The irradiation lasts four days and the dose is about 0.3 rad. One hundred and thirty millions simple events N_S are stored in a three-dimensional matrix *$M(X,Y,Z)$ with dimensions $124 \times 124 \times 96$. It corresponds to about 1.5 million* volume elements of 5.5 mm^3 with dimensions $\Delta X = \Delta Y = 1.4$ mm, $\Delta Z = 2.8$ mm. In our case, horizontal, frontal and sagittal slices of the head correspond respectively to XY, ZX and ZY planes. About 100 scattered events are stored per vel for soft tissues. Elementary planes may be summed in order to increase this number and improve the sensitivity. For hydrogen radiographs about seven millions events are obtained. To visualize the slices we use linear convention : pixels on the image have grey tones going from black to white when N_S or N_H increase.

Fig. 1 shows a comparison of horizontal slices obtained by proton (simple) and X-ray scanner. Simple radiographs show satisfactory anatomical images. The two hypodensities detected by the X-ray scanner in the two brain hemispheres are also visualized by protons despite a dose delivery five times lower. Figs. 2 (frontal slices) and 3 (sagittal slices) show the ability to do directly three-dimensional radiographs. At the upper part of the brain, on Fig. 2 one can see a transversal cut of the hypodensities visualized on the horizontal slices (Fig. 1). Adjacent sagittal slices in the central part of the head, show details like the beginning of the spine, the "sinus", the "sella turcica".

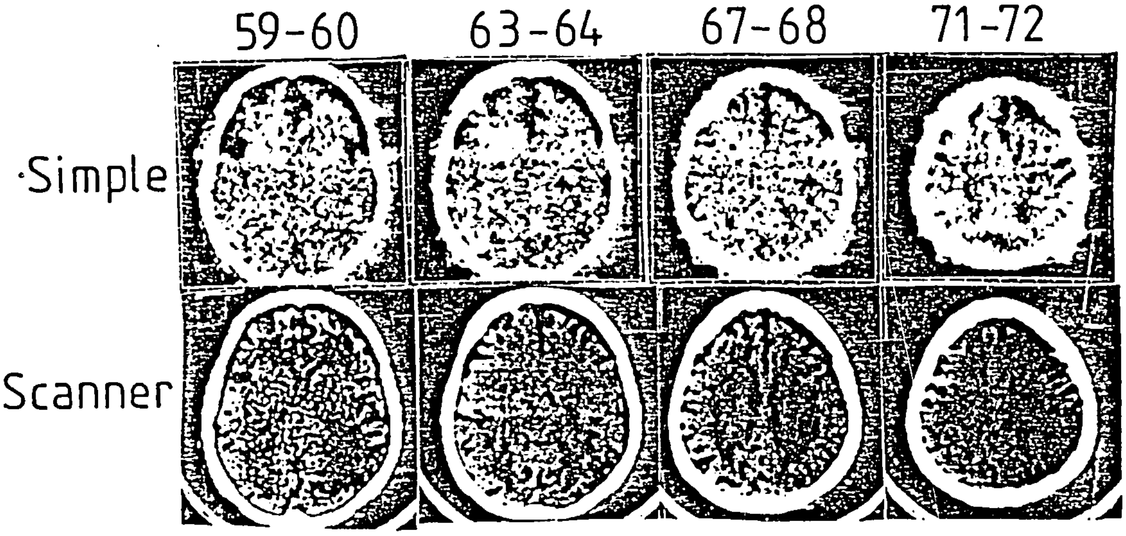

Fig. 1. Comparison of proton and X-ray scanner radiographs. The slices are horizontal. In case of proton, the simple radiographs correspond to a pixel of 1.4×1.4 mm^2 and a slice width of 5.6 mm. The numerical values are the ordering numbers of the elementary slices : 96 slices are obtained for one radiograph. The hypodensities detected by the X-ray scanner are visualized on the slices 67-68 and 71-72 of the proton scanner.

Fig. 4 shows a comparison of simple (S) and hydrogen (H) radiographs and their combination H/S and H × S in case of an horizontal slice. To be more quantitative

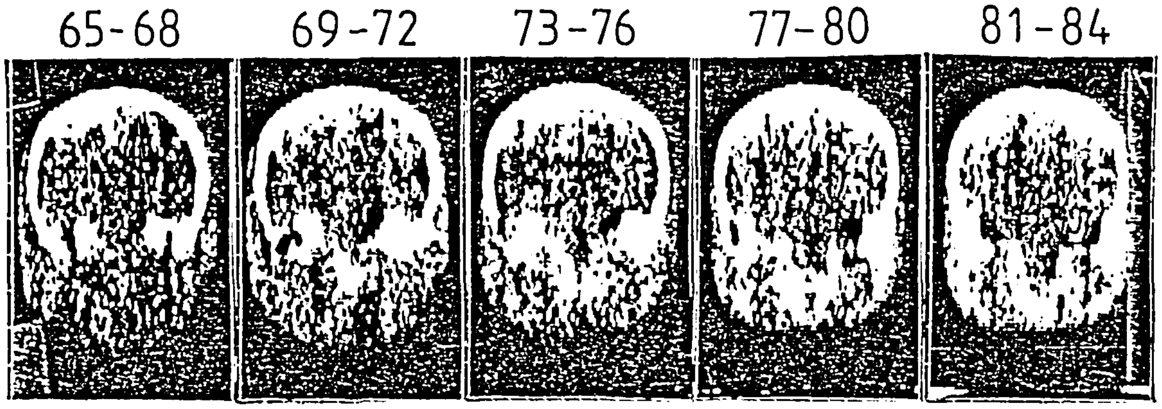

Fig. 2. Proton scanner. Simple radiographs. Frontal slices. Pixel is 1.4 × 2.8 mm^2 and the slice width is 5.6 mm.

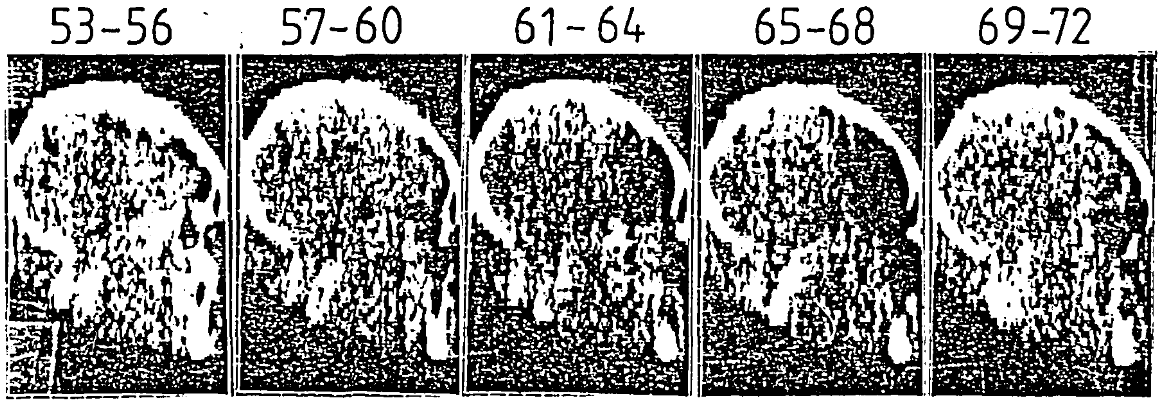

Fig. 3. Proton scanner. Simple radiographs. Sagittal slices. Pixel is 1.4 × 2.8 mm^2 and the slice width is 5.6 mm.

we give the histograms of the counting rate in function of the position along horizontal lines. On S and H radiographs bone appears respectively in white and black. This is explained by the low percentage (4) in weight of hydrogen in bone (∿ 6 %) compared to soft tissue (11 %). Taking in a crude approximation the atomic compositions (4), the densities, and the nuclear cross-sections involved, one may compute a contrast of about + 30 % between bone and smooth tissue for simple radiograph and - 13 % for hydrogen radiograph. The measured values shown on the histograms are + 25 % and - 15 %. More interesting is the fact that in soft tissues, the contrast in the brain hypodensity varies respectively from 6 % to 15 % for S and H radiographs. The difference of sensitivity of these two types of radiographs is promising. Fig. 4 shows also an H/S radiograph which is density independent. There the bone appears with high contrast (about 35 %) but the hypodensity contrast is well reduced. On the S × H radiograph which is dependent on the square of the density, the bone contrast is reduced to about 10 % but the hypodensities appear very well (20 % effect).

2. The future Improvements

The experimental results appear to us as encouraging. We are starting at Saclay a new system which will do a radiograph in about half an hour. In that way, we shall be able to make a systematic study of the advantages and limits of this method.

A particular attention will be payed to the radiography of moving systems because it is very easy with the proton scanner to correlate the scattered events to an external signal, characteristic of the movement. If the proton scanner appears of practical use, it will be possible technically to build a faster one able to obtain radiographs in one or two minutes.

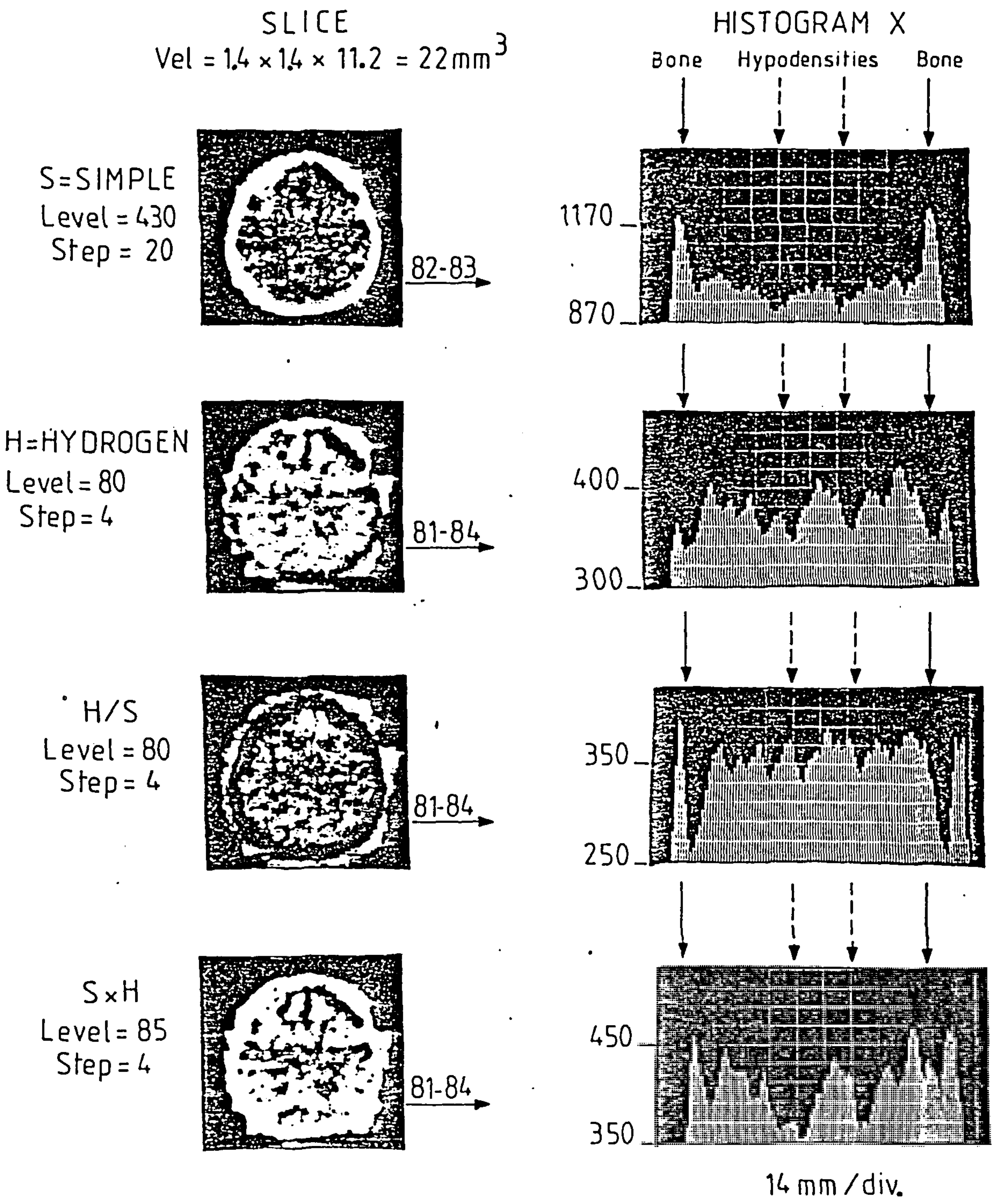

Fig. 4. Comparison of simple (S) and hydrogen (H) radiographs and their combinations in case of an horizontal slice. Histograms give a quantitative evaluation of the different contrasts.

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