сообщения
объединенного
института
ядерных
исследований
дубна

E18-94-112

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MEDICAL FACILITY FOR RADIATION THERAPY WITH JINR PROTON PHASOTRON BEAMS

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Moscow

1994

Introduction

The six-compartment clinico-physical facility for radiation therapy with proton, negative pion and neutron beams was realized at the phasotron of the Joint Institute for Nuclear Research in Dubna (Russia) after its conversion. The clinico-physical facility consists of several medical channels: three therapeutic proton beams with energies from 100 to 660 MeV; a negative pion beam; a therapeutic neutron beam and a therapeutic γ-unit with the ^{60}Co source [1,2].

The JINR accelerator is a proton phasotron with maximum energy 660 MeV. The intensity of an external proton beam is about 3 μA ($1.9*10^{13} protons/sec$). The accelerator is intended for physical research and for radiation therapy. During the course of patient irradiation we usually use the accelerator for radiation therapy twice a week.

The proton beams with lower energy are obtained by deceleration of a 660 MeV beam in a carbon energy degrader. We can use the method of Bragg peak modification based on the transformation of the existing wide energy distribution of the decelerated proton beam by means of the magnetic analysis and a multicollimator system. After the magnetic analysis the proton beam is separated in space in accordance with proton energy. Each collimator from the multicollimator system, placed in a region with a certain energy of protons, may control the number of passed protons with this energy. After mixing the passed protons we can obtain an energy distribution which allows us to form a **modified** shape of Bragg curve [3].

Treatment Rooms

A general view of the medical facility is shown in Fig.1. The **first** treatment room for proton therapy is equipped for proton beam irradiation of large deeply lying tumours (for example, cancer of oesophagus) by the method of linear and rotation scanning [4,5]. The room contains original physical and medical devices, equipment for immobilization and centration of a patient in the sitting position. Motion of a patient during irradiation procedures and the Bragg peak position are controlled by a computer. Devices for proton [6,7] and X-ray [8] computed tomography are placed there too.

The **second** room is intended for transvaginal uterus cervix cancer

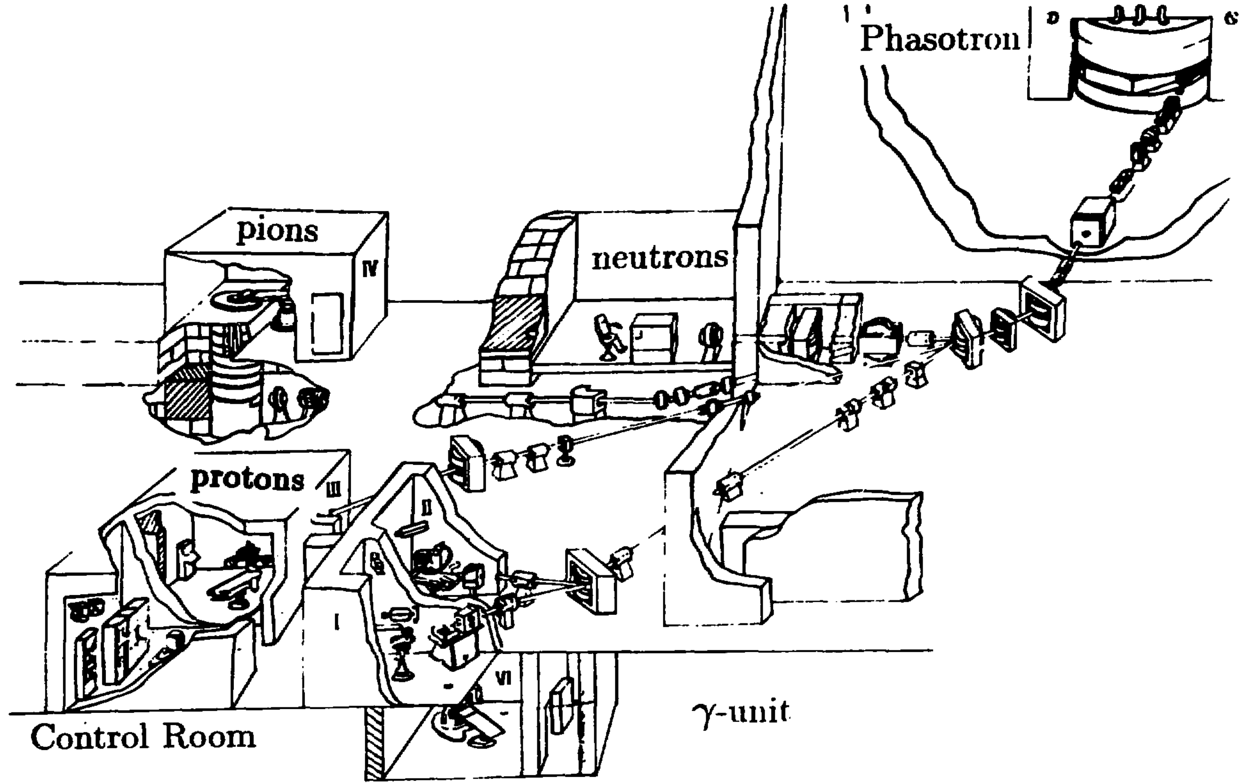


Fig.1. General view of the JINR medical facility

Table. Parameters of medical phasotron beams for an ejected proton intensity of 1 μA

Cabin number	Type and energy of particles	Particle intensity (s^{-1})	Beam diameter (cm)	Dose rate at irradiation site (Gy/min)	Remarks
1	200 MeV protons	$5 \cdot 10^8$	2-6	0.1-2.0	200 MeV protons are obtained by slowing-down in carbon degrader
1	100 MeV protons	10^8	2-6	0.3-1.2	100 MeV protons "
1	660 MeV protons	10^6	0.3	0.06	for proton tomography
2	130 MeV protons	$2 \cdot 10^8$	3-6	0.25-1.0	130 MeV protons are obtained by slowing-down in carbon degrader
3	660 MeV protons	$5 \cdot 10^7$	0.5-2	6.0	
4	30-80 MeV π-minus-mesons	$(1\text{-}2) \cdot 10^7$	2-10	0.04-0.06	π-mesons are produced in tungsten target 5 cm thick
5	neutrons of mean energy 350 MeV	$(3\text{-}5) \cdot 10^8$	5-15	0.025-0.09	neutrons are produced in beryllium target 36 cm thick
5	250 MeV protons	up to $5 \cdot 10^9$	up to 21	up to 20	250 MeV protons are obtained by slowing-down in carbon degrader

proton irradiation [8]. Regional limphatic nodules are irradiated at the γ-unit in the **sixth** procedure room.

The **third** treatment room includes equipment for stereotactical convergent irradiation of small intracranial targets by the "fly-through" method with a narrow 660 MeV proton beam [10].

The **fourth** procedure room is provided with equipment for irradiation of patients with a vertical beam of negative pions with an energy up to 80 MeV [11].

A therapeutic neutron beam with the mean energy about 350 MeV [12] will be used in the **fifth** procedure room for radiation therapy of large hypoxic tumours. The same room has also a wide 250 MeV proton beam for irradiation of large deeply lying tumours of complex shape.

The main parameters of the medical beams are presented in the Table.

Uterus Cervix Cancer Treatment

The method of the uterus cervix cancer treatment for the first time was worked out at ITEP (Moscow) [13] and developed in our group. We use the combined proton and γ-irradiations.

The depth-dose distribution is formed with the aid of a ridge filter [14]. For the dose field shaping we use a set of cylindrical collimators with a set of conical and cylindrical plexiglass heads. The ridge filter is a strong scatterer, and for the dose field defining we use the collimators. These collimators and a central probe are also used to fix the target with respect to the beam axis. The cylindrical heads of different thickness are intended for treatment depth regulation. The conical heads make it possible to irradiate both the uterus cervix and the adjacent region. Examples of isodose distributions with cylindrical and conical heads measured with a small silicon detector are presented in Fig.2. Each line indicates the isodose level with an interval of 10% of the maximum dose.

Usually 3 fractions of 20 Gy each weekly for preoperative irradiation of the uterus or 4 fractions without surgery were assigned to patients. Regional limphatic nodules were irradiated with 5 fractions of 2 Gy each a week at the ^{60}Co γ-unit during 5 – 6 weeks.

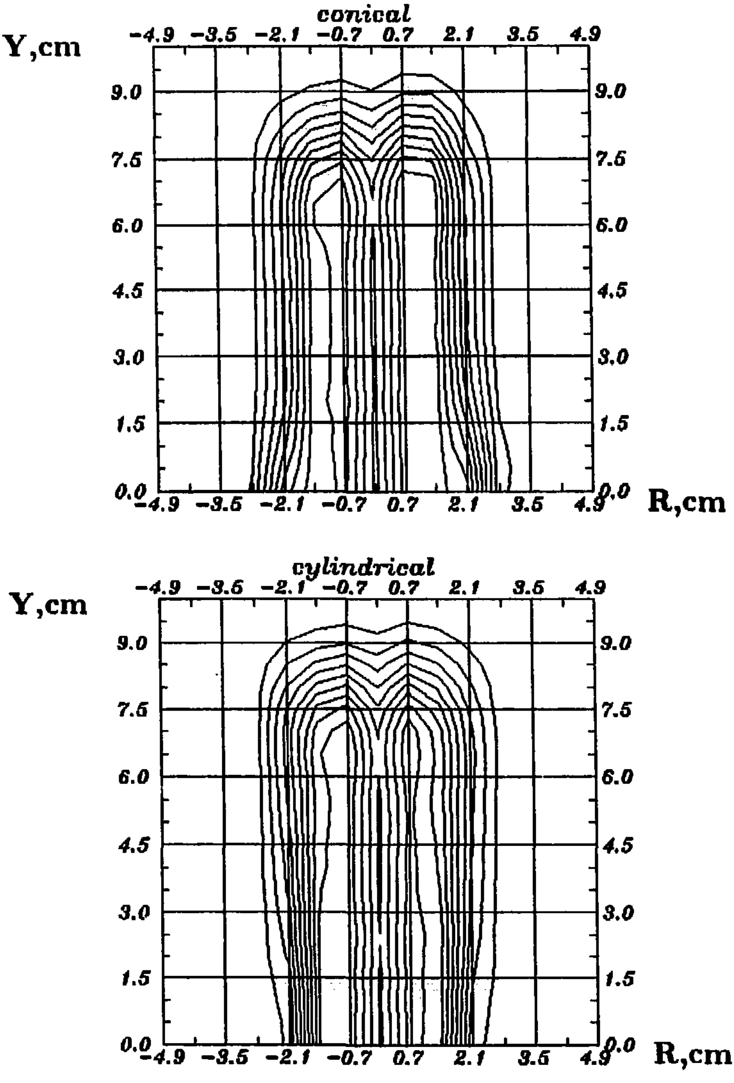


Fig.2. Isodose distributions for 160 MeV modulated proton beam in procedure room number 2 for conical and cylindrical head with central probe

Method of Rotation Scanning Irradiation

An original method of oesophagus cancer irradiation was proposed in [15] and realized at the JINR phasotron [5]. The oesophagus was irradiated with a horizontal proton beam on several levels along its length.

A setup of equipment for rotation scanning irradiation is shown in Fig.3. For rotation scanning irradiations we use a rotary computer-controlled chair. The chair design makes it possible to fix precisely the patient's feet, pelvis, back, hands, head and shoulders. Two X-ray centrators are used to install the target to the beam axis. The main parameters of the chair position are stored in the computer memory and may be reproduced for the next fractionated irradiation runs. The miniature silicon detector also can move along the oesophagus lumen inside the rubber tube under the computer control. The additional water degrader with controlled depth is intended for the Bragg peak and tumour overlapping.

We use two main methods for making the Bragg peak region coincide with the tumour. The first method is direct measurement of the full tissue depth along the proton beam axis with a miniature silicon detector placed into a cavity near the target. In the first run of rotation irradiation the distributions of full depth of tissues from the body surface to the tumour versus angle of the rotating chair on each irradiation level (so-called lines of heterogeneity) were measured. This is "the storing regime". In all next irradiations these distributions were used for making the Bragg peak coincide with the tumour by means of an additional degrader before a patient - "the reproduction regime". X-ray computed tomography allows checking the reproducibility of the patient's position in each run of irradiation.

But this method cannot be used for localizations without a cavity near the tumour. The second method is based on using X-rays tomographic images measured immediately before the irradiation run in the same rotation chair in the same patient position. The lines of heterogeneity may be calculated from the matrix of density of tomographic image.

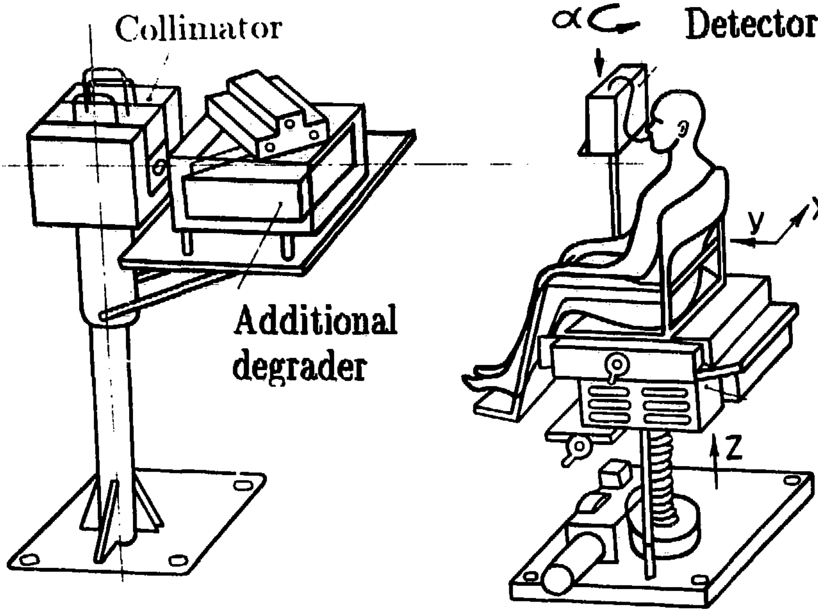


Fig.3. Equipment for rotation scanning irradiations of deeply lying tumours

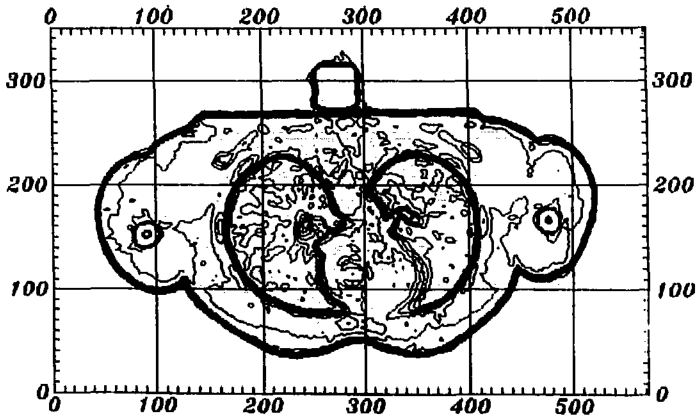


Fig.4. The X-ray tomographic image of the human chest

The X-Ray Tomograph for Proton Therapy Control and Planning

For proton therapy control and planning we use a horizontal X-ray tomograph placed in the procedure room [8]. The main feature of this device is that it is combined with the rotation chair intended for patient's irradiation.

The X-ray source with the maximal energy of 160 KeV was collimated into a horizontal fan beam. Transmitted through the treated object, the beam was captured by a system of 128 scintillation detectors. 180 one-dimensional projections were measured with an interval of 2° for full revolution of the treated object during one minute and stored in the computer memory. These projections are reconstructed into a two-dimensional 128*128 or 256*256 matrix of density by the back projection algorithm. The time of reconstruction for a 128*128 matrix is about 15 seconds for PC AT-486. The matrix with the tomographic image is stored in the computer memory and may be used for radiation therapy planning. This image may be displayed on the computer screen or printed in the form of density isolevels (Fig.4).

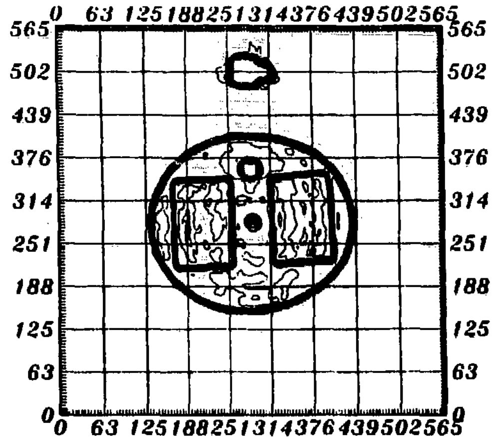
On the basis of the matrix of density the distributions of the patient depth versus the angle of the chair rotation, for the lines of heterogeneity, may be calculated.

Using the dose fields measured with a water phantom and also stored in the computer memory we can calculate the dose distribution for different conditions of patient's rotation scanning irradiations. On the basis of these calculations we can plan parameters of the patient's treatment.

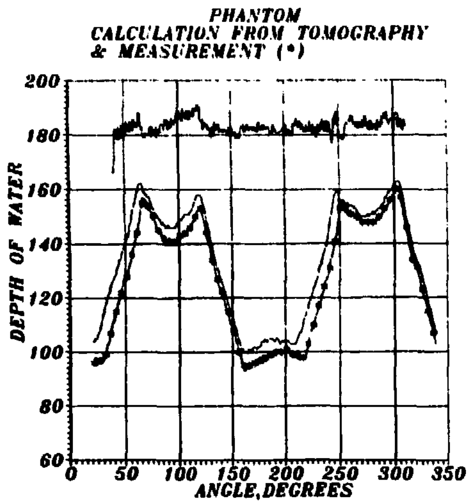
Examination of the Method of Rotation Scanning Irradiation with Phantom

The method of rotation scanning irradiation with computer-controlled Bragg peak coinciding with target was examined with a phantom similar to the human chest. The cylindrical phantom with thin plexiglass walls filled with water consists of two foam plastic parallelepipeds imitating human lungs, a teflon tube imitating the spine and a plastic tube imitating the oesophagus.

Fig. 5a shows the image of this phantom measured by means of the X-ray tomograph. The lines in the figure are isolevels of density.



a)



b)

Fig.5. The tomographic image of the phantom (a) and heterogeneity lines for this phantom calculated from this image and measured with the silicon detector (b)

From this tomographic image the line of heterogeneity was calculated for this phantom position. This line of heterogeneity was also measured by the miniature silicon detector placed into the tube imitating the oesophagus. These two lines showed in Fig. 5b are in agreement within several millimeters. The third line in this picture is the value of the pulse amplitude from the silicon detector measured in the reproduction regime on the basis of the line of heterogeneity from the tomographic image. An almost constant level of the pulse amplitude for all angles of chair position is evidence for correct Bragg peak and target coincidence.

Patient's Rotation Scanning Irradiation

After examination of the method of rotation scanning irradiation with a phantom its clinical use for oesophagus cancer treatment began.

Because the oesophagus is long and has a complex shape its irradiation must be performed at several levels. For the oesophagus irradiation the horizontal proton beam 6 cm in diameter was used. Irradiation was performed at three levels along its length with an interval of 6 cm.

At each level the line of heterogeneity was measured with a miniature silicon detector to be used in all next irradiations for Bragg peak and tumour coincidence. The main condition for correct target irradiation is high reproducibility of the patient's position on the rotation chair. To check the patient's position before each run of fractional irradiation we measured the tomographic images of the patient and calculated the heterogeneity lines. The coincidence of these lines with the line from the first run characterized the correct position of the patient.

Fig. 6 shows the tomographic images for one of the patients at three levels. For these levels the lines of heterogeneity were calculated. These lines of heterogeneity are also shown together with analogous lines measured with the silicon detector. These lines are in agreement within several millimeters for all levels.

In the next stage the following progress of the method of rotation scanning irradiation of deeply lying tumours was achieved. We treated two patients with cancer of the oesophagus grade III. In these cases we could not insert the miniature silicon detector for body depth measurements inside the oesophagus. For the overlapping of the Bragg peak and tumour we used only calculations on the basis of X-ray tomographic images, measured in the same position on the same rotation chair immediately before the irradiation run.

The irradiation was performed at three levels. The results obtained during the treatment for one of the patients are shown in Fig. 7. This figure shows three tomographic images for all levels of irradiation and calculated from them lines of heterogeneity during the full course of treatment.

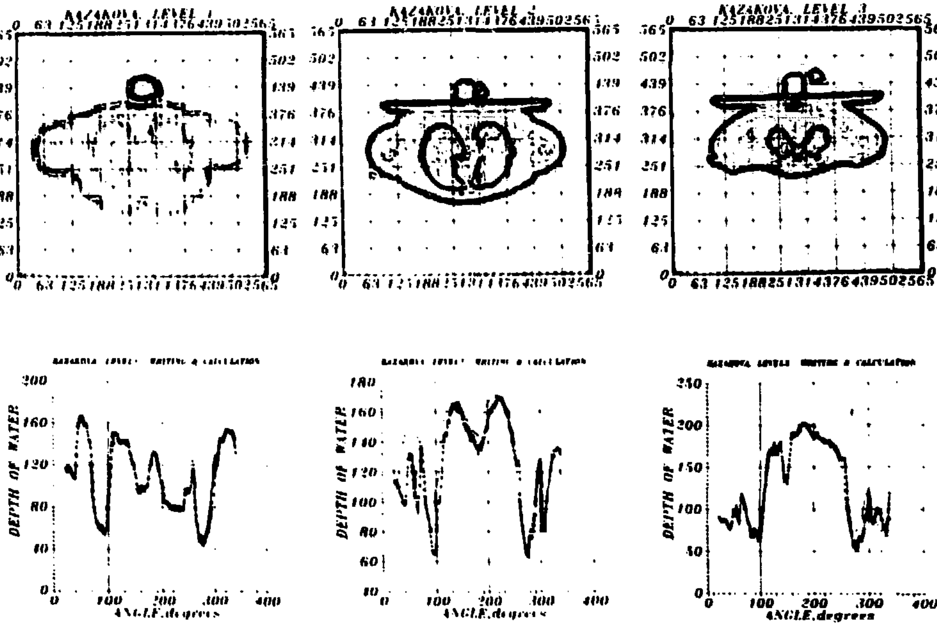


Fig.6. Tomographic images of the patient on three levels and heterogeneity lines calculated from these images and measured with the silicon detector

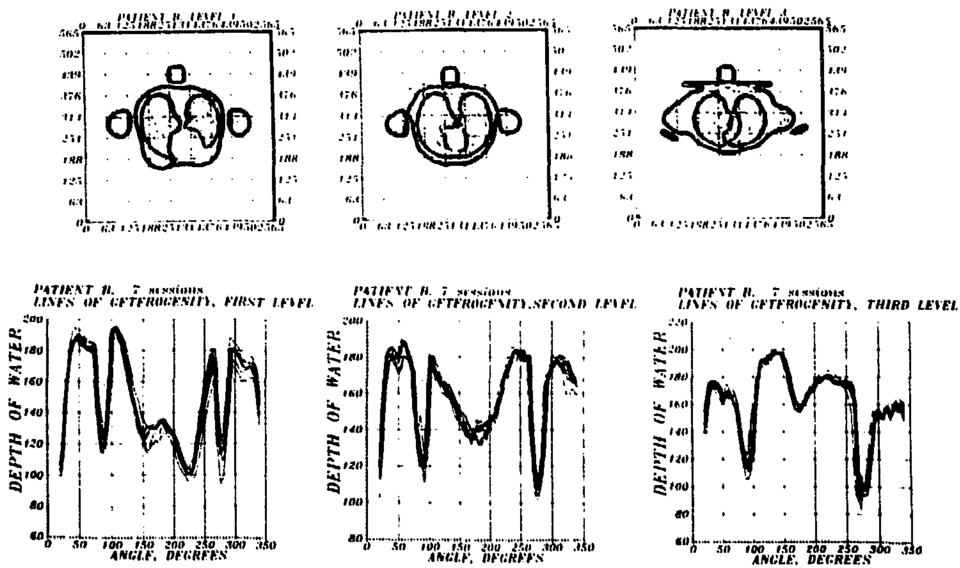


Fig.7. Tomographic images of the patient on three levels and heterogeneity lines calculated from these images during the course of treatment

On the basis of comparison of images during the long time of fractionated therapy we have come to the conclusion that the precision of the oesophagus positioning at the axis of the proton beam is several millimeters. This precision is in accordance with the medical requirements.

Conclusions

Up to April 1994, 26 patients with uterus cervix cancer and 5 patients with oesophagus cancer were treated. In future we plan to carry out rotation irradiation of deeply lying tumours, in which it is impossible to place the detector (e.g., lung cancer), on the basis of calculations from X-ray tomographic images.

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Received by Publishing Department on March 31, 1994.