Gypsum mixtures for compensator construction

K. J. Weeks, B. A. Fraass, and K. M. Hutchins
Department of Radiation Oncology, University of Michigan Medical Center, Ann Arbor, Michigan 48109

(Received 23 November 1987; accepted for publication 10 February 1988)

The characteristics and properties of a new material used for the fabrication of compensators are presented. This material is a special, refined gypsum. It requires a factor of 3 less water to prepare than ordinary gypsums and as a result the attenuation properties are stable over time. The material may be used by itself or mixed with fine metal particles to increase the attenuation per unit thickness. Gypsum, gypsum + steel, and gypsum + iron were investigated. The results of attenuation measurements in narrow- and broad-beam geometries appropriate to design of clinical dose modifying compensators are presented. Practical and technical details associated with the use of these materials are given. These compounds are found to be easy to use, versatile, reliable, environmentally safe, and inexpensive. In addition, an example of their use for dose compensation is given.

Key words: gypsum, attenuation measurements, compensators, partial transmission blocks, dose compensation, treatment planning

I. INTRODUCTION

Compensators are useful devices for tailoring the dose on a plane or surface to some desirable pattern.[1] In principle, this may be achieved in spite of the presence of irregular surfaces and/or heterogeneities. Several suitably compensated beams may then be used to achieve a uniform dose to a particular volume. Historically,[2] the design of the compensator has been based on missing tissue measurements. With the advent of three-dimensional treatment planning made possible by computed tomography, the design of compensators of increasing sophistication may be envisaged. In particular, microprocessor-controlled milling machines can be linked to treatment planning systems providing automated construction of compensators which are designed within the framework of the treatment planning process. These devices may either mill the positive from a block of the compensator material or mill a negative in a suitable mold material such as styrofoam.

This paper reports the results of an investigation of the suitability of gypsum compounds and gypsum metal mixtures for fabricating compensators (U. S. Gypsum, Chicago, IL). Our use of these products is motivated by our compensator cutter, an MCP-70-SE system (HEK Medical Systems, W. Germany). This machine, a microprocessor-controlled styrofoam milling machine, uses a hot wire loop cutter which mills the styrofoam as directed from an external computer. After the cutter produces a negative of the compensator in a standard block of styrofoam, this negative may then be filled with any liquefied compound. The gypsum is used in a liquefied state and hardens in the mold.

II. RATIONALE

Photon attenuation is described approximately by an exponential function. This can be expressed in the form

$$I(t) = I(0)\exp[-(\mu/\rho)\rho t], \qquad (1)$$

where $I(t)$ is the intensity (energy fluence) of radiation after interposing an absorber of thickness t in the beam, (μ/ρ) is the mass attenuation coefficient in cm^2/g, and ρ is the mass density. For clinical linear accelerator photon energy distributions, (μ/ρ) is roughly independent of material.[1] Thus the thickness of material required to produce a given dose compensation is approximately inversely proportional to the material's mass density.

Compensator materials of various mass densities have been studied over the years. These include tissue-equivalent substances such as wax[3] and plastic,[4] as well as higher density materials such as aluminum,[2,5] brass,[4–6] copper,[7] lead,[8] wax and tin granule mixtures,[9] and eutectic alloys.[10] The advantage of high density is smaller thickness; the disadvantage is a greater sensitivity to random and systematic errors in cutting or assembling the compensator. Factors influencing the choice of material are of both practical and physical nature.

It is our experience that ± 1 mm depth errors can be routinely expected by milling the styrofoam with our cutting device. These errors occur due to variations in wire loop temperature. The consequences of these errors are best illustrated by an example. Consider two cases wherein the dose is to be reduced by either 10% or 40%, representing mild and extreme compensation cases, respectively. For a 6-MV beam, and using lead as the compensator material, the required absorber thicknesses are 2 and 10 mm, respectively. The cutter error translates in the expected dose compensation lying between 5% and 14% in the first case and between 37% and 43% in the second. If a tissue-equivalent material were used, the required absorber thicknesses are 2.3 and 11.4 cm. The cutting error in that case produces dose variations of 0.4% and 0.2% about the desired dose compensation. The error is negligible for low density materials.

Another aspect of compensators that needs to be considered is overall thickness. In the clinical application of compensators there is a concern about scatter dose off the compensator. Since the use of blocks may be desirable in conjunction with compensators, it was decided to locate the compensators upstream from the blocks and to mount the compensators on Lucite trays which fit into the wedge tray slots of our various linear accelerators. This presented two constraints on the choice of material. First, there was only 7 cm of clearance for the compensators. From the numerical example above, it is noted that tissue-equivalent materials would not be feasible for extreme applications. Second, the material must be capable of being rigidly mounted to a tray. These considerations forced us to look for a new material which has a density between 2 and 4 and was easy to use in a routine and quality assured fashion. The gypsum materials described below are the result of this search.

III. MATERIALS AND METHODS

Gypsum is the common name for hydrated calcium sulphate ($CaSO_4{:}2H_2O$). Natural gypsum is converted to a powder hemihydrate ($CaSO_4{:}\frac{1}{2}H_2O$) by applying heat while the natural gypsum is under pressure; this is the general process of producing commercial gypsum (plaster of Paris). The gypsum used in this work is different. It is produced by heating and grinding the natural gypsum, dissolving it in an acidic solution and crystalizing out the "purer" gypsum. This refining method produces the hemihydrate powder in the form of uniform cubical crystals. When combined with water (exothermic reaction), the resulting hydrate packs more closely together than regular gypsum. The density of this relatively nonporous gypsum is approximately 2.0 g/cm^3 (depending on the water–gypsum mixing ratio). The manufacturer recommends a mixing proportion (denoted consistency) in the range of 20 to 22 (20 to 22 g of water for each 100 g of gypsum). This proportion slightly exceeds the theoretical amount of water needed to produce the hydrate and is necessary due to the impossibility of uniformly wetting the volume of hemihydrate, using the minimum amount of water. Ordinary gypsums use consistencies in the range 70–120. The excess water in that case is trapped in the solid structure after setting and can be removed by heating. Since the new gypsum has such a low consistency there is no need for heating. Minimal water loss with time means that there is little change in the attenuation properties of the compensators.

Metal particles may be added to the gypsum to increase the density and thus reduce the maximum thickness of the compensator. Two of the metals which have been investigated are iron ore aggregate and stainless steel. The iron ore aggregate mixture consists of gypsum + iron (iron 45% by weight) with a density of 2.7 g/cm^3. The stainless-steel mixture consists of gypsum + steel (steel 67% by weight) with a density of 3.4 g/cm^3. The metal particle size is less than or equal to 300 μ and the mixing proportion used was 13 (compared to pure gypsum, less water per 100 g of material is needed because there is less gypsum). Lead particles were not seriously considered due to health and environmental concerns.

Fabrication of compensators from the gypsum material is fast and simple. Once the mold is made, the compensator volume is estimated and the masses of gypsum powder and water are calculated from the density of the final mixture and the required consistency given above. Using a balance, the correct amount of water is weighed into a rubber dental mixing bowl. The gypsum or gypsum-metal powder is then weighed and added to the water. A few minutes of stirring produces a creamy viscous mix which is poured into the mold to a level just above the top of the mold. Gentle shaking and tamping of the mold facilitates air rising to the top. After 5 min, any excess is troweled off and the compensator is left to harden. This takes a minimum of 15 min but for ease in mounting to our trays, we leave it for 1 h. The tray is then lined up with marks on the styrofoam and pilot holes are drilled into the margins of the compensator. The compensator is removed from the styrofoam and attached to the tray with screws and is then ready for patient treatment.

Photon beam measurements were made on a Varian Clinic 1800 accelerator using photon energies of 6 and 15 MV. Measurements were made in various geometries (described below) using a Therados RK ionization chamber (0.1-cm^3 active volume) connected to a Keithley 616 integrating electrometer.

IV. RESULTS

The ion chamber measurements were made in air using buildup caps of 1.5- and 3.0-cm Lucite radius for 6- and 15-MV beams, respectively. The machine collimators were closed to produce a narrow beam (of sufficient size to just cover the chamber at a distance of 2 m from the machine target). The attenuators were placed at the source-block tray distance (65 cm). Relative measurements as a function of attenuator thickness were made. The results were checked with measurements at longer chamber distances and/or with additional collimation at the chamber position. The relative measurements agreed to within 0.5%

In Fig. 1, the measured narrow-beam transmission for a 6-MV photon spectrum is presented. When restricted to a 7-cm maximum thickness, only 55% transmission is possible with the gypsum. The gypsum-steel material extends that range below 40%. Also shown for comparison is Cerrobend (Cerro Metal Products, Bellefonte, PA). The extracted lin-

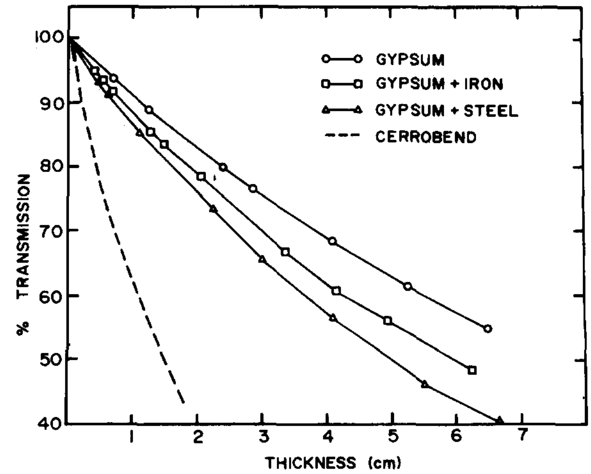


FIG. 1. 6-MV narrow-beam transmission measurements in air for varying thickness (t) of gypsum, gypsum + iron, gypsum + steel, and Cerrobend.

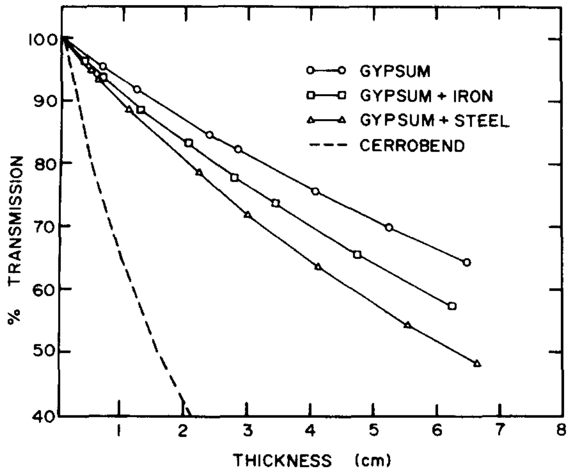


FIG. 2. 15-MV narrow-beam transmission measurements in air for varying thickness (t) of gypsum, gypsum + iron, gypsum + steel, and Cerrobend.

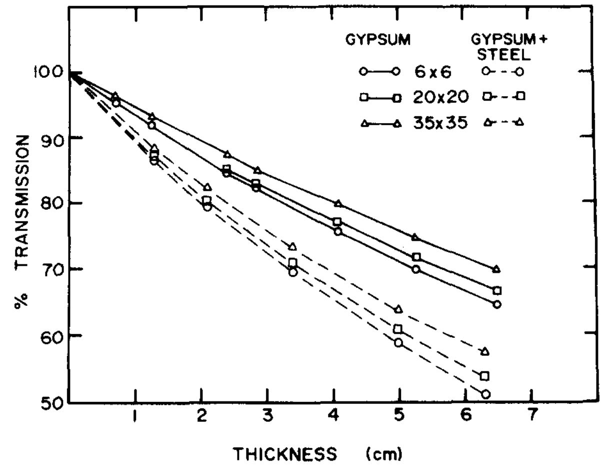


FIG. 4. 15-MV broad-beam transmission measurements in air for various field sizes: gypsum (solid lines), and gypsum + steel (dashed lines).

ear attenuation coefficients (μ_0) are 0.092, 0.139, 0.118 cm^{-1} for gypsum, gypsum + steel, and gypsum + iron, respectively.

In Fig. 2, the measured narrow-beam transmission for a 15-MV photon spectrum is presented. For our applications, only 65% transmission is possible with the gypsum. The gypsum-steel extends that range to 45%. The extracted linear attenuation coefficients (μ_0) are 0.068, 0.108, 0.091 cm^{-1} for gypsum, gypsum + steel, and gypsum + iron, respectively.

Broad-beam measurements were made to ascertain the importance of scatter. The ion chamber was positioned at the isocenter of the machine (100 cm) and the attenuating slabs were mounted to the trays in the wedge slot (source to compensator distance = 50 cm). The geometry was chosen to mimic the clinical application of the compensators.

The effect of field size on the gypsum attenuation is shown in Fig. 3 for the 6-MV beam. There is little difference for thicknesses in the 0 to 3 cm range and field sizes 4×4 to 20×20. The 4×4 results are not appreciably different from the narrow-beam measurements. Larger field sizes or thicknesses require correction factors. Similar results are shown in Fig. 4 for the 15-MV beam. The data in Figs. 1–4 may be parametrized by an effective attenuation coefficient (μ_{eff})

$$\text{transmission} = \exp(-\mu_{\text{eff}} t), \tag{2}$$

$$\mu_{\text{eff}} = \mu_0 + \mu_1 S^2 + \mu_2 t A, \tag{3}$$

$$A = \begin{cases} 0, & S < 10.0\ \text{cm}, \\ (S-10)^{1/3}, & S > 10.0\ \text{cm}, \end{cases} \tag{4}$$

where S is the equivalent field square, t is the thickness of attenuator, and the parameters μ_0, μ_1, and μ_2 are given in Table I. The parameter μ_0 is simply the narrow-beam attenuation coefficient from Figs. 1 and 2. Figures 3 and 4 show that scatter can contribute up to 6% to the central axis transmission measurement for large field sizes and 6.0-cm thickness. In Table I, the field size parameter μ_1 is larger for 6 MV than for 15 MV indicating that for given thickness the lower-energy case exhibits a larger scatter dependence on field size. The term containing parameter μ_2 permits a compensator thickness dependence that is significant for large volumes and negligible for small volumes of irradiated compensator.

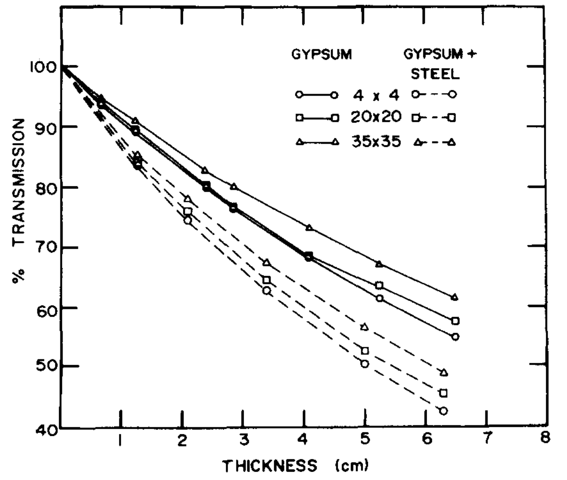


FIG. 3. 6-MV broad-beam transmission measurements in air for various field sizes: gypsum (solid lines), and gypsum + steel (dashed lines).

The variablity of the attenuation with time was investigated. Six separate mixings (over a period of three months) producing four attenuators of varying thickness for each mixing were measured at various times after setting (from 6 h to two months). Except for a few cases, there was no more than a ½% increase in transmission over the period of two months. These exceptions represent increases of less than 2%. They were attributable to irregular thickness of sample

TABLE I. Empirical parameters for the expansion of the effective attenuation coefficient (μ_{eff}) which summarizes the narrow- and broad-beam measurements of Figs. 1–4. G = gypsum, GS = gypsum + steel, 6 and 15 MV are beam qualities.

	μ_0(cm^{-1})	μ_1(10^{-5} cm^{-3})	μ_2(10^{-4}cm$^{-7/3}$)
G—6 MV	0.092	− 1.1	− 2.6
G—15 MV	0.068	− 0.8	− 1.5
GS—6 MV	0.139	− 1.5	− 3.6
GS—15 MV	0.108	− 1.1	− 3.3

which introduced problems in reproducing the setup at different times. Ordinary gypsum shows changes on the order of 15%. A thick (6.5 cm) disk of the new gypsum was sliced into three disks so as to obtain two thin pieces (7 mm) originating from the top and bottom of the original disk, respectively. These pieces were measured and no appreciable differences were found in transmission with directly poured pieces of the same thickness. A similar result was found for the metal mixtures. Thus, the poured density was uniform over the range of thickness in which we were interested.

As a test case, a right triangular water phantom was constructed (27×30 cm base, 15-cm height, 30° angle) using 6.3-mm-thick sheets of acrylic. An oblique beam, produced by rotating the gantry 70° from its vertical position, and rotating the 10×15 cm collimator setting 30°clockwise, was incident on the phantom. The phantom base plane contains the gantry rotation axis line and hence the machine isocenter. The thin edge of the phantom pointed towards the gantry stand. The central axis ray line depth to the base plane is 9.9 cm. A perspective view of the situation is shown in Fig. 5 (for clarity polystyrene backing of the base plane is not shown). The geometric and surface profile data were entered into the treatment planning system and uncompensated dose was calculated everywhere on the base plane of the phantom. A compensator was defined for this beam under the constraint that the dose, everywhere within the region of the compensation plane encircled by some chosen minimum isodose line (D_m), be made uniform. The thickness of compensator at each of its points was related to the uncompensated dose (D_μ) on the compensation plane through the relation

$$D_m = D_\mu \exp(-\mu_{\mathrm{eff}} t)\,, \tag{5}$$

for each ray line, where μ_{eff} is given by Eq. (3) using the parameters in Table I. XV-2 film (Kodak, Rochester, NY) was placed on the base plane and backed with polystyrene. Measurements were made with and without the compensator. Optical density was converted to dose using an H and D curve. D_m was chosen as the 85% line from the calculated uncompensated plan (normalized at isocenter). One sees from Fig. 6(a) that a range of compensation of 32% is being attempted. In Fig. 6(b) the compensated results indicate that the entire hot spot (lower left quadrant) was eliminated to within 1%, and the overall dose range in the compensated area is about 5%. A detailed discussion of the compensation design process and calculational algorithms will be given elsewhere.

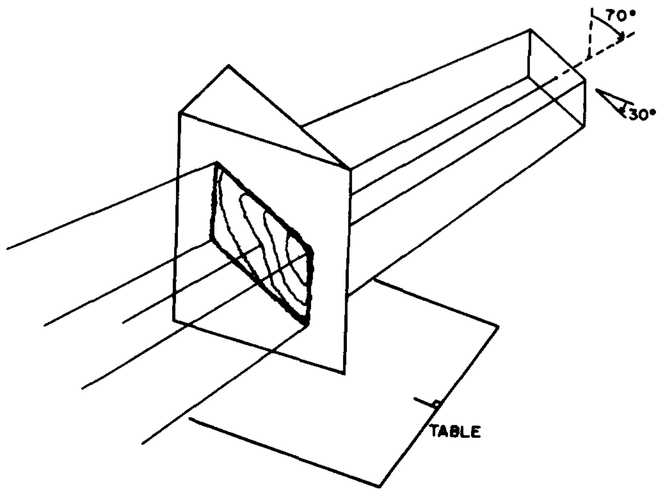
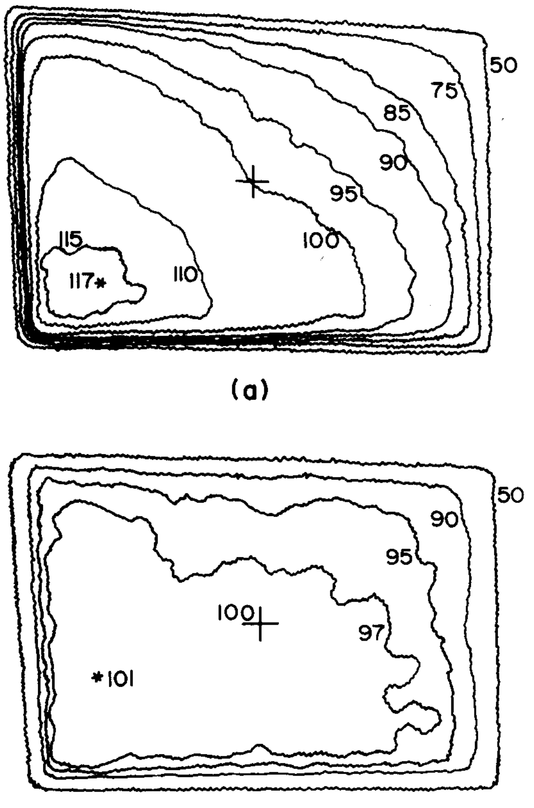


FIG. 5. Compensator test case consisting of a right triangular water phantom backed by polystyrene blocks (not shown). The phantom's cross-sectional 30° angle points at the machine gantry stand. Its base plane is vertical and contains the machine axis of rotation line. The beam is formed by rotating the gantry 70° from vertical, and rotating the 10×15 cm collimator setting 30° clockwise. The triangular phantom base plane is the chosen plane for compensation. Uncompensated isodose lines are sketched on that plane. The source–surface distance of the beam is 90.1 cm and thus the ray line central axis depth to the plane is 9.9 cm.

V. CONCLUSIONS

The use of gypsum mixtures has been instituted in our department for the construction of dose-modifying compensators as well as partial transmission blocks. The advantages of these mixtures lie in their uniformity, reproducibility, selective density, ease of preparation, and safe handling. The gypsum used here will soon be part of U.S. Gypsum's product line; its cost is estimated to be $1.25/lb. The cost of metal particle gypsums will be approximately $12/lb. Since the procedure for producing the compensator does not depend on the metal particles, one may use both the gypsum and the metal-containing products. In our system, gypsum is suitable for applications which require moderate dose compen-



(a)

(b)

FIG. 6. Measured dose on sagittal plane through isocenter for the case illustrated in Fig. 5: (a) uncompensated: (b) compensated, + denotes isocenter and * denotes the hot spot.

sation. For cases where compensation on extremely oblique planes relative to the beam is required, the higher density gypsum-metal mixes are sometimes necessary. Since the former cases will be far more common, we estimate that the average material cost of a compensator will be less than $2.

In summary, pure gypsum has many desirable features which recommend its use as a compensator or partial transmission block material. It can be drilled, attached with screws, and easily mounted. It sets quickly and no special equipment other than a weighing balance is required. The density is reproducible, uniform, and does not change appreciably with time. Gypsum-metal particle mixtures enable one to design a higher density which extends the range of compensation for special applications. Finally, the material is inexpensive and completely safe to handle.

ACKNOWLEDGMENTS

We wish to thank the United States Gypsum Company for its help and support during this project. One of us (KJW) greatly appreciates invaluable discussions with Mr. Ken Valan of U.S. Gypsum regarding the use and properties of the newer gypsums.

---

[a] Presented in part at the 29th Annual Meeting of the American Association of Physicists in Medicine, Detroit, Michigan, 19–23 July 1987.

[b] Send reprint requests to: Kenneth J. Weeks, Ph.D, Department of Radiation Oncology, University of Michigan Hospitals, UH Room B 2C490, Box 0010, 1500 E. Medical Center Dr., Ann Arbor, MI 48109.

[1] F. M. Kahn, *The Physics of Radiation Therapy* (Williams and Wilkins, Baltimore, MD, 1984), pp. 261–267.

[2] F. Ellis, E. J. Hall, and R. Oliver, "A compensator for variations in tissue thickness for high energy beams," Br. J. Radiol. **32**, 421 (1959).

[3] R. J. Boge, R. W. Edland, and D. C. Matthes, "Tissue compensators for megavoltage radiotherapy fabricated from hallowed styrofoam filled with wax," Radiology **111**, 193 (1974).

[4] F. M. Kahn, V. C. Moore, and D. J. Burns, "The construction of compensators for cobalt therapy," Radiology **96**, 187 (1970).

[5] E. J. Hall and R. Oliver, "The use of metal compensators to correct for tissue heterogeneity in radiotherapy with high energy radiation beams," Br. J. Radiol. **35**, 852 (1962).

[6] F. Ellis, A. Feldmann, and R. Oliver, "Compensation for tissue inhomogeneity in cobalt-60 therapy," Br. J. Radiol. **37**, 795 (1964).

[7] D. O. Bottrill, R. T. Rogers, and H. F. Hope-Stone, "A composite filter technique and special patient jig for the treatment of the whole brain and spinal cord," Br. J. Radiol. **38**, 122 (1965).

[8] R. Wilks and M. P. Casebrow, "Tissue compensation with lead for ^{60}Co therapy," Br. J. Radiol. **42**, 452 (1969).

[9] F. Brix and J. M. Jensen, "Materialien fur die Kompensatorherstellung in der Strahlentherapie," Roentgenpraxis **37**, 19 (1984).

[10] B. J. Walz, C. A. Perez, A. Feldmann, A. J. Demidecki, and W. E. Powers, "Individualized compensating filters and dose optimization in pelvic irradiation," Radiology **107**, 611 (1973).