Acta Radiologica Oncology 23 (1984) Fasc. 5

FROM THE RADIATION PHYSICS DEPARTMENTS, UNIVERSITY OF GOTHENBURG, S-413 45 GOTHENBURG AND UNIVERSITY OF UMEÅ, S-901 85 UMEÅ, SWEDEN.

CHARGE BUILD-UP EFFECTS IN INSULATING PHANTOM MATERIALS

L. O. MATTSSON and H. SVENSSON

Abstract

When a medium is irradiated with electrons, electric charges are injected into the medium. If this is an electric insulator and its extension in the beam direction is larger than the electron range, the electrons are trapped inside the medium. In this work the influence on the ionization chamber dosimetry of the charge trapping in insulating phantom materials, such as polystyrene and polymethylmethacrylate (PMMA), has been investigated. It has been shown that the electron fluence inside a cylindric ionization chamber used in these materials increases when the number of electrons trapped in the phantom increases. The influence of various parameters, such as electron energy, accumulated absorbed dose, type and purity of the phantom material, radiation induced conductivity and ionization chamber construction are discussed. The effect can cause errors of several per cent in the dosimetry. We conclude, in agreement with the conclusion of GALBRAITH et coll., that insulating phantom materials should therefore be avoided in electron beam dosimetry.

A major difference between roentgen and electron beam absorption is that the latter will produce a net deposition of charge in the irradiated medium. In roentgen beam absorption an approximate charge particle equilibrium exists for depths behind the absorbed dose maximum, which means that the same number of charged particles enters and leaves a mass element and thus, no net charge deposition arises. In the build-up region, where no charge particle equilibrium exists, a depletion of charge will result.

The charge deposition at different depths in water irradiated with electrons has been calculated by KESSARIS (18) and BERGER & SELTZER (2). KESSARIS solved the transport equation for electrons by the moment method under the continuous slowing down approximation and BERGER & SELTZER used a Monte Carlo technique to calculate the deposition of charge in water irradiated with electrons. The predictions made by KESSARIS and BERGER & SELTZER are in reasonable agreement with the charge deposition measurements carried out in phantoms of polystyrene and water by LAUGHLIN (20) and VAN DYK & MACDONALD (26), respectively. Calculated and measured charge deposition curves are shown in Fig. 1.

In conducting phantom materials, such as water and graphite, the deposited charge is rapidly distributed in the material. However, in insulating materials, such as PMMA (polymethylmethacrylate) and polystyrene, most electrons are trapped at the depth where all their kinetic energy has been dissipated. After an irradiation of such a phantom a charge distribution similar to those shown in Fig. 1 will thus remain in the phantom and can do so for a very long time. If the phantom is repeatedly irradiated with electrons, of a certain energy, the amount of charge in the phantom can increase until spontaneous electric break-down occurs in the material, and a so called Lichtenberg figure is formed (7). This happens when the attendant electric field exceeds the dielectric strength of the material. For PMMA a value of the dielectric strength of 13.5 MV cm^{-1}

Accepted for publication 15 February 1984.

has been reported (7). Under certain conditions, this very large electric field can influence the electron fluence in the material during irradiation. A complicating factor is that also in very good insulators, such as PMMA and polystyrene, a radiation induced conductivity will be present in the irradiated volume during and after the irradiation (4). This will alter the charge distribution inside the phantom. Furthermore, the conductivity and its decay after the irradiation is different in different materials and depends also on temperature, dose rate and purity of the material. It is thus very difficult to make accurate predictions regarding the accumulation and storage of charges in insulators after irradiation with electrons.

Various aspects of the charge build-up in insulating materials during irradiation with electrons, including calculations of the electric field, have previously been discussed in the literature, (7, 8, 9, 13, 19, 21, 25, 27). All these studies have been made using extremely high dose rates. Some of the findings are therefore not applicable to the low dose rates normally used in therapeutic electron beam dosimetry. Furthermore, none of the investigations have been directly related to problems in therapy electron beam dosimetry. However, recently GALBRAITH et coll. (5, 6) during the commissioning of a radiotherapy linear electron accelerator, observed that the reading per accelerator dose monitor unit from a cylindric ionization chamber irradiated with electrons in a PMMA and polystyrene phantom increased with accumulated absorbed dose. In the worst case an increase of 26 per cent in the ionization chamber reading per monitor unit was observed. The increase was explained by the influence, on the electron fluence in the chamber, by the space charge distribution and its attendant electric field. It is remarkable that this effect has been undetected for so many years, considering that these materials have been and are being used in electron and photon beam dosimetry at most radiotherapy departments in the world. The importance of this observation can best be seen by the fact that most international and national dosimetry protocols recommend the use of polystyrene or PMMA in electron beam dosimetry (1, 14, 15, 23, 24). It is thus most important to further investigate the effect and to find out if it is a general problem in radiation dosimetry or something which depends on certain experimental conditions. As a contribution to this discussion we have repeated some of the experiments by GALBRAITH et coll, and also done some additional investigations and considerations.

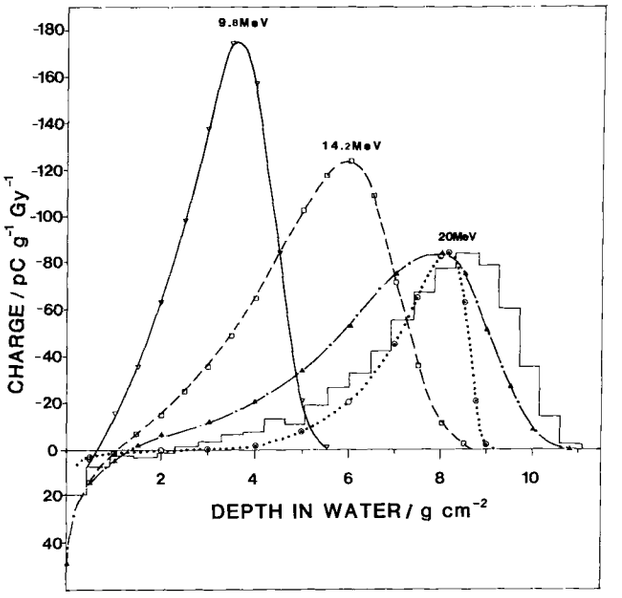

Fig. 1. Charge distributions in water produced by electrons. Both theoretic and experimental curves are given. Experimental curves: ▽ 9.8 MeV VAN DYK & MACDONALD (26), ⊡ 14.2 MeV VAN DYK & MACDONALD (26), ▲ 20 MeV LAUGHLIN (20) (normalized). Theoretical curves: ⊙ 20 MeV moment method CSDA (normalized) KESSARIS (18). ⌐⌙ 20 MeV Monte Carlo, straggling included (normalized) BERGER & SELZER (2).

In preparing the reports by MATTSSON et coll. (22) and NACP (24), several solid phantom materials were compared with water in electron beams. Measurements were made in different conducting materials, A-150, graphite, water and aluminium and in two insulating materials, polystyrene and PMMA. Measurements were made with electron beams with energies between 2 and 30 MeV. Complete depth ionization curves and the ionization at the depth of the absorbed dose maximum in the different materials were measured. The phantom materials were given very large accumulated absorbed doses. The measurements were made with the plane-parallel ionization chambers described by MATTSSON et coll. (22). These measurements did not reveal any variation in chamber response with accumulated absorbed dose in PMMA and polystyrene. In order to find out if these phantom materials had different properties from those used by GALBRAITH et coll., their measurements using a cylindric Farmer chamber (0.6 cm^3) were repeated. In addition measurements were carried out using other types of chambers in order to study the influence of the chamber design.

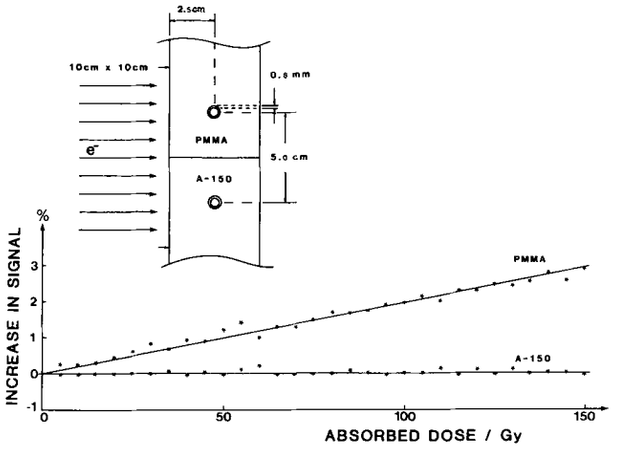

Fig. 2. The experimental conditions in the 'Umeå experiment' are indicated in the inserted drawing. The increase in the signals for the chambers per accelerator dose monitor unit are indicated as a function of the accumulated absorbed dose to the dose-maximum of the phantoms (or more strictly to a water phantom given an identical irradiation).

Experimental procedure

Independent measurements were made at the departments in Gothenburg and Umeå. The following irradiation conditions were used in Gothenburg: electron radiation from a linear accelerator (MEL SL 75/20), mean energy at the phantom surface ($\bar{E}_0$) 9.4 MeV, a cylindric ionization chamber with a graphite wall manufactured by Nuclear Enterprise Model 2505/3 and a plane-parallel chamber with graphite walls NACP-01 (22).

The measurements were made in polystyrene, PMMA, graphite and water. Two types of polystyrene, clear and white, were used. The solid phantoms consisted of machined slabs (200 mm×200 mm) of varying thickneses. Holes were made for the ionization chambers in a slab of each material. The effective point of meaurement of the chambers was placed close to the depth of the absorbed dose maximum. The experiments were performed both with slabs of polystyrene and PMMA never irradiated before and also slabs which had been used in dosimetry for many years.

The ionization chamber measurements were carried out at 3 Gy min^{-1} for an absorbed dose to dose maximum of approximately 2 Gy. To increase the accumulated dose the phantoms were irradiated in between the measurements at a dose rate of 10 Gy min^{-1}. In each of these irradiations 100 Gy was delivered.

For each accumulated absorbed dose level measurements were made alternately in the insulating phantom material and in a conducting material. The same ionization chamber was used in the insulating and in the conducting materials. When measurements were made in water the ionization chamber was covered with a thin sleeve of PMMA to prevent water leakage. Two or three measurements in each phantom were made to determine the ratio of chamber signal per monitor unit between the insulating and conducting material. In each measurement at least five readings were taken. The measurements in the conducting phantom were used to check the constancy of the ionization chamber system and also of the accelerator and monitor chamber systems. These measurements were repeated for the different accumulated doses.

In Umeå the following irradiation conditions were used: electron radiation from a microtron (MM 22), $\bar{E}_0$=7.1 MeV, cylindric chambers with walls of a mixture of graphite and Araldite.

The measurements were made in PMMA and A-150 (conducting). Two ionization chambers were placed with their centres at 2.5 cm depth in PMMA (not irradiated before) and in A-150 (see Fig. 2). The effective point of measurement of the chambers were at the slowly descending part of the depth dose curves (at about 80 per cent depth dose) in the two materials. The absorbed dose rate (to water) was approximately 4 Gy min^{-1} at the depth of the dose maximum and 5 Gy was delivered to that point at each irradiation. The durations between stop and start of the irradiations were 30 seconds.

In both sets of experiments the ionization chamber readings were corrected for changes in the air pressure during the measurements and in the temperature of the phantoms. Recombination corrections have not been applied as constant dose rates and polarizing voltages were used in the measurements.

Results

Fig. 2. (Umeå experiment) shows that the signal from the cylindric chamber inside the PMMA phantom per accelerator dose monitor unit increases with the absorbed dose to the phantom. As expected the signal for the simultaneously carried out measurements in A-150 is constant. These results are in good agreement with the experiments by GALBRAITH et coll. (6), thus the increase was 0.02 per cent/Gy in the present experiment (at $\bar{E}_0$=7.1 MeV) compared with 0.022 per cent/Gy (at $\bar{E}_0$=6 MeV) for GALBRAITH et coll.

From the 'Gothenburg-experiment' it is possible to compare the response of a cylindric chamber irradiated in a polystyrene or PMMA phantom of different irradiation history with that for a similar irradiation in a water phantom. Such factors are of great interest in practical dosimetry as measurements sometimes are made in plastic phantoms even if the absorbed dose to water in a water phantom is to be determined.

The values in Table 1 are the ratios of the readings taken in new phantoms of polystyrene and PMMA to those in water. Column two gives the ratios for measurements in white polystyrene to water and column four the ratio for PMMA to water. These values have been normalized for unity for zero accumulated absorbed dose in columns three and five. In polystyrene the signal increases 3.7 per cent after an accumulated absorbed dose of 100 Gy. Between 100 and 200 Gy no increase is observed and after 200 Gy the signal decreases. In PMMA the increase in response is less than in polystyrene but the saturation is not reached for doses used here. Measurements were also made in a PMMA phantom used in electron beam dosimetry for many years. The signal increase after an added absorbed dose of 100 Gy was in this case about 0.5 per cent. Also these results are in fair agreement with the results by GALBRAITH et coll. for corresponding electron energies.

Corresponding measurements but with a plane-parallel ionization chamber are reported in Table 2. The values in column two are for clear polystyrene and the values in column three for PMMA. In these measurements graphite was used as reference phantom material. In clear polystyrene the increase in chamber signal with accumulated absorbed dose is very small. No increase at all is observed in PMMA. The increase in ionization chamber signal with accumulated absorbed dose depends thus on the chamber construction.

Table 1

Ratios of ionization chamber signal per accelerator monitor unit measured in white polystyrene, I_{poly}, or PMMA, I_{PMMA}, and in water, I_{water}, for the cylindric ionization chamber. An indication of the high precision in the measurement procedure was that the I_{water} measurements for each accumulated dose level was constant within 0.1 per cent. Thus, I_{water} does not increase with the accumulated dose. The standard deviation of I_{water} for a single measurement was also about 0.1 per cent

Accumulated dose (Gy)	$\frac{I_{poly}}{I_{water}}$		$\frac{I_{PMMA}}{I_{water}}$	
	Not normalized	Normalized	Not normalized	Normalized
0	0.988	1.000	1.000	1.000
100	1.025	1.037	1.011	1.011
200	1.023	1.035	1.015	1.015
300	1.013	1.025	1.018	1.018

Table 2

Symbols in analogy with Table 1. The measurements were made with a plane-parallel chamber (the NACP chamber)

Accumulated absorbed dose (Gy)	$\frac{I_{poly}}{I_{graphite}}$ normalized	$\frac{I_{PMMA}}{I_{graphite}}$ normalized
0	1.000	1.000
100	1.001	1.000
200	1.003	1.001
300		1.000

Discussion

The signal per accelerator dose monitor unit for a cylindric ionization chamber used in an insulating phantom material irradiated with electrons increases with the accumulated energy imparted to the phantom. The correlation between signal increase and accumulated absorbed dose has been clearly demonstrated both for PMMA and polystyrene.

It is evident that a space charge distribution is built up in insulating phantom materials during electron irradiation. The space charge is concentrated within a narrow layer located between the depth of the dose maximum and the end of the electron range (26). This is also where the ionization chamber is placed during calibration measurements.

For a homogeneous phantom without hole the electric field can be considered as generated by infinite planar charged sheets. From symmetry considerations it is clear that in this case only the component of the electric field perpendicular to the charged sheets exists. When the chamber is inserted this will act as a cylindric equi-potential surface in the phantom causing the electric field close to the hole to be directed towards the hole. It must be pointed out that the electric field inside the ionization chamber only depends on the polarizing voltage and chamber construction and therefore is not affected by the external electric field produced by the

space charge. The observed signal increase is caused by an increasing number of electrons entering the cavity from different directions. When these electrons, which normally would have missed the cavity, enter the electric field surrounding it, they are deflected in the direction of the field, i.e. towards the cavity. Electrons which have passed through the ionization chamber will experience the retarding force of the electric field as soon as they leave the chamber wall. With the dose rates used in radiation therapy this repelling force will not be large enough to stop the electrons and then accelerate them back into the cavity.

It can be seen from Fig. 1 that the deposited charge density decreases with electron beam energy and so does the electric field. The increase in chamber signal with accumulated absorbed dose can therefore be expected to increase with decreasing electron beam energy in agreement with the experimental results reported and by GALBRAITH et coll. The effect can also be expected to vary with the depth of the ionization chamber in the phantom, as the electric field will do so.

The variation with beam energy will be masked by the fact that most hospitals use the same set of phantoms for all beam qualities available at the department. Electron beam calibration measurements are made at the reference depth, which in most cases are the same as the depth of the absorbed dose maximum. This means that the phantom block with the hole for the chamber is always placed in the region where the charge deposition is large. In each measurement, irrespective of electron energy, new charge will thus be deposited to approximately the same region in the block. The accumulated charge from all previous irradiations will therefore influence all the following measurements, including photon beam measurements. The variation with depth will not be observed in routine dosimetry if the change of measuring depth is made by adding or removing slabs of phantom material in front of that containing the chamber, keeping the material behind the same.

The influence of the space charge is very similar to the in-scattering effect responsible for the perturbation effect in electron beam dosimetry and acts as a magnification of this effect. The realization of this fact might be of importance for the interpretation of the experimentally determined perturbation factors reported by JOHANSSON et coll. (16). These factors were significantly larger than corresponding factors calculated by HARDER (11). Part of the difference has been explained by too rough approximations used in the original paper by HARDER (12). However, as JOHANSSON et coll. (16) made all measurements in PMMA it is possible that part of the spread in the experimental values comes from the influence of the space charge build-up. Work is now under way, where the measurements by JOHANSSON et coll. are repeated in water.

As discussed the conductivity of an insulator during irradiation is increased. The increase can be several orders of magnitude. This conductivity will have a significant influence on the internal electric field as it tends to distribute the charge within the irradiated volume. In electron beams, a limited volume of the phantom is irradiated, where the accumulated charge is concentrated. The conductivity of the unirradiated parts of the phantom is so low that very little of the charge is transported into this region. If the phantom subsequently is used in a high energy photon beam the whole phantom will be irradiated, which means that the previously accumulated charge now can be distributed over a much larger volume and the electric field be reduced. This can be part of the explanation why the increase in chamber signal with accumulated absorbed dose has been undetected for so long.

It is well known that discharge patterns, Lichtenberg figures, are easily formed in PMMA but not in polystyrene. This has been explained by a faster removal of deposited charges by the radiation induced conductivity in polystyrene than in PMMA (19). This limits the electric field in polystyrene to a level well below that for electric breakdown, which means that at a certain electric field approximately the same number of electrons are being removed as injected. This fact also explains why the increase in the signal from a cylindric ionziation chamber used in polystyrene saturates after approximately 100 Gy (Table 1). The saturation effect is much less in PMMA than in polystyrene, which is explained by differences in the radiation induced conductivity between the two materials (19).

The decay of the radiation induced conductivity after the irradiation differs widely from material to material (4). PMMA has a very short decay time (seconds) while the decay can take hours in polystyrene. This is important to realize if these materials are used for high precision measurements.

The radiation induced conductivity depends also on the purity of the material. As a rule, the materials

which contain the most impurity, i.e. filler, plasticizer etc. exhibit the greatest change in conductivity (3), which means that the charge build-up in materials from different manufacturers can be very different.

No increase in the signal with accumulated absorbed dose was observed with the plane-parallel NACP-chamber. One reason for this is that the material behind the air cavity and side walls is graphite. The graphite block, about 6 mm deep, occupies the space where otherwise the charge build-up having the largest influence on the electron fluence in the cavity would occur. With the plane-parallel chamber there will thus be very little charge build-up in the vicinity of the cavity. Another reason is that the collecting electrode is surrounded by a guard ring preventing electrons, entering through the side walls, from reaching the collecting volume. The conditions are thus completely different with the plane-parallel chamber compared with the cylindric one. It can thus be concluded, that it is possible to reduce the effects of the charge accumulation in insulating phantom materials with a chamber construction similar to that used in the NACP chamber.

As mentioned most dosimetry protocols recommend the use of polystyrene or PMMA as phantom material in electron beam dosimetry. The most common combination is a cylindric ionization chamber in a polystyrene phantom. This is most unfortunate, as systematic uncertainties of several per cent may be introduced in the dosimetry. Recently, comparisons of absorbed doses measured in water and polystyrene were published (10, 17, 22). The spread in the reported values is large which partly might be due to the influence of the space charge build-up as different types of chambers, cylindric and plane-parallel, were used by the different investigators.

One main concern is to evaluate how the dosimetry recommendations published by NACP are influenced. NACP (23) (photon beams with energies between 1 MeV and 50 MeV and electron beams with energies between 10 MeV and 50 MeV) recommends the use of a cylindric chamber and a plastic phantom for absorbed dose monitor checks and energy checks. NACP (24) (electron beams with energies between 1 MeV and 15 MeV) states that plane-parallel chambers shall be used and that plastic phantoms can be used especially for energies below 5 MeV, not only for absorbed dose determination at the reference depth but also to measure complete depth ionization curves for subsequent conversion to corresponding curves in water. It is also stated that the plane-parallel chamber should be calibrated by comparison against a calibrated cylindric chamber in high-energy electron or ^{60}Co gamma-beams. The comparison should be made in a phantom made of PMMA.

The recommendations in the NACP (23) must be reconsidered regarding the points cited. The most serious problem in the procedures described in NACP (24) is probably the use of a PMMA phantom for the calibration of a plane-parallel chamber. As the influence of the charge accumulation is different with the plane-parallel and the cylindric chambers errors of several per cent can be introduced in the dosimetry.

It was also recommended that depth ionization curves be measured in plastic phantoms. LACKNER et coll. (19). GROSS & NABLO (8) and HARRAH (13) have demonstrated a marked range shortening for electrons in insulating plastics, due to the space charge build-up. However, these observations were made with extremely high dose rates. With the dose rates used in electron beam therapy the influence of the space charge on the electron ranges is negligible. The charge injection rate is too low to produce an instantaneous electric field large enough to reduce the electron ranges (8). The use of insulating plastic phantoms for the measurement of depth ionization curves is thus not a serious problem, provided the NACP chamber is used.

When an ionization chamber is used in water it is necessary to prevent water from leaking into the chamber. The most commonly used method is to use a watertight sleeve made of polystyrene or PMMA. As the wall thickness of the sleeve is thin, usually 1 to 2 mm, the charge accumulation is limited. Also, as the whole sleeve normally is being irradiated, the radiation induced conductivity tends to distribute the charges into the surrounding water.

Conclusion

It is concluded that all dosimetry systems that disturb the electric field from the accumulated charges in an insulating phantom, are likely to be affected by the accumulated charge. If, for example, film is used for depth dose measurements in polystyrene the film will act as a grounded plate inserted into the polystyrene.

We conclude, in support of the conclusion of GALBRAITH et coll., that the use of insulating phan-

tom materials such as PMMA and polystyrene in radiation dosimetry must be avoided. Errors of several per cent can otherwise be introduced. The recommendations given in most dosimetry protocols regarding the use of solid phantoms must be reconsidered. Measurements should instead be made in water phantoms. When an ionization chamber is used in water it is necessary to protect the chamber with a water-tight cover. If this is made of PMMA or polystyrene it must be made as thin as possible to avoid charge build-up effects.

ACKNOWLEDGEMENTS

The authors are grateful to Drs M. Galbraith and J. A. Rawlinson for supplying a preprint of their work on charge build-up effects.

REFERENCES

1. AMERICAN ASSOCIATION OF PHYSICISTS IN MEDICINE (AAPM): Protocol for the dosimetry of high energy electrons. Phys. Med. Biol. 11 (1966), 505.
2. BERGER M. J. and SELTZER S. M.: Calculation of energy and charge deposition and of the electron flux in a water medium bombarded with 20 MeV electrons. *In:* High-energy radiation therapy dosimetry. Edited by J. S. Laughlin. Ann. New York Acad. Sci. 161 (1969), 8.
3. BURR J. G. and GARRISON W. M.: The effect of radiation on the physical properties of plastics. United States atomic energy commission, AECD-2078, 1943.
4. FOWLER J. F.: X-ray induced conductivity in insulating materials. Proc. Roy. Soc. A236 (1956), 464.
5. GALBRAITH D. M., RAWLINSON J. A. and MUNRO P.: Dose errors in irradiated plastic phantoms. *In:* 46th Annual Meeting The Canadian Association of Radiologists, 1983, p. 230.
6. — — — Dose errors due to charge storage in electron irradiation plastic phantoms. Med. Phys. 11 (1984), 253.
7. GROSS B.: Irradiation effects in plexiglass. J. Polymer Sci. 27 (1958), 135.
8. — and NABLO S. V.: High potentials in electron-irradiated dielectrics. J. Appl. Phys. 38 (1967), 2272.
9 — and WRIGHT K. A.: Charge distribution and range effects produced by 3-MeV electrons in plexiglass and aluminium. Phys. Rev. 114 (1959), 725.
10. HANSON W. F. and BERKLEY L. W.: Measurement of electron beam ionization vs. depth in various tissue-like materials. Abstract. Med. Phys. 9 (1982), 607.
11. HARDER D.: The effect of multiple electron scattering on the ionization in gasfilled cavities. Biophysik 5 (1968), 157.
12. — Personal communication (1979).
13. HARRAH L. A.: Pulsed electron beam energy deposition profiles using solid radiation sensitive plastics. IEEE Trans. Nuc. Sci. NS 17 (1970), 278.
14. HOSPITAL PHYSICISTS ASSOCIATION (HPA): A practical guide to electron dosimetry 535 MeV. HPA Report Series No. 4, 1971.
15. INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS (ICRU): Report No. 21: Radiation dosimetry: Electrons with initial energies between 1 and 50 MeV. Washington, D.C. 1972.
16. JOHANSSON K.-A. MATTSSON L. O., LINDBORG L. and SVENSSON H.: Absorbed dose determination with ionization chambers in electron and photon beams with energies between 1 and 50 MeV. *In:* International symposium on national and international standardization of radiation dosimetry. Atlanta 1978 (IAEA-SM-222/35).
17. KASE K. R., ADLER G. J. and BJÄRNGARD B. E.: Comparisons of electron beam dose measurements in water and polystyrene using various dosimeters. Med. Phys. 9 (1982), 13.
18. KESSARIS N. D.: Penetration of high-energy electron beams in water. Phys. Rev. 145 (1966), 164.
19. LACKNER H., KOHLBERG I. and NABLO S. V.: Production of large electric fields in dielectrics by electron injection. J. Appl. Phys. 36 (1965), 2064.
20. LAUGHLIN J. S.: Studies of absorption of high energy electron beams. *In:* Symposium on high energy electrons, Montreux 1964, p. 11. Edited by A. Zuppinger and G. Poretti. Springer-Verlag, Berlin 1965.
21. MATSUOKA S., SUNAGO H., TANAKA R., HAGIWARA M. and ARAKI K.: Accumulated charge profile in polyethylene during fast electron irradiations. IEEE Trans. Nuc. Sci. NS-23 (1976), 1447.
22. MATTSSON L. O., JOHANSSON K.-A. and SVENSSON H.: Calibration and use of plane-parallel ionization chambers for the determination of absorbed dose in electron beams. Acta radiol. Oncology 20 (1981), 385.
23. NORDIC ASSOCIATION OF CLINICAL PHYSICS (NACP): Procedures in external radiation therapy dosimetry with electron and photon beams with maximum energies between 1 and 50 MeV. Acta radiol. Oncology 19 (1980), 55.
24. — Electron beams with mean energies at the phantom surface below 15 MeV. Acta radiol. Oncology 20 (1981), 401.
25. TANAKA R., SUNAGA H. and TAMURA N.: The effect of accumulated charge on depth dose profile in poly(methylmethacrylate) irradiated with fast electron beam. IEEE Trans. Nuc. Sci. NS-26 (1979), 4670.
26. VAN DYK J. and MACDONALD J. C. F.: Charge deposition from high energy electron beams. Radiat. Res. 50 (1972), 20.
27. WILLIS C., MILLER O. A., ROTHWELL A. E. and BOYD A. W.: The dosimetry of very-high-intensity pulsed electron sources used for radiation chemistry. Dosimetry for liquid samples. Radiat. Res. 35 (1968), 428.