Dosimetry of pulsed clinical proton beams by a small ionization chamber

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Response of a micro volume (0.01 ml) ionization chamber has been studied with pulsed proton beams which are used for clinical purposes and has been compared with those of some JARP ionization chambers (0.6 ml). All chambers used had been calibrated by standard ^{60}Co beams at the Electrotechnical Laboratory (ETL) and exposure calibration factors, N_X, were obtained on advance. Two methods are used to compensate the general recombination which occurs during pulsed beam irradiations: theoretical correction by a Boag's formulation and a modified two-voltage technique. An evaluation of absolute absorbed dose-to-water is performed on the basis of the protocol provided by ICRU report 59. The results imply that, to a first approximation, both chambers indicate the almost same result within 2% when unknown chamber-dependent parameters of the micro chamber are tentatively assumed to be identical to those of the JARP chamber for the calibration with ^{60}Co beams. The about 1.5% discrepancy observed in the response of both chambers is not discussible due to presumably 1–2% uncertainty of the protocol of ICRU report 59 which does not include any chamber-dependent corrections for the perturbation effects in proton beams. [DOI: 10.1118/1.1380435]

Key words: micro ionization chamber, pulsed proton beams, absolute dose evaluation, recombination compensation, ICRU report 59, perturbation effects in proton beams

I. INTRODUCTION

In the charged particle therapy, such as the proton therapy, a small size ionization chamber may be suitable to determine delivering dose when the target tumor volume is small and the shape is complicated because such a small ionization chamber has good spatial resolution due to its tiny sensitive volume.[1,2] Recently-issued ICRU report 59 provides a protocol for absorbed dose determination of protons, which includes some chamber-dependent correction parameters for the calibration by ^{60}Co beams.[3] On the other hand, usually, those parameters of such a small ionization chamber are unknown. Therefore, the sensitivity of the chamber should be re-calibrated in actual charged particle beams by a comparison with the response of some ionization chambers whose sensitivity are fully apparent. Moreover, general recombination compensation must be considered when sharply bunched pulsed beams are irradiated. It is unknown whether a conventionally used theoretical correction method, Boag's formulation, is applicable or not for such a small ionization chamber.[4]

From the view points mentioned above, response characteristics of a small ionization chamber have been compared with those of a standard thimble-type ionization chamber. Validity of the application of ICRU report 59 protocol is also discussed.

II. PROTON DOSIMETRY BASED ON ICRU REPORT 59

As mentioned already, a new protocol for the determination of absorbed dose was established by the ICRU report 59 for protons. An international proton dosimetry intercomparison had been carried out at Loma Linda University Medical Center.[5] In this protocol, determination of absorbed dose-to-water is available by using the ionization chambers calibrated in terms of exposure, which is equivalent to air-kerma calibration, or in terms of absorbed dose-to-water in ^{60}Co beams. Chamber-dependent correction factors for the calibration in ^{60}Co beams are implemented for some common cylindrical ionization chambers.

According to the notation of the protocol, when using an ionization chamber with an air-kerma calibration factor N_k for ^{60}Co photons, the absorbed dose-to-water for protons $D_{w,p}$ can be written as follows:

$$D_{w,p}=M_p^{\mathrm{corr}}\times N_{D,g}\times C_p, \tag{1}$$

where M_p^{corr} is the product of the meter reading M and the corrections $P_{t,p}$ (temperature and pressure), P_{ion} (ion recombination factor) and P_j (the product of all other factors which can produce a modified response relative to the calibration condition). And

$$N_{D,g}=\frac{N_k(1-g)A_{\mathrm{wall}}A_{\mathrm{ion}}}{s_{\mathrm{wall},g}(\mu_{\mathrm{en}}/\rho)_{\mathrm{air,wall}}K_{\mathrm{hum}}} \tag{2}$$

$$C_p=(s_{w,\mathrm{air}})_p\frac{(w_{\mathrm{air}})_p}{(W_{\mathrm{air}})_c}, \tag{3}$$

where g is the fraction of secondary electron energy lost to bremsstrahlung, A_{wall} the correction for the absorption and scatter in the wall and build-up cap for ^{60}Co beams, A_{ion} the correction for ion recombination during ^{60}Co calibration, $s_{\mathrm{wall},g}$ the mean ratio of restricted mass stopping powers from wall material to the gas for the secondary electrons by ^{60}Co beams, $(\mu_{\mathrm{en}}/\rho)_{\mathrm{air,wall}}$ the mass energy absorption coefficient ratio from air to wall for ^{60}Co beams, K_{hum} the correction for the difference in response between ambient air and dry air, $(s_{w,\mathrm{air}})_p$ the mean water-to-air mass electronic stopping power ratio for protons, $(w_{\mathrm{air}})_p$ the mean energy required to form an ion pair in air for protons and $(W_{\mathrm{air}})_c$ the mean energy required to form an ion pair in air for ^{60}Co photons. The relation between N_k, an air-kerma calibration factor, and N_X, an exposure calibration factor, is

$$N_k(1-g)=N_X(W_{\mathrm{air}})_c, \tag{4}$$

where the units of N_k and N_X are $[\mathrm{J\,kg^{-1}\,nC^{-1}}]$ and $[\mathrm{C\,kg^{-1}\,nC^{-1}}]$, respectively, when the meter reading is given in the unit of [nC]. With this relation, for the calibration factor N_X in ^{60}Co beams, the product of $N_{D,g}$ and C_p is expressed as

$$N_{D,g}\times C_p=\frac{N_X A_{\mathrm{wall}} A_{\mathrm{ion}}}{s_{\mathrm{wall},g}(\mu_{\mathrm{en}}/\rho)_{\mathrm{air,wall}} K_{\mathrm{hum}}}\times(s_{w,\mathrm{air}})_p(w_{\mathrm{air}})_p\,. \tag{5}$$

In Eq. (5), except N_X, chamber-dependent parameters are A_{wall}, $s_{\mathrm{wall},g}$, and $(\mu_{\mathrm{en}}/\rho)_{\mathrm{air,wall}}$ which are all concerned with the ^{60}Co calibration. Among them, only A_{wall} depends on the geometry of chambers; other two parameters are common between different chambers if those wall materials are identical.[6] While, it has been investigated that A_{wall} is almost constant within 0.3% for 0.6 ml Farmer-type chambers with different radii up to 2.5 mm.[7] Generally, it can be assumed that the value of A_{ion} is almost unity for the usual calibration condition of standard laboratories. On the value of K_{hum}, 0.997 is recommended for ambient air filling in this protocol. But it may be also very close to unity when the ambient air filling is achieved for both the ^{60}Co calibration and the actual proton dosimetry. The parameters of $(s_{w,\mathrm{air}})_p$ and $(w_{\mathrm{air}})_p$ are universal ones for all chambers. Regarding $(s_{w,\mathrm{air}})_p$, it is recommended that the values given in ICRU report 49 should be used.[8] Though $(s_{w,\mathrm{air}})_p$ is a function of proton energy, a value of 1.132 is available with the error less than 0.4% for the proton energy from 20 to 400 MeV.[9] Regarding the value of $(w_{\mathrm{air}})_p$, there is still a relatively large uncertainty. In the protocol of ICRU report 59, a value of 34.8 ± 0.7 [J/C] is recommended for protons above about 1 MeV, which is slightly smaller and more precise than the previously recommended value of 35.2 ($\pm$4%) [J/C].[10]

It should be noted that the above formulation assumes no contribution of perturbation effects in proton beams and any chamber-dependent correction factors are not implemented for that. This is based on a fact that the mean range of the secondary electrons from proton interactions is so small that the vast majority of electrons detected in the gas cavity are produced in the gas.[11] This corresponds to assuming that p_{cav}, the correction for difference of the secondary electrons in the medium and the cavity for protons, is negligible. On the other hand, however, it has been reported that this effect can reach the order of 1% as a result of recent Monte Carlo study.[12] As far as p_{wall}, the correction of chamber wall effects for protons, is concerned, no significant dose change has been observed for modulated proton beams in the same literature.[12] Regarding p_{cel}, the correction of perturbations due to the central electrode for protons, a value of 0.997 has been reported for chamber types with an aluminum central electrode.[13] In addition to this, for ^{60}Co irradiation, it has been investigated that the enhancement of chamber response is nearly proportional to the electrode radius (up to 7% for the radius of 2.5 mm) but unaffected by the choice of material of central electrode; if the radius is less than 0.25 mm, the effect is at most 1%.[7] It can be deducible that such effect would be far smaller for protons because it is apparent that secondary electrons play a chief role in the response of chamber for ^{60}Co photons, but not for protons. Regarding p_{dis}, the displacement correction factor for protons, the value can be taken to be almost unity since the reference depth is situated in a uniform dose region [spread-out Bragg peak (SOBP)]. While, it should be stressed that this effect might depend on the resolution of the modulation. Consequently, the combined effects of these perturbations mentioned above for protons can account for up to 1–2%.

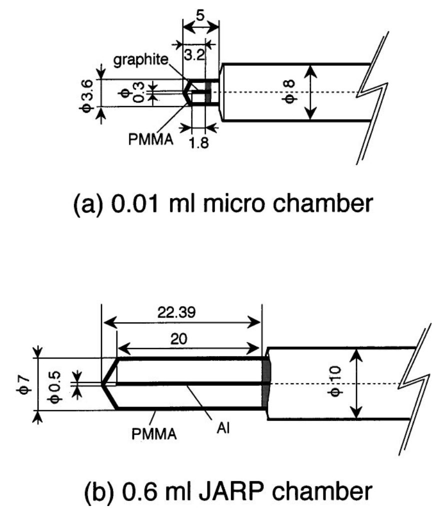

FIG. 1. Detailed design drawings of the 0.01 ml micro chamber (a) and the 0.6 ml JARP chamber (b). The physical dimensions are indicated in millimeters.

III. MATERIALS AND METHODS

Air ionization chambers used in the present work are commercially available from Applied Engineering Inc., Japan. A 0.01 ml micro chamber has PMMA (polymethylmethacrylate, ρ=1.18) (PMMA) (ρ=1.18) outer wall with the thickness of 0.5 mm; the outer diameter is 3.6 mm. The central electrode is made of graphite, which has 0.3 mm diameter and 1.8 mm effective length as shown in Fig. 1(a). On the other hand, a 0.6 ml JARP (Japanese Association of Radiological Physicists) chamber is a so-called thimble-type chamber which is universally used in Japan for dosimetry of photons and electrons.[14] The wall material is also PMMA; the outer diameter is 7 mm and the wall thickness is 0.5 mm. The aluminum central-electrode is 0.5 mm in diameter with an effective length of about 20 mm [Fig. 1(b)]. Both chambers are designed to apply a negative voltage to the outer electrodes.

Prior to the proton dosimetry, the 0.01 ml micro chamber and four 0.6 ml JARP chambers were calibrated by the primary ^{60}Co standard-field in Japan at the Electrotechnical

TABLE I. Evaluated exposure calibration factors N_X by ^{60}Co beams at ETL.[a]

Ionization chamber	0.01 ml #807	0.6 ml #823	0.6 ml #824	0.6 ml #227	0.6 ml #231
$N_X\,[\mathrm{C\,kg^{-1}\,nC^{-1}}]$	0.079 49	0.001 438	0.001 441	0.001 357	0.001 386

[a]Exposure Rate $=0.000\,302\,84\,[\mathrm{C\,kg^{-1}\,s^{-1}}]$, $T=293.15\,[\mathrm{K}]$, $P=1013.25\,[\mathrm{HPa}]$.

Laboratory (ETL) in the Agency of Industrial Science and Technology (Ministry of International Trade and Industry, Japan) in terms of the exposure calibration factor, $N_X\,[\mathrm{C\,kg^{-1}\,nC^{-1}}]$. The thickness of build-up cap wall (PMMA, $\rho=1.18$) used was 4 mm. Evaluated values of those exposure calibration factors are listed in Table I.

Proton irradiation was carried out at the vertical irradiation line of Proton Medical Research Center (PMRC), University of Tsukuba in KEK (High Energy Accelerator Research Organization).[15] This facility was established in 1980 as "Particle Radiation Medical Science Center (PARMS)" and had been re-organized to the present status, i.e., PMRC, in 1990. The PMRC has a proton beam line at the KEK Booster Synchrotron Utilization Facility to make use of the 500 MeV booster beam for medical diagnosis, radiotherapy and biological researches. In the PMRC beam line, approximately mono-energetic 250 MeV pulsed protons are delivered by the fast extraction technique with a duration time of 50 ns [in full width at half maximum (FWHM)] at the frequency of about 20 Hz as shown in Fig. 2. Because the booster synchrotron is also utilized for a pre-accelerator, some pulses are delivered to the 12 GeV main proton synchrotron. Each pulse beam consists of $2-4\times10^9$ protons. The experimental arrangement is sketched in Fig. 3. Incident narrow proton beams are scattered by a 6 mm-thick lead plate to obtain laterally uniform spatial distribution at the irradiation position. Proton energy (range) can be adjusted by an energy fine degrader. In this figure, a spread-out Bragg peak (SOBP) is formed by using a ridge filter. At the position of test chambers, the average dose rate is approximately 2.5 Gy/min and instantaneous dose rate is about 0.2 cGy/pulse. The polarity effects of the test chambers have been found to be negligible at this dose rate.

As the each pulse has such sharply bunched time structure, an effect of general recombination between positive and negative ions during charge collection cannot be ignored for the use of air ionization chambers; the collection efficiency $f(=1/P_{\mathrm{ion}})$ may become less than unity. Therefore, appropriate correction of this effect is necessary. We adopt two different methods for this purpose. One is based on a theoretical formulation of general recombination in a chamber having cylindrical geometry by Boag,[4] which is an approximated treatment to apply to the present case because the shape of the chambers is almost cylindrical but, in part, nearly hemispherical around the top as shown in Fig. 1. The other is the two-voltage technique modified by Hayakawa *et al.* for the compensation of fluctuations in beam intensity that may occur during measurement.[16,17] This method does not depend on the chamber geometry. To use the two-voltage technique, some signals proportional to beam intensity are required. For this, we use a secondary-emission chamber (SEC) as a transmission reference monitor; no recombination takes place in the SEC monitor because the inside of chamber is kept in vacuum and secondary electrons emitted from the aluminum chamber-wall are collected by an applied voltage. In the article of Hayakawa *et al.*, an iterative computerized procedure was created in BASIC language to obtain numerical solutions of Eq. (11) in Ref. 16. The equation is reproduced here

$$u_1+1=(1+Gu_1)^E, \tag{6}$$

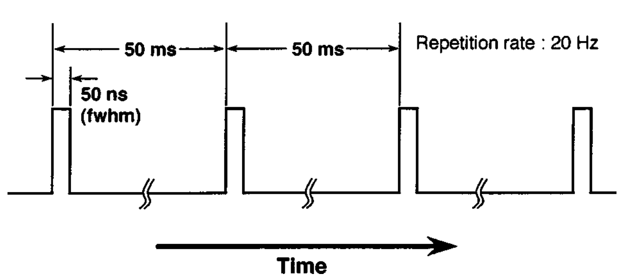

FIG. 2. Time structure of the pulsed beams delivered from KEK 500 MeV booster synchrotron with the fast extraction technique.

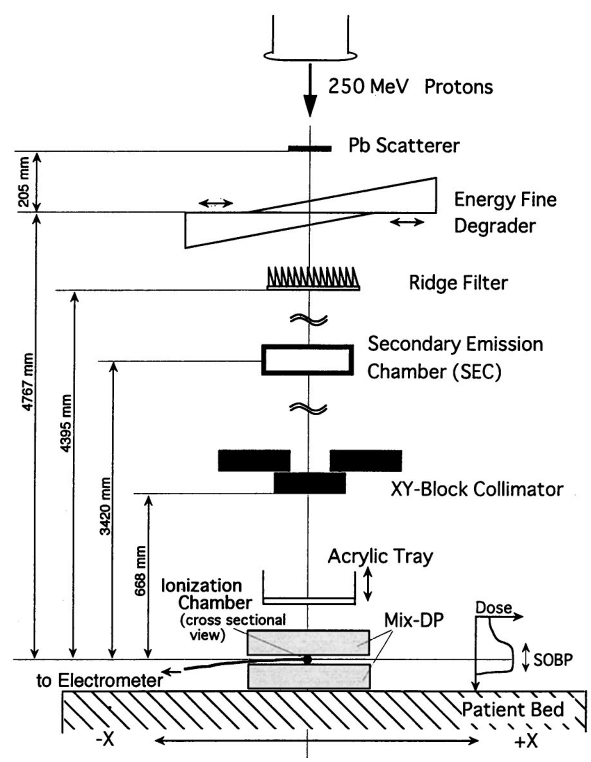

FIG. 3. Experimental arrangement for proton irradiations at the vertical irradiation line of PMRC.

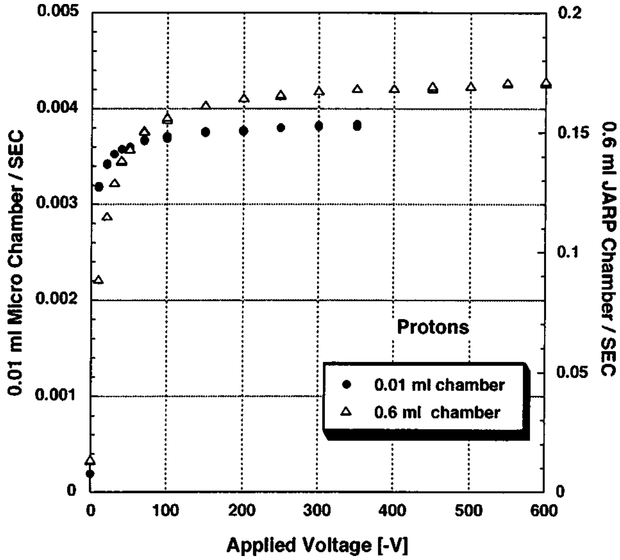

FIG. 4. Saturation curves measured with proton beams at the peak position of an ordinary Bragg curve for the 0.01 ml micro chamber and the 0.6 ml JARP chamber. A negative voltage was applied to each outer electrode.

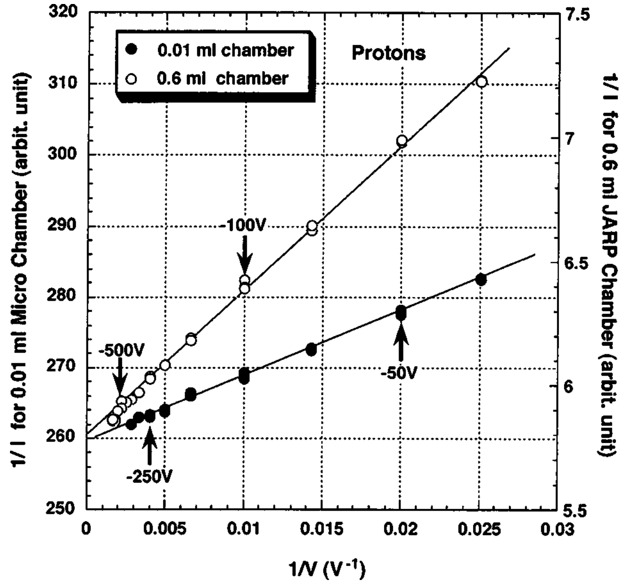

FIG. 5. The reciprocal of the chamber current I as a function of the reciprocal of the applied voltage V for the 0.01 ml micro chamber and the 0.6 ml JARP chamber (the same data with Fig. 4). The points used for the two-voltage technique are indicated by arrows with the values of applied voltage. The lines are just for eye's guide.

where G and E are constants obtained from experiment directly and u_1 is a variable u in an experimental condition 1; to apply the two-voltage technique, measurements are necessary for two different applied voltages, i.e., experimental conditions 1 and 2. The u is defined as

$$u=(Bq_{\mathrm{sat}})/(CV). \tag{7}$$

Here B is a constant which depends on the type of gas containing in it, q_{sat} the initial charge of positive or negative ions created in the chamber by the pulsed radiation, C the volume of the chamber and V the voltage applied to the chamber. The collection efficiency f in the experimental condition 1, f_1, is expressed as $f_1=(1/u_1)\ln(1+u_1)$. In order to solve Eq. (6) numerically and determine the value of u_1, we successfully utilized "FindRoot" function of a computer program MATHEMATICA.[18]

IV. RESULTS AND DISCUSSION

A. Saturation curves and operating voltage

The saturation curves measured at the peak position of an ordinary Bragg curve, without a ridge filter, are shown in Fig. 4. As already mentioned, negative voltage is applied to the outer electrode of each chamber. The output charges of ionization chambers are normalized by the signals of reference SEC monitor. Figure 4 indicates that the operation voltages should be less than −300 V for the 0.6 ml JARP chamber and less than −150 V for the 0.01 ml micro chamber. By referring to these results, in the following experiment, the standard applied voltages are chosen to be −500 V for the 0.6 ml JARP chambers and to be −250 V for the 0.01 ml micro chamber.

The same date with Fig. 4 are plotted as $1/I(V)$ vs. $1/V$ in Fig. 5. For the application of the two-voltage technique, a plot of reciprocal current against reciprocal applied voltage should be approximately linear.[19] With keeping this in mind, the another applied voltages are set to be −100 V for the 0.6 ml JARP chambers and to be −50 V for the 0.01 ml micro chamber as indicated in Fig. 5; those points are well away from saturation region.

During the saturation curves measurement mentioned above, a clear hysteresis effect was observed for the 0.01 ml micro chamber.[20] Namely, just after changing the applied voltage, the first (and sometimes also second) measurement indicated a few % higher or lower values than those of the following several successive measurements which were very stable. Therefore, those extraordinary data are omitted from Figs. 4 and 5.

B. Absolute dose evaluation

By using the micro chamber and the JARP chambers, absorbed dose-to-water for protons has been evaluated based on the protocol provided by ICRU report 59, which has been described in Chapter II. The parameters A_{wall}, $s_{\mathrm{wall},g}$, and $(\mu_{\mathrm{en}}/\rho)_{\mathrm{air,wall}}$ for ^{60}Co calibration of the JARP chamber are not included in the recommended values in Table 7.2 of ICRU report 59. But we can find the corresponding values in Ref. 14 for the JARP chamber as listed in Table II. Regarding the 0.01 ml micro chamber, those parameters are unknown. So, the same values as those in Table II are used tentatively.

TABLE II. Recommended values of physical parameters for JARP chamber for ^{60}Co photons (Ref. 14).

Chamber description	Wall	A_{wall}	$S_{\mathrm{wall},g}$	$(\mu_{\mathrm{en}}/\rho)_{\mathrm{air,wall}}$
JARP 0.6 ml	PMMA	0.990	1.103	0.925

TABLE III. Evaluated proton dose-to-water normalized by the reference SEC monitor, which are obtained in the center of 75 mm SOBP with two different methods of recombination compensation. The errors indicate one standard deviation for five times measurements only.

Ionization chamber	Boag's theory [Gy/nC]	Error	Two-voltage technique [Gy/nC]	Error
0.01 ml #807	0.015 482	0.000 018	0.015 561	0.000 024
0.6 ml #823	0.015 781	0.000 019	0.015 800	0.000 021
0.6 ml #824	0.015 768	0.000 017	0.015 777	0.000 019
0.6 ml #227	0.015 752	0.000 014	0.015 775	0.000 008
0.6 ml #231	0.015 787	0.000 024	0.015 824	0.000 008

Table III indicates evaluated proton dose-to-water normalized by the reference SEC monitor, which are obtained in the center of 75 mm SOBP with two different methods of recombination compensation. The X-Y block collimator is set to $100\times 100\,\mathrm{mm}^2$. The errors indicate one standard deviation for five times measurements only.

Firstly, from Table III, it is noticeable that values by the Boag's formulation show good agreement with the results by the two-voltage technique for all 0.6 ml JARP chambers within $\pm 0.2\%$. However, the same formulation is no longer available for the 0.01 ml micro chamber. This may be due to an invalid approximation that the micro chamber has almost cylindrical geometry.

Next, even for the evaluations by the two-voltage technique, there is an evident discrepancy between result of the 0.6 ml JARP chambers and that of the 0.01 ml micro chamber in Table III. The evaluated proton dose by the two-voltage technique for the micro chamber, 0.015 56 [Gy/nC], is about 1.5% smaller than the average of those for the four JARP chambers, 0.015 79 [Gy/nC]. As explained already, in the protocol of ICRU report 59, all perturbation effects of chambers for proton beams are ignored and any chamber-dependent correction factors are not included for such perturbation effects. So, if we faithfully obey this protocol, it may be natural to select the A_{wall} for the 0.01 ml micro chamber to be 1.005 instead of 0.990 to keep the consistency of the protocol because only A_{wall} depends on the geometry of chambers among the parameters in Table II for ^{60}Co photons. On the other hand, however, there is some evidence that these perturbation effects for protons are not negligible and the difference in the response between different chambers can reach 1–2% (see Chapter II). Therefore, the observed discrepancy of 1.5% is very subtle to judge that there really exists a meaningful difference in the response between both chambers. All we can conclude here is, to a first approximation, both chambers indicate the same result to within 2%. If such perturbation effect of chambers for protons is very small in the present case and the discrepancy between both chambers attributes to the difference of A_{wall}, a deducible reason is the different contribution of secondary electrons generated at the stem part of each ionization chamber by ^{60}Co photons.

V. SUMMARY

The 0.01 ml micro ionization chamber has been recalibrated in the clinical proton beams by a comparison with the 0.6 ml JARP chambers on the basis of the protocol provided by ICRU report 59. If we faithfully obey the protocol, it seems that the value of A_{wall} for the micro chamber ought to be estimated at 1.005. On the other hand, however, because the present protocol does not include any corrections due to the perturbation effects for proton beams, the observed discrepancy of 1.5% is very subtle to judge that there really exists a meaningful difference in the response between both chambers. Therefore, all we can conclude here is, to a first approximation, both chambers indicate the same result within 2%. It has been turned out that Boag's formulation of the recombination compensation is no longer available for the 0.01 ml micro chamber. The excellent spatial resolution of the micro chamber due to its tiny sensitive volume may be suitable for profile measurements and also applicable to the dosimetry for small size fields.

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