General ion recombination effect in a liquid ionization chamber in high-dose-rate pulsed photon and electron beams

著者	Mori Yutaro, Takei Hideyuki, Kitamura Nozomi, Isobe Tomonori, Tomita Tetsuya, Kobayashi Daisuke, Kamizawa Satoshi, Sato Tomoharu, Sakurai Hideyuki, Sakae Takeji
journal or publication title	Journal of radiation research
volume	59
number	3
page range	282-285
year	2018-05
権利	(C) The Author(s) 2018. Published by Oxford University Press on behalf of The Japan Radiation Research Society and Japanese Society for Radiation Oncol ogy. This is an Open Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (http://creativecommons.org/licenses/ by-nc/4.0/), which permits non-commercial re-use, distribution, and reproduction in any medium, provided the original work is properly cited. For commercial re- use, please contact journals.permissions@oup.com
URL	http://hdl.handle.net/2241/00152986

doi: 10.1093/jrr/rrx088

Journal of Radiation Research, Vol. 59, No. 3, 2018, pp. 282–285
doi: 10.1093/jrr/rrx088
Advance Access Publication: 24 January 2018

General ion recombination effect in a liquid ionization chamber in high-dose-rate pulsed photon and electron beams

Hideyuki Takei[1,2], Tomonori Isobe[1,3], Nozomi Kitamura[4], Yutaro Mori[1,3], Tetsuya Tomita[5], Daisuke Kobayashi[5], Satoshi Kamizawa[1], Tomoharu Sato[4], Hideyuki Sakurai[1,3] and Takeji Sakae[1,3]

[1]Proton Medical Research Center, University of Tsukuba Hospital, 2 Chome-1-1 Amakubo, Tsukuba, Ibaraki Prefecture 305-8576, Japan
[2]National Institute of Radiological Sciences, National Institutes for Quantum and Radiological Science and Technology, 4-9-1 Anagawa, Inage, Chiba, Chiba 263-8555, Japan
[3]Faculty of Medicine, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8575, Japan
[4]Department of Radiation Oncology, The Cancer Institute Hospital of Japanese Foundation for Cancer Research, 3 Chome-8-31 Ariake, Koto, Tokyo 135-0063, Japan
[5]Department of Radiology, University of Tsukuba Hospital, 2 Chome-1-1 Amakubo, Tsukuba, Ibaraki Prefecture 305-8576, Japan
*Corresponding author. Faculty of Medicine, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8575, Japan. Tel: +81-29-853-2111/+81-29-853-5600; Fax: +81-29-853-3404; Email: tiso@md.tsukuba.ac.jp

(Received 2 June 2017; revised 10 August 2017; editorial decision 8 December 2017)

ABSTRACT

Liquid ionization chambers (LICs) are highly sensitive to dose irradiation and have small perturbations because of their liquid-filled sensitive volume. They require a sensitive volume much smaller than conventional air-filled chambers. However, it has been reported that the collection efficiency has dependencies on the dose per pulse and the pulse repetition frequency of a pulsed beam. The purpose of this study was to evaluate in detail the dependency of the ion collection efficiency on the pulse repetition frequency. A microLion (PTW, Freiburg, Germany) LIC was exposed to photon and electron beams from a TrueBeam (Varian Medical Systems, Palo Alto, USA) linear accelerator. The pulse repetition frequency was varied, but the dose per pulse was fixed. A theoretical evaluation of the collection efficiency was performed based on Boag's theory. Linear correlations were observed between the frequency and the relative collection for all energies of the photon and electron beams. The decrease in the collected charge was within 1% for all the flattened photon and electron beams, and they were 1.1 and 1.8% for the 6 and 10 MV flattening filter-free photon beams, respectively. The theoretical ion collection efficiency was 0.990 for a 10 MV flattened photon beam with a dose rate of 3 Gy·min^{-1}. It is suggested that the collected charge decreased because of the short time intervals of the beam pulse compared with the ion collection time. Thus, it is important to correctly choose the pulse repetition frequency, particularly when flattening filter-free mode is used for absolute dose measurements.

Keywords: liquid ionization chamber; dosimetry; photon therapy; electron therapy; ion recombination

INTRODUCTION

Small-field irradiation with a high dose rate is becoming common these days. Liquid ionization chambers (LICs) are advantageous because of their high sensitivity and small perturbations, particularly for absolute dose measurement of small irradiation fields with a low dose rate [1]. The high sensitivity of LICs enables the performance of measurements with high spatial resolution and statistics, even in a low-dose-rate radiation field. The nearly water-equivalent stopping power of the liquid reduces the disturbance of the radiation field due to the detector itself. However, there have been reports of a decrease in LIC ion collection efficiency under high-dose-rate irradiation [2, 3]. This characteristic arises from the significant ion recombination because of the high ionization density. There are two types of recombination: initial and general ion recombination. Air-filled ionization chambers exhibit both types of recombination, which are corrected by the two-voltage method [4, 5], since the initial recombination is negligible. On the other hand, the effect of the initial recombination is significant for LICs. Methods of recombination correction such as the three-voltage and two-dose-rate methods were studied by Pardo-Montero and Gómez [6], Tölli *et al.* [7] and Andersson and Tölli [8]. They are measurement-based correction techniques and are used in the clinical field [9, 10].

Medical linear accelerators are used all over the world nowadays. They produce pulsed photon or electron beams for radiation treatment. The characteristics of LICs differ depending on whether a continuous or pulsed beam is used. Therefore, different approaches are required depending on the type of beam utilized. The dose rate of the pulsed beam is determined by dose per pulse and pulse repetition frequency. General recombination has a dependency on the dose per pulse. Lang *et al.* carried out measurements of ion recombination correction factors for several chambers, including the microLion (PTW, Freiburg, Germany), a commercially available LIC, with several doses per pulse [11]. They concluded that there were dependencies on both the dose per pulse and the pulse frequency, which resulted in a decrease in the ion collection efficiency by 6% at the maximum dose rate. In fact, many studies have been carried out on the dependency of the ion collection efficiency on the dose per pulse. However, there are fewer reports concerning its dependency on the pulse repetition frequency.

In this study, we focused on the dependency of the ion collection efficiency of LICs on the pulse repetition frequency of photon and electron beams. The LIC was irradiated with various dose rates while the dose per pulse was kept constant in order to investigate in detail the effect of the frequency alone. Although the frequency dependence had no influence on the dose distribution measurements, it was important for absolute dose measurements.

MATERIALS AND METHODS

Measurements

MicroLion (PTW, Freiburg, Germany), a manufactured LIC, was used for this study. It had a sensitive volume of 0.0017 cm^3 and was filled with isooctane. The nominal operation voltage was 800 V. Since this is higher than that commonly used for air-filled chambers, an external power supply was used.

Photon and electron beams from the TrueBeam (Varian Medical Systems, Palo Alto, USA) linear accelerator irradiated a Blue Phantom (IBA, Louvain-La-Neuve, Belgium) water phantom within an area of $10 \times 10\ cm^2$. The source-to-surface distance was set at 100 cm. The microLion was set at a depth of 10 cm for the photon beams, and at a depth planned to achieve a maximum dose for the electron beams. The changes in the collected charge were measured with various dose rates from 0.4 to 24 $Gy{\cdot}min^{-1}$ (40–2400 monitor units (MUs) per min) for the photon beams. Flattening filter-free (FFF) mode was used for the photon beams, with dose rates from 4 to 24 $Gy{\cdot}min^{-1}$. Dose rates of 1–10 $Gy{\cdot}min^{-1}$ and 0.4–10 $Gy{\cdot}min^{-1}$ were used for the 6 and 15 MeV electron beams, respectively.

The change in the dose rate resulted in a difference in the pulse repetition frequency of the beams, while the dose per pulse remained constant. The dose per pulse was measured to be 0.27, 0.71, 0.30 and 1.22 mGy for 6 MV, 6 MV FFF, 10 MV and 10 MV FFF, respectively with a 0.6 cm^3 air-filled ionization chamber. The times between two pulses of TrueBeam were measured by Lang *et al.* [11] using a Delta4 phantom (ScandiDos, Uppsala, Sweden); they showed the shortest time between two pulses of 2.8 ms in all the measured times for 6 and 10 MV photon beams, including FFF mode.

Theory

A method for evaluating the general correction efficiency has been proposed by Johansson *et al.* [12]. The theory is based on Boag's theory and has been modified for LICs. As for the pulsed beams, the time interval of the pulses should be sufficiently longer than the ion collection time. The general collection efficiency f is defined as:

$$f = \frac{1}{u} \ln(1 + u),$$

where

$$u = \frac{ih}{\varepsilon_r \varepsilon_0 \pi r_c^2 \nu U}.$$

i is the theoretical current, ε_r the relative permittivity of the liquid, ε_0 the permittivity of free space, r_c the radius of the sensitive volume, ν the pulse repetition frequency, U the applied voltage and h the distance between the electrodes. h was 3.5×10^{-4} m. The current is considered to be linear to the applied voltage, shown as

$$i = \left(c_1 + \frac{c_2}{h} U\right) \dot{D},$$

where $\dot{D}$ is the dose per pulse, and c_1 and c_2 are constants. The collected charge was measured with various voltages from +400 to +970 V. The microLion was set at a depth of 10 cm in the water phantom and irradiated with a 10 MV photon beam with a dose rate of 3 $Gy{\cdot}min^{-1}$. $\dot{D}$ was 0.296 mGy at the depth of the sensitive volume. The pulse repetition frequency was 180 Hz.

RESULTS

Figure 1 shows the relative collected charge as a function of dose rate for (a) the flattened and (b) the FFF photon beams. The collected charge was normalized to the lowest dose rate for each beam. The relative collected charge decreased as the dose rate increased for all energies of the photon and electron beams. The relationships were almost linear in flattened photon and electron beams, while the magnitude of the decrease became greater with higher dose rate in FFF photon beams. Especially for the 10 MV FFF beam, two slopes could be seen connected at 9 $Gy{\cdot}min^{-1}$. The ion collection efficiencies decreased by 0.8% and 0.3% at a dose rate of 12 $Gy{\cdot}min^{-1}$ with 6 and 10 MV photon beams, respectively, compared with those at 4 $Gy{\cdot}min^{-1}$. The largest decrease was observed to be 1.8% at 18 $Gy{\cdot}min^{-1}$ with the 10 MV FFF beam.

Figure 2 shows the relative collected charge as a function of dose rate for the electron beams. A linear relationship was also observed. Decreases in the sensitivity were 0.6% and 0.5% at 10 $Gy{\cdot}min^{-1}$ with the 6 and 15 MeV electron beams, respectively, compared with those with 1 $Gy{\cdot}min^{-1}$.

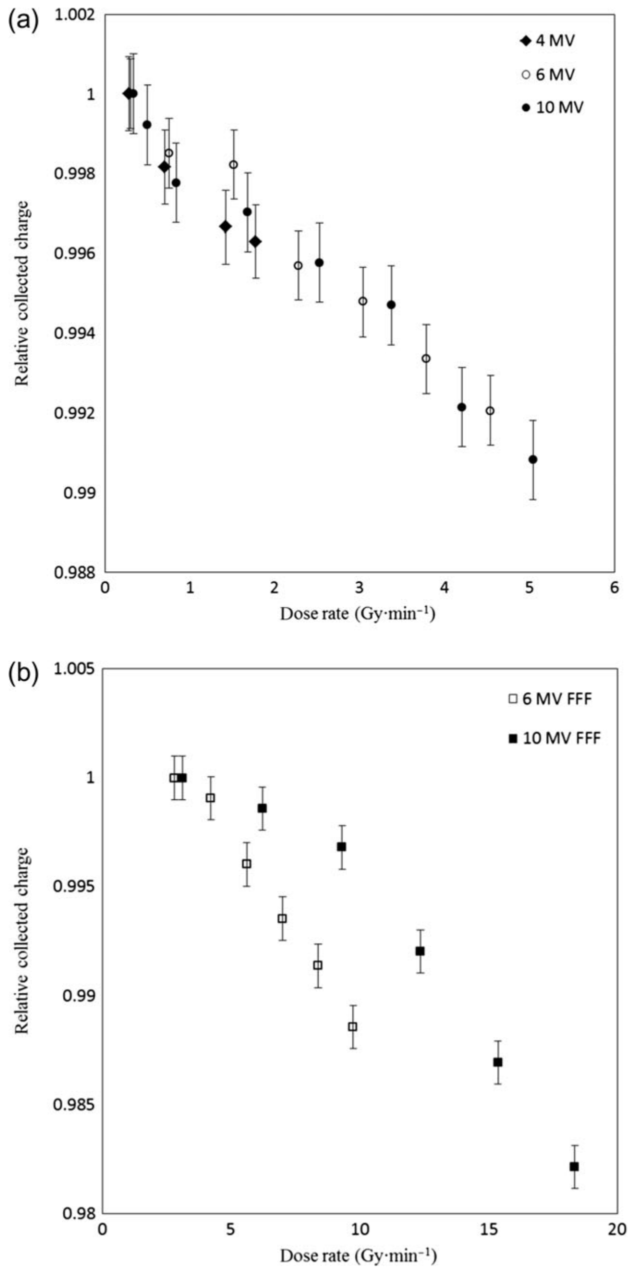

Fig. 1. Relationships between the dose rate and the relative charge collection for (a) flattened and (b) FFF photon beams. The relative collected charge was normalized to the lowest dose rate of each beam. FFF = flattening filter-free mode.

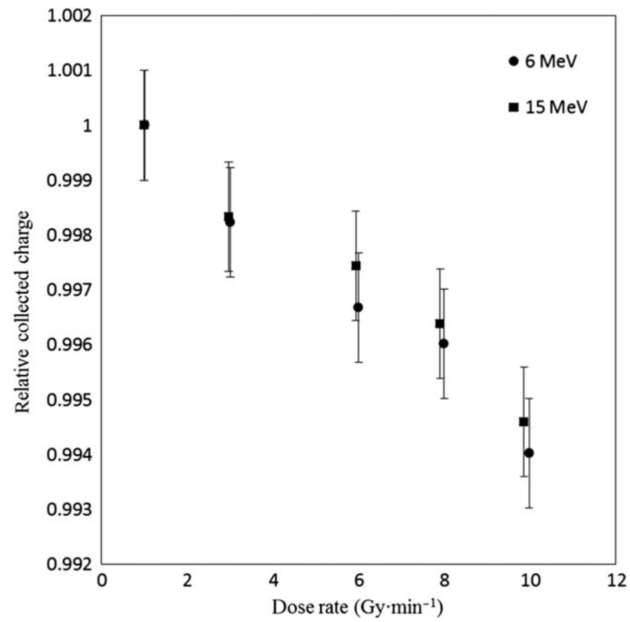

Fig. 2. Relationships between the dose rate and the relative charge collection for the 6 and 15 MeV electron beams. The relative collected charge was normalized to the lowest dose rate of each beam.

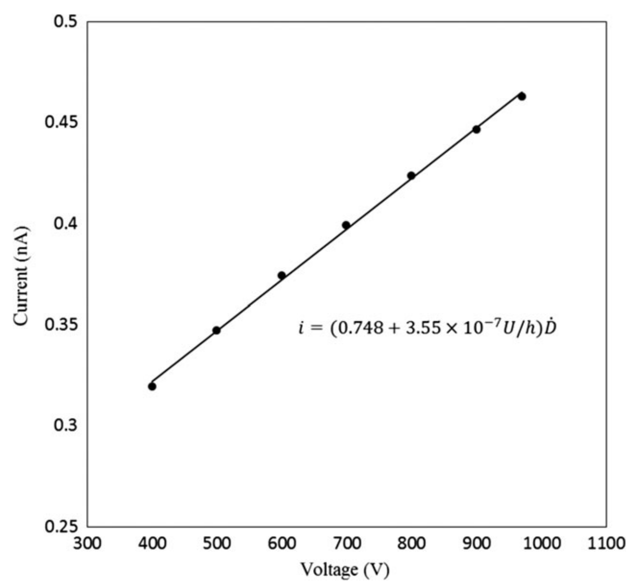

Fig. 3. Electric current as a function of applied voltage. The line represents the linear fitting result of the measured values. The dose per pulse $\dot{D}$ was 0.296 mGy at the depth of the sensitive volume.

There was a linear correlation between the voltage and the collected charge (Fig. 2). The decrease in the collected charge shown previously was mainly caused by the ion recoupling because of the high frequency of the pulse.

Figure 3 shows the electric current as a function of the applied voltage. The result of the linear fitting of the measured values is indicated by the line. Fitting parameters c_1 and c_2 were acquired, and the general collection efficiency f obtained was 0.990.

DISCUSSION

The collected charge decreased as the dose rate increased for all energies of the photon and electron beams. The decrease was within 1.0% for all energies of the flattened photon and electron beams. As for the FFF photon beams, there were 1.1% and 1.8% decreases at the maximum dose rate with 6 and 10 MV, respectively.

Since the dose per pulse was kept constant in this study, only the pulse repetition frequency changed with dose rate. Generally, the time between adjacent pulses (time interval) should be greater than the ion collection time of the chamber; otherwise, the collection efficiency decreases. The collection time of the microLion was 5.3 ms at 800 V, which almost corresponded to the time interval of 3 $Gy{\cdot}min^{-1}$ with the flattened photon beam. The results showed, however, a constant decrease in the collected charge as the frequency increased, even in the region lower than 3 $Gy{\cdot}min^{-1}$. The lowest dose rate had a time interval of ~17 ms. In FFF mode, one in every four or five pulses were not used to adjust the dose rate, while the dose per pulse was kept constant, as reported by Lang *et al.* [11]. The change in the frequency due to the pulse omission was considered to be the cause of the non-linear decreases in the relative collected charge in the FFF photon beams. The use of higher voltages decreased the collection time and improved the collection efficiency. Since the maximum voltage for the microLion was limited to ±1000 V, the collection efficiency could not be significantly improved by applying a higher voltage.

The ion collection efficiency f obtained was 0.990 by theoretical calculation and is in good agreement with previous studies [11, 12]. With this value, the relative collected charge shown in Fig. 1 could be converted to the absolute ion collection efficiency.

In this study, only the effect of the pulse repetition frequency was investigated. As reported by Lang *et al.*, the ion collection efficiency of LICs have dependency on both the pulse frequency and the dose per pulse. They reported that the efficiency decreases to 0.94 at the maximum dose rate with a 10 MV FFF beam. With a comparison of two pulse frequencies in their report, the decreases were observed for all energies of flattened and FFF beams, which is consistent with our results. Therefore, although choosing the lowest frequency may improve the efficiency, it still remains low because of the dose per pulse. The dose per pulse is independent of the dose rate options in TrueBeam and changes along the depth or along the off-axis. It may result in distortion of the percentage depth dose or off-center ratio curve when a measurement is done using an LIC. When a relative dose measurement is performed, the change in the dose per pulse should be considered, rather than the pulse repetition frequency. The same effect of general ion recombination can be observed in commonly used devices based on the use of a liquid ionization chamber, such as one- or two-dimensional chamber arrays. This can be a cause of disagreements in dose distribution analysis for stereotactic radiation therapy with a high dose rate [13].

The dose rate dependency of ion collection efficiency in a liquid ionization chamber was examined. Decreases in the collected charge were within 1% for all the flattened photon and electron beams, while they were 1.1% and 1.8% for the 6 and 10 MV flattening filter-free photon beams, respectively. The results suggested that ion collection efficiency could be improved by 1% by choosing the lowest dose rate option in Linac. This study provided characteristic information about general recombination in LICs using an experimental method.

CONFLICT OF INTEREST

There is no conflict of interest in relation to this study.

FUNDING

This work was supported by the Japan Society for the Promotion of Science (JSPS) KAKENHI Grant Number JP16K01405.

REFERENCES

1. Wickman G, Johansson B, Bahar-Gogani J et al. Liquid ionization chambers for absorbed dose measurements in water at low dose rates and intermediate photon energies. *Med Phys* 1998; 25:900–7.
2. Wickman G, Nystrom H. The use of liquids in ionization chambers for high precision radiotherapy dosimetry. *Phys Med Biol* 1992;37:1789–812.
3. Stewart KJ, Elliott A, Seuntjens J. Development of a guarded liquid ionization chamber for clinical dosimetry. *Phys Med Biol* 2007;52:3089–104.
4. Boag JW, Currant J. Current collection and ionic recombination in small cylindrical ionization chambers exposed to pulsed radiation. *Br J Radiol* 1980;53:471–8.
5. Weinhous MS, Meli JA. Determining Pion, the correction factor for recombination losses in an ionization chamber. *Med Phys* 1984;11:846.
6. Pardo-Montero J, Gómez F. Determining charge collection efficiency in parallel-plate liquid ionization chambers. *Phys Med Biol* 2009;54:3677–89.
7. Tölli H, Sjögren R, Wendelsten M. A two-dose-rate method for general recombination correction for liquid ionization chambers in pulsed beams. *Phys Med Biol* 2010;55:4247–60.
8. Andersson J, Tölli H. Application of the two-dose-rate method for general recombination correction for liquid ionization chambers in continuous beams. *Phys Med Biol* 2011;56:299–314.
9. Task Group 21, Radiation Therapy Committee, AAPM. A protocol for the determination of absorbed dose from high-energy photon and electron beams. *Med Phys* 1983;10:741–71.
10. Almond RP, Biggs JP, Coursey MB et al. AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams. *Med Phys* 1999;26:1847–70.
11. Lang S, Hrbacek J, Leong A et al. Ion-recombination correction for different ionization chambers in high dose rate flatteningfilter-free photon beams. *Phys Med Biol* 2012;57:2819–27.
12. Chung E, Davis S, Seuntjens, J. Experimental analysis of general ion recombination in a liquid-filled ionization chamber in high-energy photon beams. *Med Phys* 2013;40:6.
13. Knill C, Snyder M, Rakowski JT et al. Investigating ion recombination effects in a liquid-filled ionization chamber array used for IMRT QA measurements. *Med Phys* 2016;43:5.