Thermal and scatter effects on the radiation sensitivity of well chambers used for high dose rate Ir-192 calibrations

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High dose rate (HDR) iridium sources must be calibrated regularly because of the short half-life of Ir-192. High dose rate sources can now be calibrated using a new well-type chamber that allows easy, reproducible source calibrations. The chamber includes a styrofoam insulator that surrounds the source in the well. A study of the radiation sensitivity of the well chamber exposed to an HDR Ir-192 source at two different activities (300 and 230 GBq) revealed that the sensitivity of the chamber varies by as much as 1.1% as the chamber is moved toward a scattering surface. Second, with the styrofoam insulator removed, the air temperature within the ion collecting volume increased during exposure, causing a gradual decrease in chamber sensitivity of 0.15% in 30 min. This temperature increase was caused by heat transfer from radiation emitted by the Ir-192 source, and diminished as the source decayed. However, with the styrofoam insulator around the central aluminum tube in the well, the source cannot heat the collecting volume and thus thermal equilibrium between the ion collecting volume and its environment is maintained throughout an exposure. The radiation sensitivity of the commercial well chamber was found to be constant for exposure times of 30 min.

Key words: Ir-192, brachytherapy, heat convection, well-type ionization chambers

I. INTRODUCTION

High dose rate (HDR) brachytherapy using an Ir-192 source installed in a remote afterloader (Microselectron remote afterloader, Nucletron Trading B.V., Leersum, Holland.) is a common treatment modality. Its popularity is evidenced by the large number of patients referred for therapy and by the increasing number of anatomical sites targeted for treatment. The short half-life of the Ir-192 source (73.83 days[1]) necessitates a source change approximately every 3 months. Current standard source calibration methods require the use of thimble ionization chambers, complex experimental setups, and time consuming data analysis procedures.[2] Recently a new well-type ionization chamber, designed by Attix (F.H. Attix, U.S. Patent applied for by the Wisconsin Alumni Research Foundation, 1990.),[2] was introduced. Once calibrated, this chamber simplifies the calibration of HDR Ir-192 sources.

The well-type chamber has close to a 4π measurement geometry and a high level of geometrical reproducibility. Its use is simple; the HDR Ir-192 source is inserted into a plastic bronchial catheter that fits closely inside an aluminum tube located on the axis of the chamber. This thin-walled tube guides the catheter to the bottom of the well. Studies of ionization current as a function of the distance of the source from the bottom of the well have been reported,[2] and the existence of a flat maximum for reproducible calibrations has been established. The well chamber is calibrated by measuring the ionization current for an Ir-192 source previously calibrated by the inverse-square method using a calibrated thimble chamber.[2] The stability of the well-type chamber was $\pm 0.1\%$ for repeated current measurements of an Ir-192 HDR source during a one month time period.[3]

Further measurements with the original chamber showed a small gradual decrease in ionization reading when the source remained inside the well for more than 30 min. Attix (F.H. Attix, personal communication.) identified this as a heating problem, and redesigned the chamber to include a styrofoam insulating sleeve around the central source tube, as shown in Fig. 1. All chambers of this type, including the new commercial model (Standard Imaging, Middleton, WI 53562.), are so equipped.

This heating effect along with concern about possible variations in the scatter contribution to the ionization current of the well-type chamber motivated the studies reported in this paper.

II. EFFECTS OF SCATTER RADIATION ON CHAMBER RESPONSE

Unlike most radiation detectors, the sensitivity of the well-type chamber is only weakly dependent on the proximity of the chamber to nearby scattering surfaces such as walls, floors, etc., because the source in the well is so close to the sensitive volume. The outside aluminum wall of the commercial chamber (Standard Imaging, Middleton, WI 53562.) is 2 cm thick and attenuates most scattered low energy photons. However, some scatter radiation arising outside the chamber, and directed back toward it, may contribute to the ionization within the collecting volume. Figure 2 shows a plot of the ionization current as a function of the distance between the chamber and a concrete wall. All readings are normalized to the ionization current

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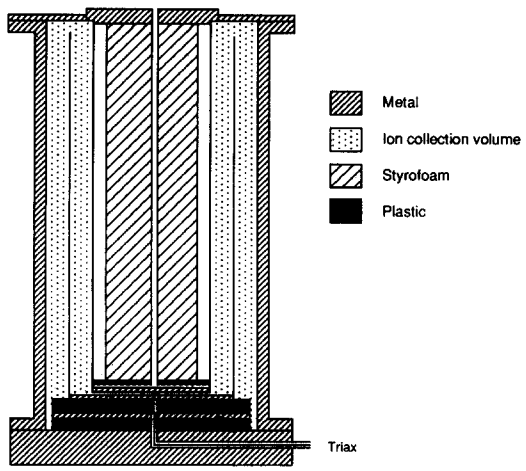

FIG. 1. Schematic diagram of the well-type chamber designed by Attix showing the cylindrical styrofoam sleeve around the central aluminum shaft. The styrofoam sleeve slows the transfer of heat between the source and the ion collecting volume by inhibiting convection currents within the chamber.

obtained with the chamber in the center of the room (8×6 m^2). The ionization current gradually increases as the chamber is moved from the center of the room, where few room-scattered photons reach the collecting volume, to a position in contact with a wall or the floor, where the signal exhibits maximum scatter radiation contribution. Signal increase is negligible until the chamber is within 25 cm of a wall or 7 cm of the floor where the scatter radiation contribution reaches 0.1%. With the chamber in contact with a wall or the floor, the ionization current was 1.1% and 0.3% higher, respectively, than that measured in the center of the room.

The geometry and method used for the chamber calibration normally involves minimum room scatter. Source calibrations must be done with the chamber in a similar minimum scatter position. Therefore, the chamber should be more than 25 cm from a wall or any other scattering material to maintain a scatter radiation contribution less than 0.1%. If the chamber is used for source quality-assurance measurements, it may be practically useful to mount the chamber on a wall. In this case, the scatter radiation contribution must be accounted for, either as a correction factor measured in the room and applied to all ionization current measurements or by calibrating the chamber fixed to the wall. However, in view of the steepness of the scatter radiation contribution curve within 25 cm of a wall, maintaining a greater distance is advisable.

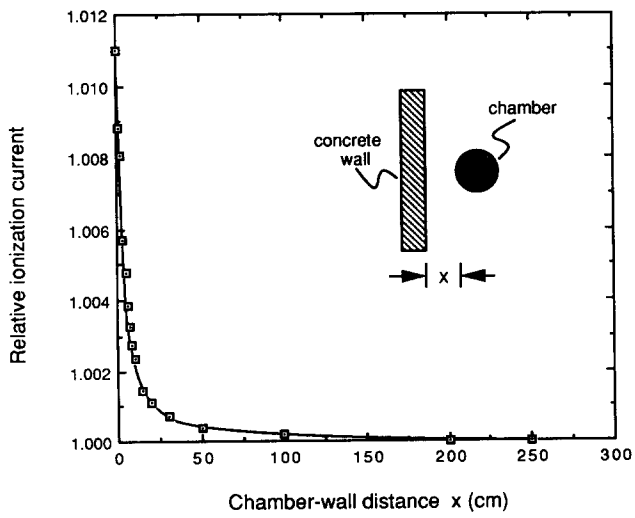

FIG. 2. The relative ionization current in Attix's well chamber during exposure to an HDR Ir-192 source as a function of the distance between the chamber and a concrete wall. A similar, although less pronounced, effect is seen as the chamber is moved towards the floor. The experimental geometry is shown in the inset to the figure.

III. EFFECTS OF THERMAL GRADIENTS ON CHAMBER RESPONSE

A change in chamber radiation sensitivity also results from variations in the temperature and pressure of the gas (air) within the collecting volume of the well chamber. Since Attix's chamber is open to the atmosphere, ambient temperature and pressure fluctuations affect the chamber sensitivity; corrections are made using the conventional temperature-pressure gas law equations.

Through the process of radioactive decay an Ir-192 source converts mass into energy. The radioactive source and its surroundings are warmed by absorption of the radiation, e.g., beta particles and γ rays. Even if ambient temperature conditions remain constant, the HDR Ir-192 source, through energy deposition and heat transfer mechanisms, will elevate the temperature of the metal and air comprising the well chamber producing a decrease in the radiation sensitivity of the chamber if the styrofoam insulator is removed. Correcting for a decrease in chamber sensitivity due to source heating is impossible since, in the absence of the styrofoam insulator, there is no direct correlation between ambient air temperature, which can be measured, and the temperature of the air inside the ion collecting volume, which cannot be easily measured.

To study the magnitude and dynamics of the heating effect, the styrofoam insulator was removed and thermocouples (Trendicator 400 A Type T thermocouple, Doric Scientific, San Diego, CA 92123.) were inserted into three different cavities within the well chamber allowing temperatures inside the chamber to be monitored as a function of time. One thermocouple was placed in contact with the outside wall of the aluminum tube half way down the well. Two others were placed within the ion collection volume on either side of the collecting electrode, not in contact with any metal, at the same level as the first thermocouple. The source ($\sim$300 GBq) was positioned at the level of the thermocouples and exposed for 999 s. In addition to the temperature profiles, the ionization current also was monitored during the exposure. The room temperature was 23.2 °C. As shown in region I of Fig. 3(a), the temperature of the tube initially rose very quickly, reaching a maximum value of 1.00 °C above room temperature in $\sim$4 min. The temperature of the air in the inner-most collecting volume rose by only 0.15 °C, indicating that heat was being transferred, at a slow rate, from the source to the collecting

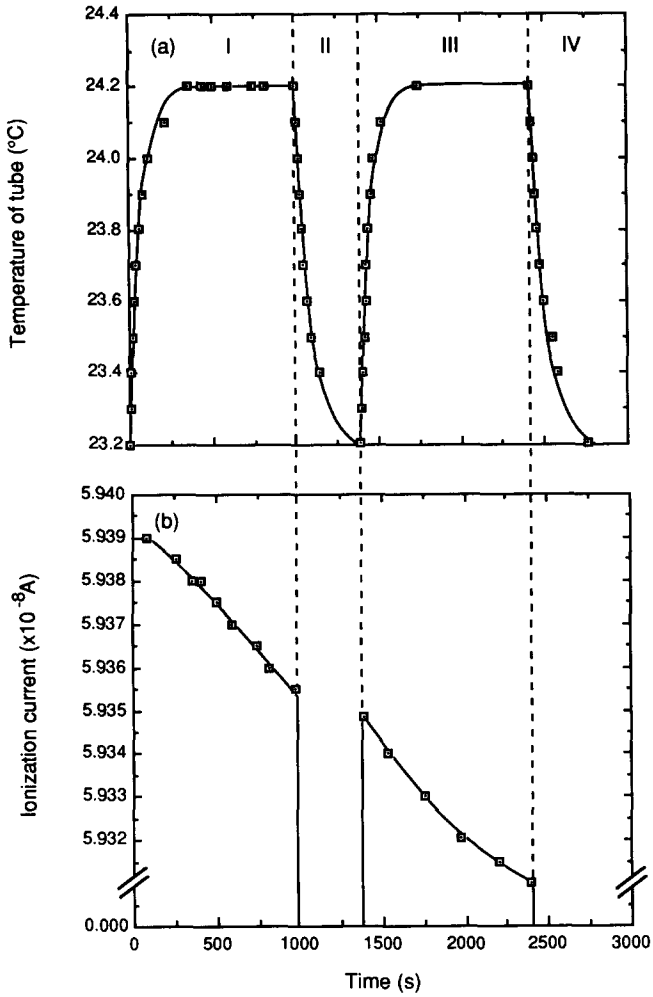

FIG. 3. (a) Temperature profiles of the central aluminum tube within the well chamber. Regions I and III represent temperature change of the shaft during exposure of the chamber to an Ir-192 HDR source. Regions II and IV show cooling of the tube after exposure. (b) The ionization current measured with a well chamber without a styrofoam insulator during the exposures. For regions II and IV the ionization current is zero as the exposure was interrupted to allow the aluminum tube to cool to room temperature.

volume. Since the ion collecting volume is vented to the atmosphere, this increase in air temperature lowers air density. Hence region I of Fig. 3(b) shows a steady decrease in the ionization current over the exposure time. Although this effect is small (-0.1%), it correlates with the air temperature change in the ion collecting volume. The air within the outer collecting volume showed no measurable temperature increase during 30 min of exposure, probably due to the presence of the massive outer aluminum wall which serves as a heat sink.

Heat transfer between the cavities inside the chamber occurs through both conduction and convection.[4] First, a thin film of stagnant air next to the central tube absorbs heat, which is then transferred via convection currents to a second stagnant layer of air next to the well wall. Thermal conduction through the thin chamber wall (~ 0.31 g/cm^2) ultimately causes an increase in the temperature of the air within the collecting volume, although the air temperature does differ on the two sides of the collecting electrode. This temperature gradient inside the collecting volume is due in part to the collecting electrode, which reduces the thermal transfer between the two volumes, and to the inefficient convection of heat through the chamber volume, in addition to the heat sink effect noted above.

The observed decrease in ionization current is due both to the temperature rise and to source decay (0.01% in 15 min): Since atmospheric conditions were constant during the exposure, variation in ionization current remaining after correction for decay can be explained theoretically by an average increase of 0.14 °C in air temperature within the total chamber collecting volume. The temperature increase of the air in the collecting volume is not as large as that of the aluminum tube because heat transfer from the source to the air in the chamber collecting volume involves several steps and is inefficient, as described above. If the exposure is continued for longer periods of time, more heat will be transferred to the collecting volume, increasing the air temperature and causing a further decrease in the ionization current. This was verified by repeating the exposure for an additional 999 s once the central shaft had cooled to room temperature. As shown in regions III of Fig. 3, the temperature of the aluminum tube followed a similar profile to that in the first exposure and, as expected, the ionization current decreased even more. The temperature of the air within the collecting volume, however, had not reached room temperature when the second exposure was begun, and therefore the initial ionization current in the second exposure, corrected for source decay, was less than the initial current in the first exposure. The temperature gradient within the collecting volume was still present. If these exposures were repeated many more times, eventually an equilibrium temperature between the two collecting volumes, the environment, and the source would be reached any further signal decrease would then be due to source decay alone.

IV. VERIFICATION OF RESULTS

The experiments described above were repeated after the Ir-192 source had decayed to 230 GBq. As expected, during exposure, the ionization current in a chamber positioned against a wall was still 1.1% higher than the current measured when the chamber was moved into a minimal scatter environment in the center of the room. For a chamber with the styrofoam insert removed and exposed for 999 s, the measured increases in the temperature of the aluminum tube within the well and the air within the collecting volume were 0.60 °C and 0.10 °C, respectively. The decrease in the ionization current over the exposure time, corrected for source decay, was approximately 0.04%. The dynamics of the heat transfer between the source and air in the ion collecting volume were similar to those seen for exposure with a higher activity source. Again, the effect of the thermal transfer was small but measurable. A source of lower activity produces less radiation energy that can be transferred between the cavities of the chamber and has less effect on the temperature of the air in the collecting volume than a higher activity source. As the source decays further, an activity level will eventually be reached where

the air in the ion collecting volume will no longer be heated by the source and any signal decay over an exposure can be explained by source decay alone. Not surprisingly, when the styrofoam insert was replaced within the well the ionization current was constant (corrected for source decay) and there was no measurable temperature change in the ion collecting volume over a 999-s exposure.

V. CONCLUSIONS

Attix's well chamber simplifies routine calibration of HDR Ir-192 sources, although there are two factors that can alter the sensitivity of the chamber. If absolute ionization current readings are required, the chamber should be used in a location that provides minimum room scatter. When placed near a wall we measured up to a 1.1% error in ionization current arising from scatter radiation contribution to the signal. The temperature of the air within the collecting volume of a well chamber depends on the ambient temperature and, in the absence of the styrofoam insulator, also on the source activity. Since direct temperature measurements of the air within the collecting volume of the chamber are not possible, it must be ensured that there is no disequilibrium between the temperature of the air in the collecting volume and the environment. The styrofoam insulator, which prevents the transfer of heat from the source to the collecting volume, should therefore always be kept in place when calibrating or operating these chambers. In the commercial chamber, equilibrium between the collecting volume and the environment was maintained throughout the duration of our exposure (30 min) and the chamber calibration factor was valid independent of the source activity.

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