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HIGH PRECISION IN DOSE DELIVERY: ROUTINE USE OF A MICROCOMPUTER

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1. Abstract

For the last four years a high precision dose delivery system for neutron beam therapy has been in use at the Fermi National Accelerator Laboratory. This system would be equally suitable for photon, electron, or charge particle therapy.

This two-step method consists of

1. calibration of the ionization chamber, immediately before calibration of the therapeutic beam; and
2. calibration of the therapeutic beam.

Precision jigs and laser beams are used to position the ionization chamber first with respect to a ^{137}Cs-source, and then in the neutron beam. Errors in most of the critical measurements are cancelled out by the procedures used. A microcomputer system based on a Motorola M6800 CPU does all the calculations and maintains necessary book-keeping. This system essentially eliminates human error except for the possibility of mispositioning the ionization chamber during calibration of the neutron beam.

Introduction

In the delivery of radiation for therapeutical purposes, the long term reproducibility of daily doses is as important as the accuracy of the absolute calibration of the dose monitor system. At the Fermilab Neutron Therapy Facility (NFT), precision in dose delivery is achieved through the use of a microcomputer for daily checks on the calibration of the probe ionization chamber in a ^{137}Cs irradiator. This probe is then used to check the calibration of the neutron beam monitors. The choice of a highly reproducible geometry and of the same circuitry for both daily calibrations cancels out most sources of uncertainties.

This method effectively compares the dose delivered by the neutron beam to the exposure in a reference photon field.

A small computer based on the M6800 central processor unit (CPU) does the measuring, calculating, book-keeping and controlling of dose delivery to patients.

3. The Microcomputer System

The microcomputer system itself has been

described elsewhere [1], so only a short description is included here for completeness. This system, built around the M6800 CPU, is designed as a bus-oriented card file that accepts up to sixteen printed circuit cards. An operational system contains a CPU card, a controller, enough memory cards to contain the programs for the application and an assortment of both analog and digital input/output (I/O) cards to interface with the external equipment. These cards are accessed by the CPU as though they were memory locations, so that a single instruction transfers data to and from registers on the cards. Much of digital I/O for these systems is accomplished using the Motorola 6820 peripheral interface adapter (PIA). These LSI circuits are programmable and provide interrupt handling for the computer as well as interface to a variety of external equipment. Two separate microcomputers are actually used in the system.

3.1 The Beamline Microprocessor

The first system is the beamline microcomputer, a front end processor that functions as the real-time data and control computer for the NTF (synchronized to the 15 Hz clock of the Fermi

National Accelerator Laboratory linear accelerator). The information acquired by it includes all the analog data associated with both the beam-line operation and the safety interlocks as well as all transmission ion chamber integrators, thermocouple and barometer digital information. Because the beamline microcomputer is an interrupt-driven, dedicated real-time processor, it can provide accurate timing for functions such as source calibration of ion chambers and synchronous integrator resets. The beamline system communicates with the main accelerator computer and with the medical microcomputer, another M6800 system located in the treatment control room.

3.2 The Medical Microcomputer

The medical microcomputer is a disk-based system that supports the console in the NTF control room. The system includes a CRT screen terminal for the console, a line printer to provide permanent records, a real time clock to enable treatment and calibration records to be dated and a dual spindle floppy disk unit for program and data storage. All interactions of the medical personnel with the beam controls and the beamline system occur through the keyboard associated with the treatment microcomputer.

4. Photon Calibration of Probe Ionization Chamber

The probe ionization chambers used at the NTF are spherical chambers, EG&G model I-17 [2]. They have a nominal volume of 1 cm^3, A-150 T. E. plastic walls 5 mm thick and outside diameter of 2.3 cm.

4.1 ^{137}Cs Irradiator

For the purpose of checking the photon sensitivity of the probe ionization chamber, a cylindrical irradiator was built to ensure maximum geometrical reproducibility. A hermetically sealed flat cylinder containing ^{137}Cs lies at the bottom of a funnel-shaped lead well. This well is coaxial with the irradiator. At about 15 cm above the source, an insulated hollow thin wall steel tube crosses the irradiator wall perpendicularly to the axis of the well. The inner diameter of this tube is just large enough to enable the probe ionization chamber to slide in snugly. One end of the tube is plugged by an Al stopper, designed to position the center of the probe chamber on the axis of the well, above the source. The other end of the tube is open to receive the probe chamber. The irradiator has a holder to keep the stem of the chamber horizontal. A brass plug blocks this opening when the irradiator is not in use. Two thermocouples monitor the

temperature of the irradiator. The first is actually imbedded in the Al stopper and measures the temperature of the irradiation area. The second is attached to the outside casing of the irradiator but is thermally insulated from the surroundings. Their readings differ by at most 0.1°C. The ^{137}Cs irradiator is kept in the treatment room. Thus, the temperature differences between the probe ionization chamber, ^{137}Cs irradiator, the beam calibration phantom, and ambient about the therapy isocenter are very small. The ionization chamber orientation (rotation around the axis of symmetry) is always the same.

4.2 Electronics

The probe ion chamber is polarized at +600 V from a stabilized power supply. Its charge is collected by a high quality electrometer integrator having a capacitor of value C in the feedback loop. The voltage across this capacitor is digitized by a 12-bit analog-to-digital converter (ADC) and read by the microcomputer.

4.3 Calibration Procedure

Every morning the probe chamber is positioned in the ^{137}Cs irradiator, the polarizing voltage is applied and the system is allowed to stabilize for 10-15 minutes. When a calibration is requested

through the microcomputer, the integrator is unclamped and 33.3 msec later both the initial voltage (V_i) and initial time (t_i) are recorded. About 70 seconds later, when the voltage reaches a preset limit (about 7 V) the final time and voltage (t_f and V_f) are again recorded and the integrator is clamped. This procedure is then repeated any requested number of times, typically 9, with sufficient time given for the capacitor to fully discharge between cycles. For each cycle, the value $\Delta V/\Delta t$ is computed (where $\Delta V = V_f - V_i$ and $\Delta t = t_f - t_i$) and corrected for gas density effects due to temperature and pressure effects (TPC1). Temperature and pressure are read by the thermocouple in the irradiator and a digital barometer. At the end of the run, a mean and standard deviation of the corrected $\Delta V/\Delta t$ value are displayed. The mean current ($C\Delta V/\Delta t$), plus a knowledge of the source strength decay, is used to evaluate the photon sensitivity G_γ(R/C) of the ionization chamber based on previous calibration of the irradiator. This value of G_γ is stored and used in the subsequent neutron beam calibration. At midnight each day, this stored value is erased, forcing a fresh photon calibration each day.

4.4 Accuracy of Photon Calibration

The ^{137}Cs irradiator is basically a very reproducible constancy check source. It is being used as a transfer standard, provided the chamber geometry does not change, by calibrating it with a chamber of know sensitivity. For this purpose, one ionization chamber is sent to N.B.S. once a year for calibration in a ^{60}Co field, and it is used to verify the calibration of the ^{137}Cs irradiator in terms of ^{60}Co for E.G.&G. IC-17 ionization chambers. Successive N.B.S. calibrations of the ionization chamber and calibrations obtained with the calibrated irradiator agree within $\pm$ 0.5% .

4.5 Alternate System and Constancy of Electronics

Since all computer systems are prone to failure, a back-up system is also used. It consists of a digital electrometer (Keithley 616) connected directly to the chamber by a low noise coaxial cable, and a 0.1 sec resolution timer. This system is used weekly to rederive the source strength, using as input the value of $G\gamma$ and gas density correction TPC1 obtained from the microcomputer just before. A constant value for the exposure rate $\dot{X}_0$ (corrected for decay) would indicate that both electronic systems are working properly, as fluctuations in either would be unlikely to cancel out exactly. The value of $\dot{X}_0$ as monitored over the

last two and a half years has a standard deviation of 0.2%.

5. Calibration of Neutron Monitors

5.1 The Transmission Chambers

The neutron beam is monitored through a pair of transmission ionization chambers located downstream from the neutron source. They consist of parallel aluminum plates spaced 2.9 mm and ceramic insulators. They are enclosed in the same air volume and are polarized to +1500 V. The chambers are open to the atmosphere. A thermocouple is permanently in thermal contact with the chamber casing. Thus, the gas density correction factor, TPCX, for the transmission chambers can be continuously calculated and used.

5.2 Calibration Phantom

To calibrate the neutron beam monitors, the probe ionization chamber is positioned in the neutron beam inside a calibration phantom. This phantom consists of a parallelepiped 15x15x16 cm^3 made of A-150 tissue equivalent plastic [3]. It is mounted in a 1.25 cm thick lucite holder that holds

a thermocouple and leaves the entrance face open. It is marked to allow its precise positioning in the neutron beam using the available patient localization laser beams.

5.3 Calibration Procedure

Following the photon calibration, the probe chamber is inserted in the phantom without disturbing the H.V. and signal connections. The assembly is then positioned at the treatment isocenter at the center of a 10x10 cm^2 neutron beam. The thermocouple is connected to the microcomputer. Thus the gas density correction factor, TPC5, for the probe chamber can be continuously calculated and used. The transmission chamber integrators are unclamped, read before the beam pulse, read after the beam pulse, and then clamped synchronously with the operation of the Fermilab 200 MeV linac. This means that the output of the transmission chambers is read at 15 Hz. The chamber and phantom are allowed to attain thermal equilibrium during the beam tune-up procedures, prior to the calibration runs. When calibration is requested, the microcomputer unclamps the probe integrators , waits a small time interval and records the probe integrator initial output voltage. Then, it begins integration of the transmission

chambers output voltages. The sum of these voltages, suitably multiplied by a constant and by TPCX, constitute the so called MONITORING UNIT (MU). When the voltage output of the probe integrator reaches about 7 V (the same as in the photon calibration), the actual voltage is recorded, the summation of transmission chamber output voltages is stopped, and the probe chamber integrator is clamped. This procedure can be repeated automatically for a given number of times. The mean and standard deviation of the voltage ratio $\Delta V_n/\Delta V_x$ (the probe and transmission chambers integrator voltage changes) are displayed at the end of the requested number of cycles in the form of dose ratios. The dose to the probe chamber is derived from the mean value of ΔV_n, the value of G_γ previously determined and the gas density correction factor TPC5. This information is used to update a calibration factor KCOR which interprets the corrected output of the transmission chambers (ΔV_x TPCX) in terms of the absorbed dose at the point in the phantom where the probe is located.

5.4 Patient Treatment Monitoring

The final outcome of both the photon and the neutron monitor calibrations is thus an updated value of KCOR, ensuring that the displayed monitor

units (M. U.) are correctly calibrated. This value is used in beam control during patients treatment, as described below. The desired number of monitor units (determined for each field ' the physicist and depending on prescribed dose, collimator, depth of the tumour, wedges and other factors) is entered into the microcomputer by the radiation therapy technologist. These MUs are converted to a limit for the sum of output voltages from the transmission chamber integrator outputs, using KCOR and TPCX. Once the neutron beam is energized, the microcomputer integrates the outputs of the transmission chambers and compares them, at 15 Hz, to the preset limits. The exposure is automatically terminated when the sum of output voltages reach or exceed the preset values. This information, together with other relevant data for the exposures, is continuously displayed and also automatically printed at the end of each exposure for permanent record.

The stored value of KCOR is automatically erased at midnight, forcing a recalibration of the neutron beam monitors each treatment day.

5.5 Check on Patient Treatment Monitoring

As a precaution against computer malfunction, the precision of the patient dose delivery system is

checked daily immediately after the neutron beam calibration described in Section 5.3. The probe chamber output is switched from the microcomputer to the digital electrometer referred to in Section 4.5, the calibration of which is known. A requested number of M.U.s is then delivered to the phantom using the microcomputer. The dose received by the probe chamber is calculated using the known value of the electrometer capacitor, the output voltage change, TPC5, and the value of G_γ obtained the same morning.

6. Precision and Uncertainties

6.1 Accuracy of Absolute Calibration

The total dose from the neutron beam is quoted in rads. No attempt is made to separate neutron and photon contributions. This is standard American practice. The accuracy of the quoted values depends on both the photon calibration of the probe chamber and on the values of the various conversion factors. The former is quoted by N.B.S. as being accurate within 2.0%. The latter have uncertainties of the order of 7-10%, including the uncertainty in the

photon calibration. This situation is common to all high energy neutron beams [4].

6.2 Precision of Daily Calibrations

The procedures outlined in Sections 4 and 5 suffer from few experimental uncertainties, especially when combined.

6.2.1 The value of G_γ in Section 4.3 is obtained from:

$$G_\gamma\left(C\ \Delta V_\gamma/\Delta t\right)\ TPCl = \dot{X}_0\ \exp(-T\ \ln 2/30.0\ yr) \qquad (1)$$

where:

$\dot{X}_0$ is the originally determined exposure rate,

T is the time elapsed since that determination,

ln2/30.0 yr is the decay constant for ^{137}Cs,

TPCl depends on thermocouple readout and a digital barometer and

$C\Delta V_\gamma/\Delta t$ is the ion current collected.

ΔV_γ is measured with an ADC having an absolute accuracy of $\pm$ 0.005 V., Δt is determined by using a 1 MHz quartz controlled oscillator having a long term stability of better than 100 ppm. The thermocouples are checked annually against a precision mercury thermometer traceable to the N.B.S.. The absolute value of these temperature differences is less than 0.2° C. The digital barometer is checked weekly against an anneroid barometer. The standard deviation of these pressure

ratios is 0.1%.

6.2.2 The value of KCOR is section 5.3 is obtained from equating the dose received by the probe chamber to that delivered by the monitors:

$$D = k\ G_\gamma\left(C\ \Delta V_n\right)TPC5 = KCOR\ TPCX\ \Delta V_x = M.U. \quad (2)$$

where:

D is the total (neutron) dose to the probe chamber,

k is a constant including all conversion factors from Roentgens to neutron rads,

$C\Delta V_n$ is the charge collected by the probe in the neutron beam, using the same capacitor and ADC as for the photon calibration,

TPC5 and TPCX depend on readings of their respective thermocouples,

M.U. are the requested monitor units and

ΔV_x is the voltage related to the charge integrated from the transmission chambers.

6.2.3 Thus, the daily value of KCOR depends in fact on:

$$KCOR = k\left(TPC5/TPC1\right)\left(C\ \Delta V_n/C\ \Delta V_\gamma\right) x \quad (3)$$
$$x\ \dot{X}_0\ \exp(-T\ \ln 2/30.0\ yr)\ \Delta t/\left(\Delta V_x\ TPCX\right)$$

Now, k and $\dot{X}_0$ are constants, and the atmospheric pressure being essentially constant and room temperature constant and uniform, lead to a value of (TPC5/TPC1) of unity. The values of ΔV_γ and ΔV_n are equal by software design. Δt is the run time in the

^{137}Cs-calibrator.

6.2.4 Thus, the above expression reduces to:

$$KCOR = k\ \dot{X}_0\ \exp(-T\ \ln 2/30.0\ yr)\ \Delta t/\left(\Delta V_x\ TPCX\right) \quad (4)$$

Obiously, further reduction in uncertainty would be possible using sealed transmission chambers, making TPCX an unnecessary correction. The ADC digitizing ΔV_x is checked at 15 Hz against a $\pm$ 0.1% stability power supply and a voltage divider made with wire wound resistors. Therefore, the sources of uncertainty in the value of KCOR reduce to:

(a) accurate knowledge of the decay constant of ^{137}Cs,

(b) precision of the oscillator frequency

(c) fluctuations in the sensitivity of the transmission chamber electronics and

(d) fluctuations in the readings of the thermocouple and the digital barometer readouts.

In addition, two more factors could affect the daily value of KCOR, namely the saturation of the transmission chambers (which depends on instantaneous dose-rate and actual H. V. accross it) and their volume, which may change due to thermal expansion or tampering during rare maintenance work.

6.2.5 It is difficult to assign individual

uncertainties to each of the above factors. However, over the last two and one half years, the value of KCOR obtained each treatment day has remained constant with a standard deviation of 0.5%.

7. Acnowledgements

The Mid Atlantic Neutron Therapy Association (MANTA) had in use a somewhat similar ^{137}Cs irradiator which we used as a model.

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