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Dosimetry with a diamond operating as a resistor

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Abstract. A very pure diamond with contacts of graphite has a linear current–voltage characteristic when subjected to irradiation. The resistivity is inversely proportional to the dose rate and the sensitivity is extremely high for γ- and x-rays and electron beams. It is concluded that diamond resistors are suitable for clinical radiation dosimetry. This conclusion is also based on earlier work in which diamonds were used as pinpoint counters.

1. Introduction

The existence of so-called counting diamonds is well known (the literature was reviewed by Champion and Kennedy in 1965). Cotty (1956) showed that these diamonds can be used as pinpoint counters in medicine. Apart from their small size, an advantage of these counters is that they are nearly tissue-equivalent with respect to absorption of radiation as a function of quantum energy. Cotty’s work was confirmed by Kozlov et al (1975), by Bampton (1976) and by Kozlov et al (1977). However, up to the present, diamond counters have not been produced in quantity, most probably because the selection of counting diamonds is a laborious process (Lightowlers and Dean 1965) and the making of good electrical contacts requires special techniques (Collins et al 1970, Koronova and Kozlov 1971). This paper describes a series of tests on one diamond probe when subjected to various types of radiation that are normally used in Institutes of Radiotherapy. With a low voltage applied to the diamond, the probe was found to operate as a radiosensitive resistor and this is a further extension of Cotty’s finding.

2. The diamond probe

Curtiss and Brown (1947) found that counting diamonds should be colourless (water-white), Friedman et al (1948) indicated that they should be of type IIa and Freeman and Van der Velden (1952) reported that they should show little birefringence. For the present work, several thousand natural diamonds were preselected on the basis of one or other of these criteria. For selection, each diamond was clamped between contact points, a voltage was applied and the current response to $^{60}$Co radiation was determined. Most stones gave nearly zero response, but one of them gave a very high signal. This was a colourless type IIa diamond with little birefringence ($<10^{-4}$) and was assumed to be very pure. A specimen of nearly cylindrical shape (volume $0.80 \text{ mm}^3$ and length $1.0 \text{ mm}$) was cut from this stone. Layers of graphite of

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0.01 mm thickness were deposited on the two opposite faces of the specimen; they have low resistance \((\approx 5 \, \Omega)\). An electrical lead was mounted onto each layer with a very small drop of silver paint.

The specimen was mounted in a Teflon (PTFE) tube and subsequently mounted with axial symmetry in the tip of a long stainless steel needle of 2.0 mm diameter and 0.1 mm wall thickness. Relatively simple equipment was used to apply a voltage, \(V\), over this probe and to measure the current, \(I\), under irradiation. In all tests described here, the radiation beams were directed perpendicular to the length of the probe, which was placed in a polystyrene or a water phantom. Unless otherwise specified, the probe was calibrated against Baldwin–Farmer secondary standard ionisation chambers.

3. Results and discussion

Figure 1 shows that the current stabilises within a few seconds when the probe is irradiated at room temperature with a \(^{60}\)Co teletherapy unit. There is some residual current after the beam is switched off. If the various signals are compared one second after the beam is switched on, a small difference is observable according to whether the probe is primed or not. This difference, which was found to be larger at low dose rates, is attributed to the existence of traps. The effect of trapping, however, does not disturb the working of this probe in measuring steady-state currents. No attempt was therefore made to reduce trapping effects by means of external illumination. The value of \(|I|\) remains the same upon reversing the polarity. This shows that the graphite contacts are good and symmetrical.

![Figure 1. Responses of the probe to several irradiation pulses. The time dependence of the current was registered with a standard recorder. The arrows indicate when the irradiation beam \((2.77 \times 10^{-2} \, \text{Gy s}^{-1}\) from \(^{60}\)Co) was switched on and off or when the voltage was changed.](image)

Figure 2 shows typical results for the \(^{60}\)Co source and also for an 8 MeV linear accelerator producing pulsed x-rays with a frequency of 400 s\(^{-1}\). The dose rates, \(D\), in these two tests are those normally used in radiotherapy. The plot of \(I\) against \(V\) is concave above about 50 V (corresponding to 500 V cm\(^{-1}\)) up to the maximum voltage applied (1200 V); however, there is a good linear dependence below 50 V. In nearly all tests, the deviations from linearity below 50 V are less than 5%. (They are slightly greater than 5% in tests with low dose rates or at high temperatures.) At voltages below
50 V, the diamond is thus a radiosensitive resistor and its resistivity, ρ, was further analysed. It follows from the characteristics of figure 2 and from the diamond shape that ρ = 65 × 10^3 and 36 × 10^3 Ω m for D = 2.00 × 10^−2 and 3.50 × 10^−2 Gy s^−1, respectively. When not irradiated, it was found with the measuring equipment used that ρ is higher than 10^12 Ω m at room temperature (in darkness). This is consistent with the literature value for type IIa diamond and with the specification of the Teflon insulation.

The dose-rate dependence of the probe was determined for irradiations from the 60Co source and the 8 MeV linear accelerator with effective energies of 1.25 and 2.7 MeV, respectively, and also from 137Cs needles with γ-quanta of 0.66 MeV. Since the dose rate of the accelerator fluctuates slightly, a BF chamber was connected to an electronic device giving dose-rate readings for calibration of the probe; mean dose-rate values are used. Figure 3 shows the results. It can be seen that there is no difference in response for the various energies and that the conductivity, given by 1/ρ, is linearly dependent on D over more than four decades. For the range of the experiments, the sensitivity of the probe is defined by

\[ n = 1/\rho D \]  

It follows from the points in figure 3 that \( n = 7.8 \times 10^{-4} \text{ s Gy}^{-1} \text{ Ω}^{-1} \text{ m}^{-1} \). This value thus applies to room temperature and to γ- and x-ray quanta of the order of 1 MeV.

The probe was also used at various temperatures and subjected to irradiation from the 60Co source and from the 8 MeV linear accelerator. The results of one of the first experiments with the probe are shown in figure 4 and indicated by open circles and those after a dose of nearly 5 kGy by filled circles. It can be inferred that the signal varies with temperature by −0.5% per °C near room temperature. This value is rather small and correction can be easily applied when the probe is used at a known
Figure 4. Conductivity divided by dose rate plotted against the temperature of the probe under continuous γ- and pulsed x-rays at dose rates of about $2.0 \times 10^{-2}$ Gy s$^{-1}$. Circles represent results for $^{60}$Co and squares those for an 8 MeV linear accelerator. Data for open circles were obtained at an early stage and those for filled ones at the last stage of the tests described in this paper.

Figure 5. Conductivity divided by dose rate plotted against the effective quantum energy of γ- and x-rays. The line was drawn through the experimental points (circles) to show the energy dependence of the probe. A diamond in a thin Al casing was measured for comparison and the results are represented by squares.

temperature which differs from 20 °C. This temperature correction is much more simple than that for surface barrier detectors made of silicon (Petushkov and Parker 1973) or other semiconductor materials. During the experiments described in this paper and some additional stability tests, the total dose of the probe was about 5 kGy. No damage was found in terms of reduction of sensitivity as is evident from figure 4.

In addition, the calibration of the probe at room temperature was carried out with an x-ray apparatus producing radiation with effective quantum energies up to 0.155 MeV. Surface dose rates on a polystyrene phantom were measured. It was found for various chosen energies that the signal was proportional to the dose rate. Values of $n$ at these low quantum energies were derived in the same way as was the $n$ value at quantum energies of the order of 1 MeV. The results are shown in figure 5. Measurements were also performed on the diamond specimen, with graphite layers but without silver paint, encapsulated in thin Al shielding of 0.02 mm. This specimen was subjected to irradiation from the x-ray apparatus and the results are also given in figure 5. It can be concluded that the sensitivity of the probe depends to some extent on the energy. This energy dependence is apparently caused by the stainless steel shielding and by the diamond itself.

The energy dependence of a detector for medical application is determined by its $Z$ value compared to the effective $Z$ of human soft tissue which is 5.92 for fat and 7.42 for muscle (Johns and Cunningham 1977). This is one of the properties favouring the use of diamond ($Z = 6$) as detector material. On construction of the probe, a compromise was made between robustness and energy independence. Figure 5 indicates that the design of the probe could be improved by the use of a more soft-tissue-equivalent casing. However, the energy dependence of the present probe is already much less than that of any other semiconductor detector.

The probe was calibrated under electron irradiation from a linear accelerator against a Pitman electron beam chamber (Morris and Owen 1975). The current was again linear with voltage (below 50 V) and the results for $1/p$ were again proportional to the dose rate. The electron sensitivities at room temperature were found to be $6.3 \times 10^{-4}$, $7.3 \times 10^{-4}$ and $7.4 \times 10^{-4}$ s Gy$^{-1}$Ω$^{-1}$ m$^{-1}$ for mean electron energies of 1.8,
4.1 and 7.5 MeV, respectively. Thus, the electron sensitivity converges upon increasing energy to the $n$ value for $\gamma$- and $x$-rays with energies of about 1 MeV. This energy dependence may be attributed to the steel shielding of the diamond.

Four other specimens of identical shape were cut from the same rough diamond and contacts were prepared in the same way as for the present probe. Initial measurements of these specimens before mounting them in needles showed that they were also radiosensitive resistors giving a signal proportional to the dose rate for various kinds of irradiation. However, it was found that specimens with similar contacts which were cut from other counting diamonds showed less linearity when $I$ was plotted against $V$ as well as smaller current values. Specimens cut from the second-best rough diamond selected so far, have $0.03 \times$ the sensitivity of the specimen described above, but are still good dosemeter elements. The impurities in the natural diamonds are of great importance. Further work will be done on the selection of diamonds and the design of soft-tissue-equivalent probes.

None of the dosemeter systems (Dearnaley and Northrop 1966, Becker 1973 and Johns and Cunningham 1977) in use in radiotherapy combines all the properties of the present diamond dosemeter. Only one system was based on a radiosensitive resistor which was made of CdS (Hollander 1956) but, for CdS, the energy dependence is much greater than for diamond.

4. Brief theoretical considerations

Pairs of free carriers are produced by irradiation and these may reach the electrodes, may recombine, or may be trapped on various impurities in the diamond. It is possible that carriers of one type are more often trapped. These might be the holes (De Blasi et al 1979). The recombination rate would then be relatively low and the lifetime of free electrons relatively long.

A simple model (Rose 1963, Fowler 1966) which is based on the mechanism of photoconductivity, gives the current according to

$$I = \left(\frac{e\mu\tau}{L^2}\right)VF$$

(2)

where $e$ is the electron charge, $\mu$ the mobility of free electrons, $\tau$ the lifetime of free electrons, $V$ the voltage over the diamond with an electrode spacing $L$, and $F$ is the number of free electrons produced per second. Assuming that neither $\mu$ nor $\tau$ are voltage-dependent, equation (2) shows that the model accounts for the observed operation of the diamond as a resistor. The observed deviation of $I$ against $V$ from linearity above 50 V (figure 2) is consistent with the saturation of the drift velocity of free carriers observed by Canali et al (1979). Refined models (Rose 1963) should be used in a more complete analysis, since comparison of the present results with the theoretical relation between current and dose rate (Fowler 1966) indicates that trapping of carriers combined with thermal release is involved in the operation.

The value of $\tau$ in equation (2) can be derived from the experimental results. For the present diamond of 2.81 mg, the conversion from $D$ in Gy s$^{-1}$ (section 3) to $F$ obeys

$$F = (1.75 \times 10^{13}/\epsilon)D$$

(3)

where $\epsilon$ in eV represents the effective energy for creation of electron–hole pairs. Using $\epsilon = 13$ eV and $\mu = 2 \times 10^3$ cm$^2$ V$^{-1}$ s$^{-1}$, the results for the present diamond yield, via equations (2) and (3), that $\tau = 1.3 \times 10^{-5}$ s. This value, and the one for the second-best diamond ($\tau \sim 4 \times 10^{-7}$ s), are much higher than the upper limit value of $10^{-8}$ s reported
by Koronova et al (1966). The $\tau$ value found by Canali et al (1979) is slightly higher than $10^{-8}$ s. Diamonds which are less pure than the present one have $\tau \ll 10^{-5}$ s; equation (2) indicates that a detector geometry with a smaller $L$ value may then compensate to some extent.

The transit time for free electrons is given by

$$T = \frac{L^2}{\mu V}. \quad (4)$$

Equations (2) and (4) give

$$I = \frac{eF\tau}{T} \quad (5)$$

where the factor $\tau/T$ is usually called photoconductive gain (although its value is not necessarily larger than unity). For $\tau/T \gg 1$, Fowler (1966) gave the picture that many electrons stream rapidly across from one electrode to the other during the time that one electron–hole pair remains unrecombined. Gain factors of $10^3$ or $10^4$ have been observed for CdS. The gain increases with voltage up to a certain limit at which space-charge effects dominate. It follows from equation (4) that $\tau/T = 2.6 \ V$ and thus gain factors of the order of 10 or 100 were observed in this work. The current–voltage characteristics of the present diamond (figure 2) differ from those for air chambers (exhibiting field-independent currents upon complete charge collection) because photoconductive gain is present in the kind of solid state detector described here and is absent in a gas.

5. Conclusion

A diamond has been found which can operate as a radiosensitive resistor with the following properties. The resistivity value is inversely proportional to the dose rate over a wide range. It has high sensitivity and a very high ratio of signal to noise. It gives a direct reading (during irradiation) and the temperature correction can easily be applied. The resistor is therefore suitable for many dosimetry applications. It requires only very simple equipment: a small electronic amplifier, a milliammeter and a stabilised power supply or battery. Other properties in relation to clinical use are that the detector volume is less than 1 mm$^3$, which allows point or in vivo measurements. It is composed basically of carbon and is thus nearly equivalent to human tissue. It operates at low voltage and is therefore usable in vivo. It is not fragile and can be heat sterilised. Unfortunately, diamonds which perform as well as the one described in this paper are extremely rare.

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Note added in proof

I wish to add that the sensitivity of the dosemeter used in the present study is 1000 times higher than for the best diamond dosemeter used by Planskoy for clinical evaluation.
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Résumé
Dosimétrie à l’aide d’un diamant fonctionnant comme une résistance.

Un diamant d’une grande pureté équipé de points de contact en graphite possède une caractéristique de courant-voltage linéaire lorsqu’il est soumis à des rayonnements. La résistivité est inversement proportionnelle au taux de dose et la sensibilité est extrêmement élevée pour des rayons γ et X et des faisceaux d’électrons. On en conclut que les résistances de diamant peuvent très bien être utilisées en clinique pour la dosimétrie. Cette conclusion est également basée sur une expérience antérieure au cours de laquelle des diamants avaient été utilisés comme compteurs ‘pinpoint’.

Zusammenfassung
Dosimetrie mit einem als Widerstand arbeitenden Diamanten.


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