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Criteria for the Equivalence of Spherical and Cylindrical Proportional Counters in Microdosimetry[1]

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KELLERER, A. M. Criteria for the Equivalence of Spherical and Cylindrical Proportional Counters in Microdosimetry. *Radiat. Res.* **86**, 277–286 (1981).

The proximity functions, or the closely related geometric reduction factors, of cylinders and spheres are compared in order to assess the degree of equivalence that can be achieved if cylindrical microdosimetric detectors are substituted for spherical instruments. Equality of the dose mean energy imparted per event, $\bar{\epsilon}_D$, is chosen as a criterion for equivalence. A cylinder of height and diameter equal to 0.895 d is found to be closely equivalent to the sphere of diameter d. In an isotropic field of any radiation the values $\bar{\epsilon}_D$ for the cylinder and the sphere can never differ by more than 1.7%. The equivalence is largely preserved even if the radiation is unidirectional and perpendicular to the axis of the cylinder. A cylinder with mass equal to that of the sphere and height and diameter 0.87 d is therefore also nearly equivalent to the sphere. The equivalence does not pertain to the frequency mean energy imparted per event, $\bar{\epsilon}_F$, or to the event frequencies, Φ, per unit absorbed dose. The event frequencies are higher by a factor between 1.07 (short-range particles) and 1.2 (long-range particles) for the cylinder compared to those for the sphere. For unidirectional beams, perpendicular to the axis of the cylinder, the differences in event frequencies are less. The quantities $\bar{\epsilon}_F$ are smaller by a factor between 1 (short-range particles) and 0.9 (long-range particles) than the corresponding quantities in the sphere. For beams perpendicular to the axis of the cylinder the factor is between 1 and 1.05. Cubes are also considered, since they are occasionally invoked in microdosimetric computations. One finds that a cube of side length 0.837 d is most closely equivalent to a sphere of diameter d. The quantity $\bar{\epsilon}_D$ for the cube cannot differ by more than 4% from the value of the sphere.

INTRODUCTION

Microdosimetric quantities and functions are most frequently related to spherical reference volumes. Suitable instruments, the "Rossi counters," have been developed that permit the determination of microdosimetric distributions for various types of radiation in spherical gas-filled regions. Both the walled and the wall-less constructions have broad applicability (*1–3*). In certain cases it is desirable, however, to employ simpler cylindrical detectors instead of the spherical instruments. It is then necessary to assess the degree of equivalence that can be attained between cylindrical and spherical detectors.

Various criteria could be used to judge the degree of equivalence between different detectors, but a particularly suitable parameter of reference is the dose

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mean energy imparted per event, $\bar{\epsilon}_D$ [see (*4*)]. This quantity is relevant to various biophysical interpretations; it also varies substantially with radiation quality and with size and shape of the reference volume. If the quantity $\bar{\epsilon}_D$ has for all radiations the same values in a cylindrical and spherical detector the two instruments can be considered as largely equivalent.

This article uses the concept of the proximity functions to assess the equivalence of spherical and cylindrical detectors. Proximity functions are in essence probability distributions of the distances between energy transfers (ionizations or excitations) in particle tracks, or applied to geometric volumes, they are probability distributions of the distances between elements of these volumes. They offer a convenient and compact—although limited—characterization of the spatial configuration of the particle tracks or the volumes of interest. They also permit simple solutions of various problems of the random intercept of configurations, such as particle tracks and geometric sites. For formal definitions and detailed explanations the reader may consult the accompanying article (*8*) that also contains the derivation of the proximity functions for cylinders.

ASSESSMENT OF EQUIVALENCE IN TERMS OF THE PROXIMITY FUNCTION OR THE RELATED QUANTITY GEOMETRIC REDUCTION FACTOR

It has been shown (*5, 6*) that the mean energy, $\bar{\epsilon}_D$, imparted per event to a region in a uniform and isotropic radiation field depends only on the proximity function $t(x)$ of the radiation and the proximity function $s(x)$ of the region. It is numerically convenient to use, instead of the proximity function $s(x)$, the related quantity $U(x) = s(x)/4\pi x^2$ that has been termed "geometric reduction factor" by Berger (*7*). The following relation applies rigorously for all radiations and for arbitrary volumes, and it is one of the reasons for the importance of the functions $t(x)$ and $s(x)$ or $U(x)$:

$$\bar{\epsilon}_D = \int_0^{x_{max}} \frac{s(x)t(x)}{4\pi x^2}\, dx = \int_0^{x_{max}} U(x)t(x)dx. \tag{1}$$

Equation (1) shows that different reference volumes will be largely equivalent for all types of radiations if their respective functions $U(x)$ are similar. A comparison will therefore be made between the functions for a spherical volume and those for cylinders.

The formula for the geometric reduction factor of the sphere of diameter d is

$$U(x) = 1 - \frac{3}{2}\frac{x}{d} + \frac{x^3}{2d^3}, \qquad x \le d. \tag{2}$$

For cylinders of height h and diameter δ an equation for the geometrical reduction factor has been obtained (*8*) that contains one relatively simple integration

$$U(x) = \frac{2}{\pi x}\int_a^b \left(1 - \frac{z}{h}\right)(\cos^{-1}((x^2 - z^2)^{1/2}/\delta) - ((x^2 - z^2)(\delta^2 - (x^2 - z^2)))^{1/2}/\delta^2)dz$$

$$a = (\mathrm{Max}\,(0, x^2 - \delta^2))^{1/2}; \qquad b = \mathrm{Min}\,(x, h); \qquad 0 < x \le (h^2 + \delta^2)^{1/2}. \tag{3}$$

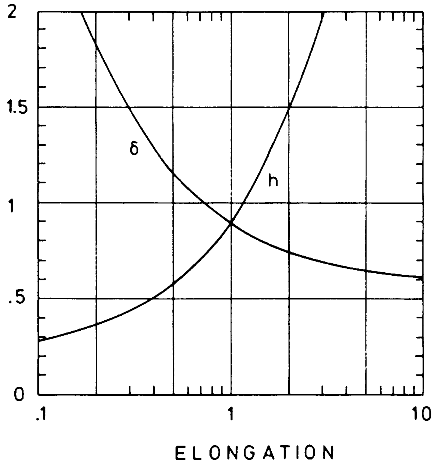

FIG. 1. Height h and diameter δ of the circular cylinders that have the same mean chord length $\bar{x}_I = 0.75$ as the unit diameter sphere (see also Table I). For the specified elongations these cylinders are most closely equivalent to the unit diameter sphere.

To assess the degree of similarity between the functions $U(x)$ one may consider a special condition. This is the familiar approximation of the LET concept that pictures charged-particle tracks as simple straight lines with constant rate L of energy transfer. The proximity function $t(x)$ is then equal to $2L$. Equivalence between cylinders and the sphere will first be assessed under this condition. It will then be seen that the LET approximation is not essential and that the equivalence of the spherical and cylindrical detectors will be preserved for all radiations, regardless of the complexities of the microdistribution of energy.

In the LET approximation the mean energy imparted is proportional to the integral over $U(x)$:

$$\bar{\epsilon}_D = 2L \int_0^{x_{max}} U(x)dx. \tag{4}$$

The mean chord length $\bar{x}_I$ for I-randomness [random chord through a random point in a convex body; see (*8*)] is equal to

$$\bar{x}_I = 2 \int_0^{x_{max}} U(x)dx. \tag{5}$$

Therefore one has in the same LET approximation

$$\bar{\epsilon}_D = L\bar{x}_I. \tag{6}$$

Two volumes with equal mean chord length $\bar{x}_I$ are equivalent in the sense that has been discussed. The mean chord length $\bar{x}_I$ must be distinguished from the mean chord length $\bar{x}_\mu$ for μ-randomness that is used in the definition of y [see (*4*, *9*)].

The mean chord length $\bar{x}_I$ for a sphere of diameter d is equal to $3d/4$. For cylinders the quantity is obtained numerically on the basis of Eq. (3). For a circular cylinder of unit height and diameter one finds $\bar{x}_I = 0.838$. Therefore a cylinder of height and

TABLE I

Dimensions of the Circular Cylinders with the Same Mean Chord Length $\bar{x}_l = 0.75$ as the Unit Diameter Sphere[a]

Elongation (*e*)	*Height* (*h*)	*Diameter* (δ)	$\frac{V}{V_{sphere}}$	$\frac{S}{S_{sphere}}$	$\frac{\bar{x}_\mu}{\bar{x}_{\mu,sphere}}$
1/32	0.1972	6.311	11.78	21.15	0.557
1/16	0.2402	3.843	5.32	8.31	0.641
1/8	0.3039	2.431	2.69	3.69	0.730
1/4	0.4054	1.621	1.60	1.97	0.811
1/2	0.5788	1.158	1.16	1.34	0.868
1	0.8948	0.8948	1.07	1.20	0.895
2	1.496	0.7481	1.26	1.40	0.898
4	2.666	0.6665	1.78	2.00	0.888
8	4.964	0.6205	2.87	3.27	0.876
16	9.495	0.5934	5.01	5.81	0.863
32	18.36	0.5736	9.05	10.69	0.847

[a] Also listed are the ratios of volume, surface, and mean chord length $\bar{x}_\mu$ to the corresponding values for the unit diameter sphere (see also Figs. 1 and 5).

diameter equal to 0.75/0.838 = 0.895 has optimal equivalence to a unit diameter sphere.

Cylinders with different elongations can have the same value $\bar{x}_l$. Figure 1 gives those combinations of diameter and height that are associated with the same value $\bar{x}_l = 3/4$ as the unit diameter sphere. Table I lists corresponding numerical values.

Figure 2 represents $U(x)$ for certain of these cylinders and the sphere. For the cylinder of elongation 1 one finds very close agreement with the sphere. A cylinder of diameter and height equal to 0.895 d is therefore very nearly equivalent to a sphere of diameter d.

Except for small distances x that are below the resolution of the microdosimetric detectors, the proximity functions $t(x)$ are always decreasing functions of x.[2] One can show—although the proof will be omitted here—that under this condition the quantity $\bar{\epsilon}_D$ for the equivalent cylinder will never exceed $\bar{\epsilon}_D$ for the sphere and will always differ from this value by less than 1.7%.

One must note, however, that this equivalence applies only to isotropic radiation fields or randomly oriented detectors. Furthermore one must note that microdosimetric quantities other than $\bar{\epsilon}_D$ may differ more markedly for the two detectors. These aspects will therefore be considered next.

EQUIVALENCE IN THE NONISOTROPIC CASE

In practice it will often be necessary to use a microdosimetric detector in a unidirectional, or otherwise nonisotropic, field. Frequently measurements will be taken with the axis of a cylindrical counter perpendicular to the radiation beam.

[2] Rossi and co-workers (*11*) have performed experiments with pairs of correlated particles that are separated by variable lateral distances. For this extraordinary radiation modality the functions $t(x)$ are not monotonically decreasing.

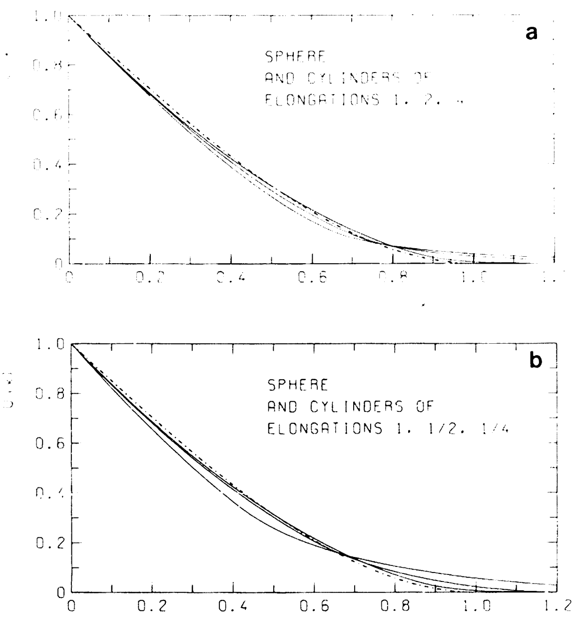

FIG. 2. The geometric reduction factor $U(x)$ for the unit diameter sphere (broken line) and for the equivalent cylinders of elongations 1, 2, 4 (panel a) and 1, 1/2, 1/4 (panel b). The function for the unit elongation cylinder is given in both panels; it is in best agreement with the sphere. The largest differences result for the elongations 4 and 1/4.

The charged particles registered in the detector will then not be isotropic but will have a preferred direction perpendicular to the axis of the cylinder. To obtain an estimate of the differences in $\bar{\epsilon}_D$ that may result in such cases, one may consider the limiting case of particle tracks that are all perpendicular to the axis of the cylindrical counter. It will be seen that even in this case the change of $\bar{\epsilon}_D$ is minor.

For a uniform unidirectional fluence of charged particles perpendicular to the axis of the cylinder Eq. (1) will still apply, but the function $U(x)$ is then the geometric reduction factor for a circular surface [see (*8*)] of diameter δ:

$$U(x) = \frac{2}{\pi}\left(\cos^{-1}\left(\frac{x}{\delta}\right) - \frac{x}{\delta^2}(\delta^2 - x^2)^{1/2}\right)$$

and

$$\bar{x}_I = 2\int_0^\delta U(x)dx = \frac{8}{3\pi} = 0.849\delta. \quad (7)$$

The value $\bar{x}_I = 0.849\delta$ is remarkably close to the value 0.838δ for the cylinder of elongation 1. According to Eq. (6) one obtains, therefore, very nearly the same value $\bar{\epsilon}_D$ that results in the isotropic case. One concludes that the cylindrical detector of diameter 0.895 *d* will remain closely equivalent to the spherical detector of diameter *d*, even if it is utilized in a unidirectional beam perpendicular to its axis. From Fig. 3 it follows that this applies not only in the LET approximation but generally for all radiations. This figure juxtaposes the functions $U(x)$ for the sphere,

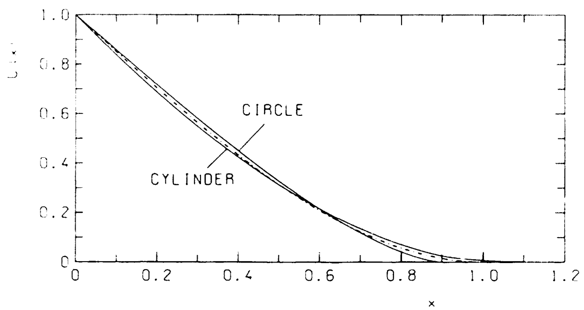

FIG. 3. Comparison of the geometric reduction factor $U(x)$ for the unit diameter sphere (broken line), for the equivalent cylinder of unit elongation ($h = \delta = 0.895$), and for the circular cross section of this cylinder.

the equivalent cylinder (isotropic field), and the circular cross section of the cylinder (beam perpendicular to the cylinder axis).

The values $\bar{\epsilon}_D$ for beams perpendicular to the cylinder axis and for isotropic fields will, according to these curves, show similarly small deviations from the values for the sphere. However, the possible differences are of opposite sign. The agreement between cylinder and sphere will therefore be even better for intermediate cases.

LACK OF EQUIVALENCE FOR EVENT FREQUENCIES

It has been found that there is close equivalence between cylindrical and spherical proportional counters with respect to the quantity $\bar{\epsilon}_D$. In many applications of microdosimetry this is indeed the parameter of foremost importance. However, no perfect agreement can be attained in the explicit microdosimetric spectra of spherical and cylindrical detectors. The magnitude of the remaining differences can be judged from a comparison of event frequencies, Φ, per unit absorbed dose or of the frequency averages, $\bar{\epsilon}_F$, of the spectra.

The comparison will be based on the LET approximation and is therefore less rigorous than the statements on $\bar{\epsilon}_D$. It will nevertheless serve to indicate the magnitude of the differences between spectra obtained by cylindrical and spherical detectors.

The relevant formulas for Φ and $\bar{\epsilon}_F$ are readily obtained and are therefore relegated to the Appendix. The resulting ratios of quantities for the cylinder to those for the sphere are given in Table II. The values to the left of the hyphen apply to the case of very short tracks, the values to the right to the case of long tracks. Results are given for isotropic fields and, in parentheses, for tracks perpendicular to the axis of the cylinder.

The volume of the equivalent cylinder exceeds that of the sphere by a factor of 1.07 (see Table I). The cylinder of equal volume has the slightly reduced height and diameter 0.874 d. Equality of volume (mass) would be a somewhat simpler but not greatly different condition of equivalence; values for this condition are therefore also given in Table II.

TABLE II

Ratio of Microdosimetric Quantities in a Cylinder of Height h and Diameter δ and a Sphere of Diameter d

	Equal $\bar{x}_l$ ($h = \delta = 0.895\ d$)	*Equal volume* ($h = \delta = 0.874\ d$)
$\bar{\epsilon}_D/\bar{\epsilon}_{D,\text{sphere}}$	1 (1.01)	1–0.98 (1–0.99)
$\Phi/\Phi_{\text{sphere}}$	1.07–1.20 (1.07–1.02)	1–1.15 (1–0.97)
$\bar{\epsilon}_F/\bar{\epsilon}_{F,\text{sphere}}$	1–0.90 (1–1.05)	1–0.88 (1–1.03)

Note. The values to the left of the hyphens apply to short tracks, the values to the right to long tracks. The upper values refer to isotropic fields, the lower values in parentheses to tracks perpendicular to the axis of the cylinder.

CONSIDERATION OF CUBIC VOLUMES

Cubes are of no particular interest in experimental microdosimetry. However, in Monte Carlo calculations it has been found to be practical to divide the exposed medium into elementary cubes (*10*). To permit a comparison of computed results for cubes and for spheres the degree of equivalence of these volumes will be considered.

Geometric reduction factors for regular parallelepipeds have been obtained from the formula for right cylinders with arbitrary cross sections (*8*). One finds that a cube of unit side length has the mean chord length $\bar{x}_l = 0.896$. A cube of side length $0.837\ d$ has therefore the same mean chord length $\bar{x}_l = 0.75\ d$ as the sphere of diameter d.

Figure 4 compares the geometric reduction factor $U(x)$ for the unit diameter sphere and for the equivalent cube of side length 0.837. The differences are larger than those between cylinder and sphere; however, the agreement is still good. One therefore concludes that, regardless of the type of radiation, the dose mean energy per event $\bar{\epsilon}_D$ is nearly the same for the sphere and for the equivalent cube. A numerical analysis shows that the difference must always be less than 3.5% provided the function $t(x)$ is monotonously decreasing.

The volume of the equivalent cube exceeds the volume of the sphere by the factor 1.12; the surface of the equivalent cube exceeds the surface of the sphere by the factor 1.34. The event frequency in the equivalent cube will therefore differ from the event frequency in the sphere by a factor between 1.12 (short-range particles) and 1.34 (long-range particles). The quantity $\bar{\epsilon}_F$ will differ from the value for the sphere by a factor between 1 (short-range particles) and 0.84 (long-range particles).

APPENDIX: EQUATIONS FOR Φ AND $\bar{\epsilon}_F$

The quantities $\bar{\epsilon}_F$ and ϕ are linked by the relation

$$\bar{\epsilon}_F \Phi = m = \rho V, \tag{A.1}$$

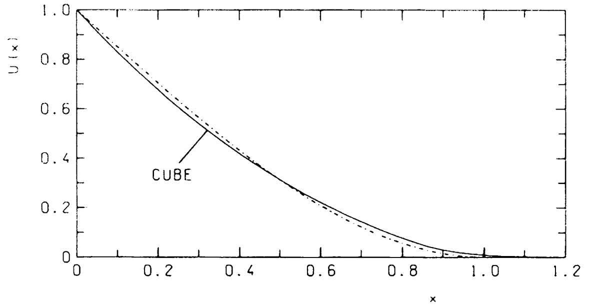

FIG. 4. Comparison of the geometric reduction factor $U(x)$ for the unit diameter sphere (broken line) and for the equivalent cube of side length 0.837.

where m and V are the mass and the volume of the region of reference. With density $\rho = 1$ and with the usual units:

$$\Phi(\mathrm{Gy}^{-1}) = 6242V\ (\mu\mathrm{m}^3)/\bar{\epsilon}_F\ (\mathrm{eV}). \tag{A.2}$$

For particles of short range, $\bar{\epsilon}_F$ is equal to the mean energy of the particles. Therefore

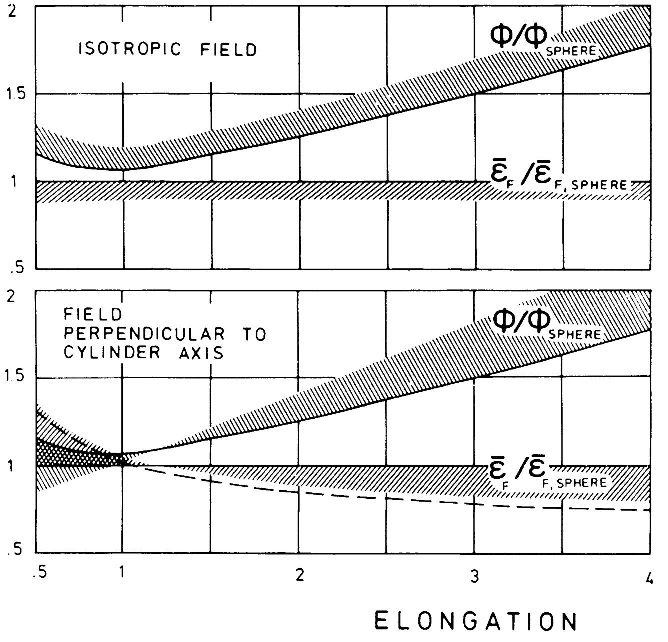

FIG. 5. Ratio of the quantities Φ and $\bar{\epsilon}_F$ in the equivalent cylinders (see Fig. 1 and Table I) to the corresponding quantities in the sphere. The upper panel refers to an isotropic field, the lower panel to a unidirectional field perpendicular to the axis of the cylinder. The solid lines apply to particle ranges that are short compared to the dimensions of the site. The other borders of the shaded areas correspond to particles of long ranges. The ratio $\bar{\epsilon}_D/\bar{\epsilon}_{D,\mathrm{sphere}}$ is 1 for the isotropic field. For the unidirectional field its value is given by the broken line in the lower panel.

$$\frac{\bar{\epsilon}_F}{\bar{\epsilon}_{F,\text{sphere}}} = 1 \quad \text{and} \quad \frac{\Phi}{\Phi_{\text{sphere}}} = \frac{V}{V_{\text{sphere}}} = \frac{3\delta^2 h}{2d^3}, \tag{A.3}$$

where d is the diameter of the sphere and δ and h are the diameter and height of the cylinder. These equations are rigorous and apply to both isotropic and nonisotropic radiation fields. The following relations for particles of long range are based on the LET approximation and depend on the direction of the field.

For long-range particles of track-average linear energy transfer L one has

$$\bar{\epsilon}_F = L\bar{x}_\mu \quad \text{and} \quad \Phi = V/(L\bar{x}_\mu). \tag{A.4}$$

The mean chord length $\bar{x}_\mu$ for the sphere is $2d/3$. With the cylinder one has for an isotropic field $\bar{x}_\mu = \delta h/(\delta/2 + h)$, and for tracks perpendicular to the axis $\bar{x}_\mu = \pi\delta/4$.

For an isotropic field one therefore has

$$\frac{\bar{\epsilon}_F}{\bar{\epsilon}_{F,\text{sphere}}} = \frac{3\delta h}{(\delta + 2h)d} \quad \text{and} \quad \frac{\Phi}{\Phi_{\text{sphere}}} = \frac{\delta(\delta/2 + h)}{d^2}. \tag{A.5}$$

For tracks perpendicular to the cylinder axis one obtains

$$\frac{\bar{\epsilon}_F}{\bar{\epsilon}_{F,\text{sphere}}} = \frac{3\pi\delta}{8d} \quad \text{and} \quad \frac{\Phi}{\Phi_{\text{sphere}}} = \frac{4\delta h}{\pi d^2}. \tag{A.6}$$

The values in Table II are derived from these equations with $\delta = h$.

Figure 5 indicates the possible range of the ratios $\bar{\epsilon}_F/\bar{\epsilon}_{F,\text{sphere}}$ and $\Phi/\Phi_{\text{sphere}}$ for equivalent cylinders of different elongations; the corresponding values of δ and h are given in Fig. 1 and Table I. It is evident that the best overall equivalence to the sphere is obtained by cylinders with elongation close to 1.

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