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Dosimetry and Quality Assurance in High Dose Rate Brachytherapy with Iridium-192

Recommendations No. 13

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Contents

1 Introduction

The present recommendation covers dosimetry and quality assurance for high dose rate (HDR) brachytherapy with Ir-192 sources. It succeeds the SSRMP recommendation No. 2 of 1984 [1]. Brachytherapy with β-sources is covered by another SSRMP recommendation [2].

The methodology adopted in the present text is largely inspired from IAEA technical document 1274 [3] and AAPM code of practice TG No. 56 [4]. For the dose calculation formalism, AAPM recommendation TG No. 43 [5] is at present the standard reference.

The recommended instrument for source calibration in the clinic is a well-type chamber (section 2.2.2). For a redundancy standard, we recommend a PMMA phantom dose measurement with a thimble chamber (section 2.2.3).

Characteristics of the Ir-192 HDR brachytherapy sources used in Switzerland at publication of the present recommendation are given in Table 1.

Table 1

	MicroSelectron "Classic design"	MicroSelectron ‘‘New design"	GammaMed 12i HDR	GammaMed Plus HDR 0.9 mm
Active length [mm]	3.5	3.6	3.5	3.5
Active diameter [mm]	0.6	0.65	0.6	0.6
Total diameter [mm]	1.1	0.9	1.1	0.9
Encapsulation	stainless steel	stainless steel	stainless steel	stainless steel
Manufacturer	Nucletron	Nucletron	MDS Nordion	MDS Nordion

2 Metrological traceability

This chapter starts with the definition of the reference dosimetric quantity (Section 2.1) and the different instruments involved in the measurement of the Ir-192 HDR sources (Section 2.2). Then the recommended methodology to verify the local instruments is described (Section 2.3). Finally, this chapter ends with the different steps involved in the practical calibration and acceptance of an Ir-192 HDR source (Section 2.4).

2.1 Reference dosimetric quantity: Air kerma strength S_K

The fundamental dosimetric quantity of an Ir-192 HDR source is the *air kerma strength* S_K:

$$S_K = \dot{K} d_{ref}^2 \quad , \tag{1}$$

where $\dot{K}$ is the air kerma rate at the reference distance d_{ref}, d_{ref} = 1 m.

The unit of air kerma strength is μGy/h m^{2*}. Air kerma strength should be used at each level: for specification of the source strength as well as for source ordering, dose computation, treatment planning and implant description.

2.2 Instruments characteristics

2.2.1 Primary standard: interpolative free-air secondary standard

One of the main problems of the metrological traceability of Ir-192 HDR sources is the absence of a true primary standard. The best calibration is obtained by the *interpolative free-air secondary standard*, which consists in measuring the air kerma rate at different large distances from the source [6]. This has become the *de facto* primary standard and more details about this method are given in Appendix A.

The realization of such a primary standard is out of the reach of the present document and is *not recommended* at the hospital level. The strategy adopted here is through a local standard traceable to a primary standard.

2.2.2 Local standard: well-type chamber

The local standard is a well-type ionization chamber open to the atmosphere. The goal of this instrument is to provide the user with a reference air kerma strength.

A dedicated holder should be placed in the well-type chamber in order to allow the source to be accurately centered in the middle of the measuring volume. Special care must be taken in order to guarantee the same position characteristics as during verification of the well-type chamber.

Pressurized well-type chamber like those used in nuclear medicine (also called activimeter or dose calibrators) are not appropriate due to the serious recombination problems occurring with high activity sources used in HDR brachytherapy.

2.2.3 Redundancy standard: phantom and thimble chamber

The redundancy standard is a cylindrical PMMA phantom[1] in which the Ir-192 HDR source is positioned at the center and measured in the periphery by a calibrated thimble ionization chamber (see Figure 1). Its use is not compulsory to follow this recommendation.

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[*] This is sometimes abbreviated by U: 1 U = 1 μGy/h m^2 = 1 cGy/h cm^2.

[1] The phantom can be home-made or purchased at PTW (PTW 9193). Note however that for home-made phantoms, the numerical value of k_{zp} as given in Appendix B will not be valid.

The goal of the redundancy standard is to check the Ir-192 HDR source with an independent instrument that measures a quantity closer to what is of interest in brachytherapy: this instrument measures a dose in a solid medium while the well-type chamber rather measures a kerma in a gas. The redundancy standard does *not* deliver the reference value.

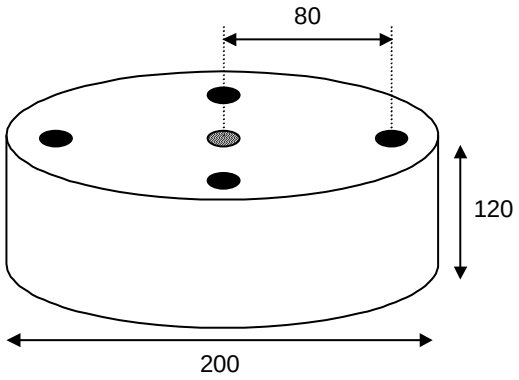

Figure 1: Scheme of the cylindrical PMMA phantom. The Ir-192 HDR source is located in the center hole. Holes indicated in black are for the thimble chamber. Dimensions are given in millimeters. The measuring depth and the source location are at phantom mid-depth.

2.3 Instruments verifications and calibrations

2.3.1 Verification of the local standard

The well-type chamber is verified in the clinic with its own Ir-192 HDR source by comparing the response of the chamber to be calibrated with a national standard. This latter instrument is a well-type chamber traceable to international standards.

The verification is performed by a verification laboratory authorized by METAS.

The validity of the verification is four years if the source stability checks described below stay within the tolerances. If this were not the case, the verification has to be redone.

Stability check

The stability of the well-type chamber is checked with a long-life source for long-time stability and with Ir-192 for energy-response and linearity stability.

Long-life source

Long-time stability is checked with a long-life source inserted in the measuring volume within a dedicated holder guaranteeing geometrical reproducibility. Typically, a sealed Cs-137 of about 150 MBq can be used. The long-time stability-check should be performed each time an Ir-192 HDR source is calibrated.

The value of the measured long-life source is compared with the value obtained at the instrument verification, corrected for radioactive decay.

Ir-192 HDR source

Energy-response stability as well as the linearity of the well-type chamber are checked with the Ir-192 HDR source itself. Geometrical measurement conditions are the same as in the source calibration process. This check is performed at least once at the end of the normal use of the Ir-192 HDR source before its replacement by a new source.

The measured air kerma strength is compared with the value obtained at the source calibration corrected for radioactive decay.

Tolerances

Both stability checks (long-time and Ir-192) should be within a 0.5 % tolerance. Differences above 0.5 % should be investigated and documented.

2.3.2 Calibration of the redundancy standard

The metrological traceability of the phantom and thimble chamber assembly is not as robust as the well-type chamber. In Appendix B, two expressions of air kerma strength based on a dose measured within the phantom are given [7]. In the first case, the dosimeter is calibrated in absorbed dose to water, whereas in the second case, it is calibrated in air kerma. The calibration of the thimble chamber should be performed in a Co-60 or in the lowest high-energy accelerator X-ray radiation available for a field instrument measurement.

Stability check

The stability check performed with the thimble ionization chamber is the one performed in routine with such instruments. Typically, it consists in performing a Sr-90 source check.

Tolerances

The stability check should be within a 0.5 % tolerance. Deviations above 0.5 % should be investigated and documented.

2.4 Source calibration

Prior to using a newly received source, it should be calibrated with the local standard. It may additionally be checked with the redundancy standard. The local standard measurement (i.e. the measurement with the well-type chamber) gives the user reference value of the air kerma strength of the source.

2.4.1 Consistency with the vendor reference

The user reference value is compared with the vendor-supplied measurement of the source strength. If the difference between these values is below 3 %, then the user reference value is used without investigation. If the difference is greater than 3 %, then the reasons should be investigated and if the difference remains, it should be reported to the vendor.

2.4.2 Consistency of the user measurements

If the redundancy measurement is performed, the air kerma strength measured with the local standard should be compared with the value obtained with the redundancy standard. If the difference is below 3 %, then the user reference value is used without investigation. If the difference is greater than 3 %, then the reasons should be investigated.

3 Treatment dose calculation

3.1 Dose calculation formalism

Compared to teletherapy, treatment planning in brachytherapy is rather primitive: basically, the dose rate in water is calculated by the inverse square law with small corrections for absorption, scattering, and anisotropy. There is no correction for inhomogeneity of the patient's tissues. The dose calculation formalism recommended in this document has been worked out by the Interstitial Collaborative Working Group (ICWG) and has been described in detail in the AAPM document [5] of Task Group No. 43 (see Appendix C for a brief description). It decouples the following interrelated quantities: air kerma strength, dose rate constant, geometry factor, radial dose function, and anisotropy function. It requires input data consisting of dose rates from an actual source in a tissue equivalent phantom. These data depend on the specific source geometry, and have been worked out using Monte Carlo calculations and measurements. For the Nucletron sources, we refer to [8] for "classic design" and [9] for "new design", and for the GammaMed sources to [10]. Additionally, [11] provides fitting functions for the radial dose function and the anisotropy function.

Checks

If the dose calculation of the treatment planning system (TPS) used in clinical routine is different from the ICWG formalism, they should be compared against another. We recommend comparing the output for typical treatment situations. For such a calculation it is presumably most convenient to use the dose rate distributions in Cartesian ("away-and-along") coordinates provided by [8, 9, 10].

Tolerances

A difference between the ICWG formalism and the clinical TPS calculation below 3 % for the dose at prescription points for typical treatment plans is acceptable.

3.2 Treatment planning

The treatment planning should be done or supervised by the physicist and reviewed by the physician. We refer to the SSRMP report No. 18 [12] for dose prescription, optimization, and documentation guidelines.

Checks

Before each application, check that the source strength in all systems where it is specified (treatment planning computer and/or control station) matches the decayed value.

Each individual treatment plan should be checked. Before a first application of an individual treatment plan, an independent calculation should be performed (see for example Reference [13]). For a follow-up application, check that the dwell times of the source are correctly adjusted for decay.

4 Quality control of the afterloading unit and security equipment

The goal of the general quality controls is to guarantee an optimal use of the device and technique from the physical and safety point of view. Therefore, even if general guidelines can be given, the procedures have to be specified according to the device and technique used.

Specific quality controls have not been described in detail in this section as their labeling is self-explicative. They are only given in the summary list in Section 5.

Appendix D contains a suggestion for an emergency procedure (for the MicroSelectron HDR afterloading device) for the case that the source fails to return to the safe. For the case that after these emergency actions the source is still within the patient and not within the application room, the radiation oncologist has to be prepared to take the appropriate actions. (This worst case should never happen when – as is well-established – only closed catheters are used.)

5 Summary of the different tests and tolerances

All actions and tests for quality assurance of the HDR brachytherapy system are summarized below. Those described in sections 2 and 3 are ordered as occurring in the text, and those from section 4 are ordered according to their frequency: daily (d) if the unit is used, monthly (m), quarterly during source exchange (q), annually (a), and at commissioning (c).

Ref.	Control	Type of action	Freq.	Tolerance
Metrological traceability				
2.3.1	Verification of local standard	Verification by an authorized laboratory	4a	N/A
2.3.1	Stability of the local standard	Measurement with long-life source	q	0.5 %
		Measurement with Ir-192 source	q	0.5 %
2.3.2	Calibration of the redundancy standard	Calibration of thimble chamber in Co-60 or the lowest high-energy accelerator X-ray	a	N/A
2.3.2	Stability of the redundancy standard	Measurement with long-life source	q	0.5 %
2.4.1	Calibration of the source	Air kerma strength measured with local standard compared with vendor-supplied value	q	3 %
2.4.2	Calibration of the source	This test is optional. Air kerma strength measured with local standard compared with the value obtained with the redundancy standard	q	3 %
Treatment dose calculation				
3.1	Compliance with ICWG formalism	If the treatment planning system does not use ICWG formalism, compare for typical treatments	c	3 %
3.2	Source strength	Check that the source strength is correctly specified	d	no
3.2	Treatment plan, first application	Independent calculation		3 %
3.2	Treatment plan, follow-up application	Check that dwell times are correctly adjusted for decay		no
Afterloading unit				
4	Date and time	Check that it corresponds to the actual date and time	d	no
4	Integrity of transfer tubes and applicators	Tube used for treatment; done by dummy run	d	no
		Visual inspection of all transfer tubes and applicators	q	no
4	Source and dummy position	Using a transparent test phantom, a check ruler, or a film, run a treatment test at different positions	m	2 mm
4	Timer absolute accuracy	Run a test treatment	m	2 %
4	Leakage radiation	Use a dose-rate meter to measure room ambiance dose rate	q	10 µSv/h
4	Applicator too long or too short	Run a test treatment	q	2 mm
4	Missing applicator	Do not connect the catheter to the trolley and run a test treatment	q	N/A
4	Device disabled	Check that the source retracts if console is turned off	q	N/A
		Run a test treatment and check if the battery works when the main switch is turned off	a	N/A

Ref.	Control	Type of action	Freq.	Tolerance
4	Simulation markers	Verify construction/spacing of all simulation markers	a	1 mm
Security equipment				
4	Door interlock	Run a test treatment	d	no
4	Warning lights	Run a test treatment	d	no
4	Audio/Visual communication	Check the audio and video systems	d	no
4	Emergency and interrupt buttons	Run a test treatment	d	no
4	Radiation monitor and/or personal alarm dosimeter	Run a test treatment Check their presence and that the correct threshold alarm is inserted	d d	no no
4	Emergency equipment	Check their presence through a list and their ease to be used (e.g. the lid of the shielded storage container could be opened)	d	N/A
4	Emergency procedure	Review and update if necessary	a	N/A
4	Practice emergency procedure	Dry run	a	N/A
4	Quality assurance manual	Review and update if necessary	a	N/A

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Appendix A: Interpolative free-air secondary standard

The interpolative free-air secondary standard is de facto the interim standard [4] and can be provided (at the time of publication of this document) by two primary laboratories in the world: PTB and NIST. The method consists in measuring the air kerma rate with a secondary standard ionization chamber calibrated in air kerma at different X-ray (for instance the ISO N series), Cs-137 and Co-60 beam qualities. The appropriate weighting of the calibration factors according to Ir-192 emissions and adequate correction factors allow the physicist to measure the air kerma rate of the source at a distance sufficiently large to consider it punctual.

For that, an ionization chamber is positioned in the middle of the room in order to minimize scatter radiations. Air kerma rate is measured at different distances in order to estimate the air kerma rate at 1 m from the source as well as the room scatter correction. The air kerma rate is obtained by the following relationship:

$$\dot{K} = N_K \frac{M_U}{t} k_{Tp} k_{recom} k_{air} k_{scatt} k_n \left(\frac{d}{d_{ref}} \right)^2 \quad , \tag{2}$$

- N_K : Air kerma calibration factor of the ionization chamber,
- M_U : Instrument reading during measuring time t,
- k_{Tp} : Correction factor for air density,
- k_{recom} : Correction factor for recombination,
- k_{air} : Correction factor for attenuation of primary photons,
- k_{scatt} : Correction factor for scatter in the room,
- k_n : Correction factor for non-uniformity in the ionization chamber (Kondo-Randolf),
- d : measuring distance,
- d_{ref} : reference distance (1 m).

IAEA [3] recommends an ionization chamber volume greater than 0.5 cm^3 and specifically mentions the Farmer chamber. For Ir-192, N_K should not be too energy dependent. IAEA recommend that the maximum variation of N_K between Co-60 and Am-241 be smaller than 5 %.

Appendix B: Calculation of air kerma strength with the redundancy chamber

Here we describe how to determine the air kerma strength of an Ir-192 HDR source from a measurement in a PMMA phantom with a thimble chamber calibrated in air kerma or absorbed dose to water for Co-60 radiation [7, 14].

If the thimble chamber is not calibrated for Co-60, the lowest high-energy X-ray can be taken instead. In this case, the definition of k_λ (defined below) has to be modified accordingly.

Air kerma strength calculation from absorbed dose to water measurements

The air kerma strength S_K [μGy/h m^2] can be determined from a dose measurement made by an ionization chamber calibrated in absorbed dose to water for Co-60 radiation:

$$S_K = \underbrace{\frac{1}{1-g_w}\frac{(\mu_{en}/\rho)_a}{(\mu_{en}/\rho)_w}k_{w\to p}\cdot k_r \cdot k_{zp}}_{=0.00684}\cdot k_\lambda \cdot N_w \cdot k_\tau \cdot k_{pT} \cdot M \quad , \tag{3}$$

- M : Instrument reading [digit].
- k_{pT} : Air density correction factor $\left(\frac{T_{ph}+273.15}{293.15}\frac{1013.25}{P}\right)$,where T_{ph} is the phantom temperature [°C] and p is the air pressure [hPa].
- k_τ : Time correction factor $\left(\frac{60}{\tau}\right)$, where τ [min] is the measurement time.
- N_w : Calibration factor for dose absorbed to water for Co-60 radiation [μGy/digit].
- k_λ : Correction factor for Ir-192. This value is calculated from the instrument specifications. Assuming the instrument response is 1.00 for Co-60, the correction factor is equal to the interpolated response between Co-60 and the highest x-ray available assuming a mean Ir-192 energy of 380 keV.
- k_{zp} : Geometry correction factor for the cylindrical phantom described in section 2.2.3: k_{zp} = 1.187 ± 0.012 [7, 14]. This factor contains the volume correction for the chamber M23332 (PTW) at distance 8 cm. If another chamber ("i") is used, correct k_{zp} by the quotient of the displacement factors $k_{V,i}$ / $k_{V,M23332}$.
- k_r : Inverse square law correction factor ($k_r = (8/100)^2 = 0.0064$).
- $k_{w\to p}$: Perturbation factor from water to PMMA environment ($k_{w\to p}$ = 1.00).
- $(\mu_{en}/\rho)_a$ and $(\mu_{en}/\rho)_w$: mass energy absorption coefficients for air and water respectively ($(\mu_{en}/\rho)_a / (\mu_{en}/\rho)_w = 0.899$).
- g_w : Relative energy lost by bremsstrahlung ($g_w = 0.001$).

Air kerma strength calculation from air kerma measurements

If the dose measurement is performed by a chamber calibrated in terms of air kerma for Co-60 radiation, then the air kerma strength is given by:

$$S_K = \underbrace{k_{a\to p}\cdot k_r \cdot k_{zp}}_{=0.00760}\cdot k_\lambda \cdot N_K \cdot k_\tau \cdot k_{pT} \cdot M \quad , \tag{4}$$

- N_K : Calibration factor for air kerma for Co-60 radiation [μGy/digit].
- $k_{a\to p}$: Perturbation factor from air to PMMA environment ($k_{a\to p}$ = 1.00).

Appendix C: ICWG dose calculation formalism

As IAEA [3] and AAPM [4], SSRMP recommends the use of the *Interstitial collaborative working group* (ICWG) formalism [5]. It is designed for sources which are cylindrically symmetric and expresses the absorbed dose rate as a function of air kerma strength.

The dose rate at the point (r,θ) in medium is given by (see Figure 2):

$$\dot{D}(r,\theta) = \Lambda S_K \frac{G(r,\theta)}{G(r_0,\theta_0)} F(r,\theta) g(r) \quad , \tag{5}$$

- Λ : dose rate constant,
- (r,θ) : point of interest in a cylindrical coordinate system,
- (r_0,θ_0) : reference point, $r_0 = 1$ cm and $\theta_0 = \pi/2$,
- S_K : air kerma strength of the source,
- G(r,θ) : geometry factor,
- F(r,θ) : anisotropy function,
- g(r) : radial dose function.

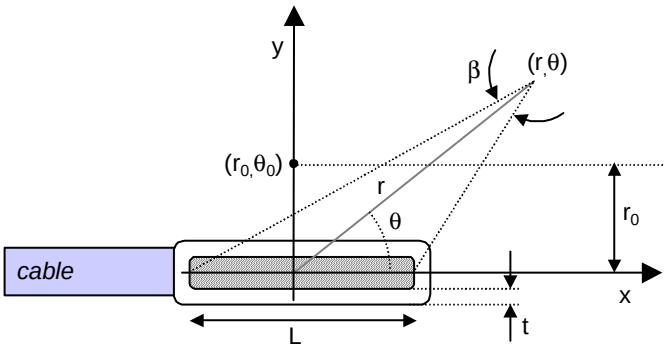


Figure 2: General scheme of spatial dose description according to ICWG.

Dose rate constant Λ

$$\Lambda = \frac{\dot{D}(r_0,\theta_0)}{S_K} \quad . \tag{6}$$

The dose rate constant depends on the radionuclide and the design of the source. It includes the following effects: spatial distribution of radioactivity within the source, encapsulation, self-filtration within the source, and scattering in water. Numerical value can be found in references [8] and [9] for the Nucletron sources and in reference [10] for the GammaMed Sources. All these values are within 1.11 ± 0.01 Gy/Gy cm^{-2}.

Geometry factor G(r,θ)

The geometry factor describes the variation of relative dose due only to spatial distribution of activity within source ignoring photon absorption and scattering in source structure:

$$G(r,\theta) = \frac{\int_V \frac{\rho(r')}{|r'-r|^2} dV'}{\int_V \rho(r') dV'} \quad , \tag{7}$$

- $\rho(r')$: density of radioactivity at point r' = (x',y',z'),
- V : volume of the source,
- dV' : volume element located at r'.

For the HDR sources covered by this document, it is recommended to use the line source approximation:

$$G(r,\theta) = \frac{\beta}{L\, r \sin\theta} \quad , \tag{8}$$

where L is the active source length, and β is the angle subtended by the active source with respect to point (r,θ). This equation is remarkably close to the point source approximation $G(r,\theta) = 1/r^2$ (with errors less than 2 % in most practical treatment situations).

Radial dose function g(r)

The radial dose function accounts for absorption and scatter in the medium along the transverse axis:

$$g(r) = \frac{\frac{\dot{D}(r,\theta_0)}{G(r,\theta_0)}}{\frac{\dot{D}(r_0,\theta_0)}{G(r_0,\theta_0)}} = \frac{\dot{D}(r,\theta_0) G(r_0,\theta_0)}{\dot{D}(r_0,\theta_0) G(r,\theta_0)} \quad . \tag{9}$$

This function is free from $1/r^2$ variation.

Anisotropy function F(r,θ)

The anisotropy function describes the anisotropy of dose distribution around the source including the effects of absorption and scatter in the medium:

$$F(r,\theta) = \frac{\frac{\dot{D}(r,\theta)}{G(r,\theta)}}{\frac{\dot{D}(r,\theta_0)}{G(r,\theta_0)}} = \frac{\dot{D}(r,\theta) G(r,\theta_0)}{\dot{D}(r,\theta_0) G(r,\theta)} \quad . \tag{10}$$

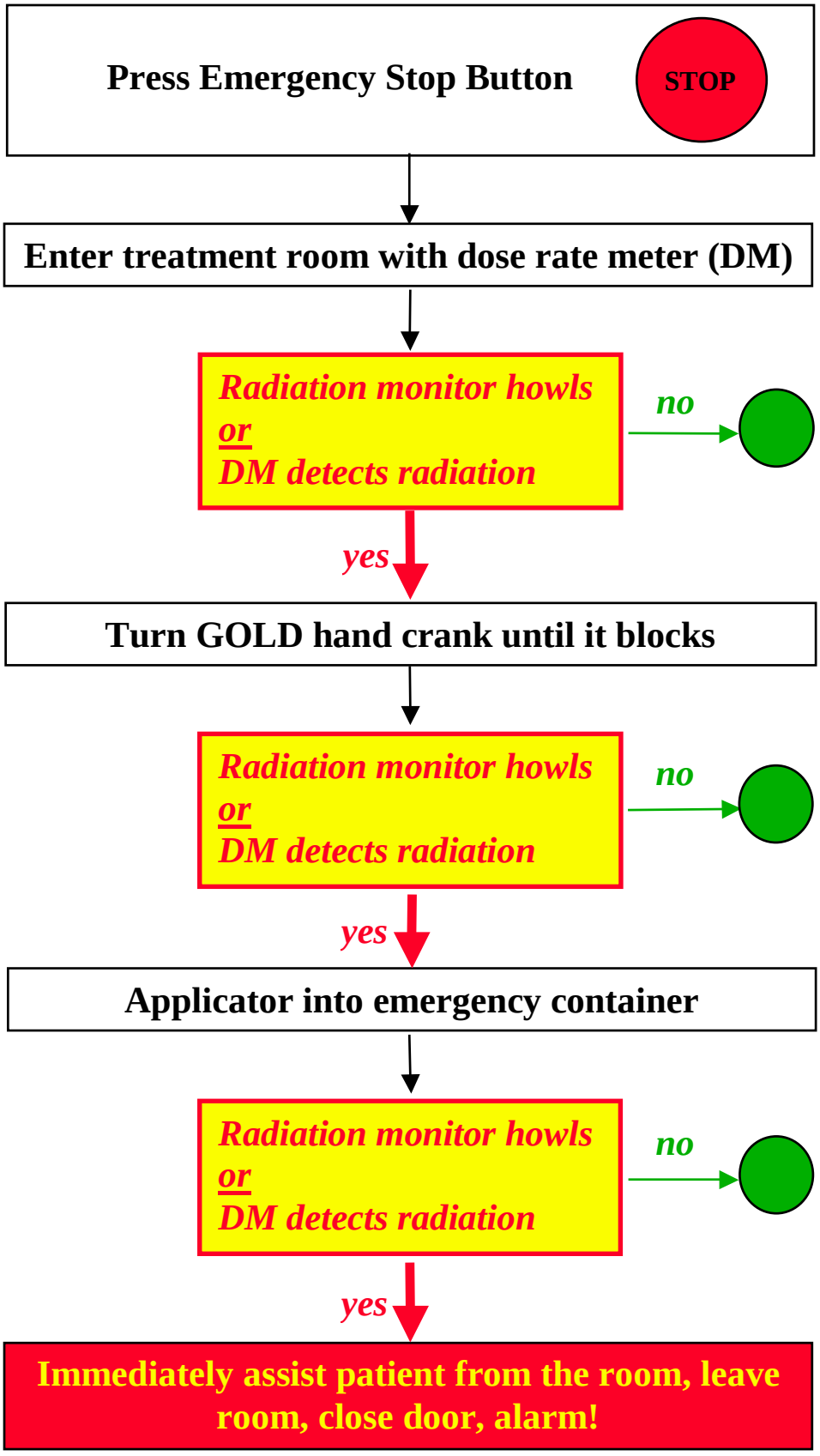
As for the radial dose function, the presence of G in Expression (10), inverse square law effect is suppressed. This allows interpolation and extrapolation in areas difficult to measure in practice.

For the radial dose function g and the anisotropy function F, we recommend using values obtained by Monte Carlo and measurements given in Tables displayed in reference [5]. More recent publications have worked out data using the correct geometry of commercial sources: [8] and [9] for the Nucletron sources, and [10] for the GammaMed sources. Additionally, fitting functions for the tabular data are given by [11].

Uncertainties

The determination of the dose rate at a point (r, θ) around a source according to equation (5) requires the knowledge of several quantities each of which is subjected to some uncertainty – estimated as 5 % for S_K, Λ, F and g – resulting in an estimated overall uncertainty of about 10 % (see ref. [5], section VI.C).

Appendix D: Emergency plan (Example)



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