Calculation of Minimal Detectable Activity for Scintillation Detection Systems

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This paper analyzes the statistical approach to the determination of minimum detectable radioactivity for nuclear medicine counting data. Based upon measurements of the background level and detector counting efficiency this method allows calculation of the counting time necessary to detect a specified minimum amount of radioactivity. This method is important both in the application of bioassay measurements of radiation workers for measuring thyroid burden and in the measurement of radioactive wipe test samples.

The Nuclear Regulatory Commission (NRC) requires bioassay evaluation of all personnel who deal with radioiodine (*1*). The NRC, for example, requires the reporting of any incident in which personnel receive a 40 nCi (1480 Bq) or greater thyroid burden of iodine-131 (^{131}I) (*1*). In addition, the *as low as reasonably achievable* (ALARA) principle requires the ability to detect a significantly smaller quantity than this for the protection of these workers, e.g., 4 nCi (148 Bq) (*2*). In order to accomplish this requirement one must count both background and subject, and must be able to determine: 1) if any radioactivity has been detected, 2) the minimal activity that can be detected, and 3) how much activity has been detected.

In order to determine if radioactivity has been detected one must determine whether the background and subject counts are statistically different. This is accomplished by use of a normal deviate test (z statistic) (*3,4*).

$$z = \frac{S - \left(\frac{t_S}{t_B} \times B\right)}{\sqrt{(sd_S)^2 + \left(\frac{t_S}{t_B} \times sd_B\right)^2}}$$

where S = subject total counts (in the presence of background)

B = background total counts

t_S = subject counting interval

t_B = background counting interval

S − B = net subject counts (counts above background)

sd_S = standard deviation of subject total counts

sd_B = standard deviation of background total counts

z = the number of standard deviations by which S and B are separated.

At background and subject counts greater than 50, nuclear

counts approach a Gaussian distribution (*3*). At this point the standard deviation of a count is equal to the square root of the count, and for equal counting intervals ($t_S = t_B = t$) the z-test equation simplifies to:

$$z = \frac{S - B}{\sqrt{S + B}}$$

$$z^2 = \frac{(S - B)^2}{S + B} \qquad \text{Eq. 1}$$

It should be noted that the division of the counting time equally between sample and background ($t_S = t_B = t$) is not necessarily the most optimum choice for quickly finding any minimum detectable activity (*3*). It is, however, the simplest choice and it simply requires a longer counting time to detect a certain minimum detectable activity level than does a more optimum (but complex) division of counting times.

We then define a subject count as being different from background by first defining how many standard deviations apart they must be to be considered different. This is a one-tailed test since S is presumed greater than B.

After obtaining a background count (B) and choosing the number of standard deviations of separation (z), one substitutes for B and z in the following equation.

z	p
1.64	0.05
2.3	0.01
3.0	0.0013

The minimum detectable subject count (S_{min}) is derived directly from equation 1 as

$$S_{min} = \frac{2B + z^2 + z\sqrt{8B + z^2}}{2} \qquad \text{Eq. 2}$$

where S_{min} = that subject count at or above which activity is detected.

The counting efficiency can be determined as follows by measuring a source of known activity with the detector system.

$$\text{counting efficiency (eff}_c) = \frac{\text{counts detected}}{\text{photons emitted}}$$

$$\text{eff}_c = \frac{\text{CPS detected from a known activity source}}{\text{DPS (Bq) occurring in that same source} \times n_i}$$

where n_i = photon abundance/disintegration (*5*).

It is more useful, however, to use a counting efficiency that reflects the fraction of disintegrations detected eliminating the need to know n_i for each photon examined as well as Compton energies detected from higher energy photons. This activity efficiency (eff$_a$) can be defined as follows:

$$\text{counting activity/efficiency (eff}_a) = \frac{\text{counts detected}}{\text{disintegrations emitted}}$$

$$\text{eff}_a = \frac{\text{CPS detected from a known activity source}}{\text{DPS (Bq) emitted by that same source}}$$

The source must be counted in the same geometric configuration and energy window as the sample and background are counted. For thyroid monitoring, probe efficiency is measured using a known activity source of ^{131}I counted in a neck phantom with the same geometry and energy window as used for subjects.

$$\text{MDA (Bq)} = \text{minimum detectable activity}$$

$$\text{MDA (Bq)} = \frac{S_{min} - B}{\text{counting time (sec)} \times \text{eff}_a} \qquad \text{Eq. 3}$$

where $S_{min} - B$ = the minimum detectable counts above background.

Application problem 1. At a confidence level of $p = 0.05$, what is the 3-min subject count at or above which activity is detected, as well as the minimum detectable counts (above background), and the minimum detectable activity? A 3-min background count is 133 counts. The thyroid probe counting activity efficiency (eff$_a$) $= 1.8 \times 10^{-3}$.
Solution (using Eq. 2):

$$S_{min} = \frac{2B + z^2 + z\sqrt{8B + z^2}}{2}$$

$$S_{min} = \frac{2 \times 133 + 1.64^2 + 1.64\sqrt{8 \times 133 + 1.64^2}}{2}$$

$$S_{min} = 161 \text{ counts}$$

$$S_{min} - B = 161 - 133 = 28 \text{ counts}$$

In other words, the test fails to detect activity in this counting interval (3 min) if $S < 161$. The minimal detectable counts (MDC) is 28 counts above background, and the minimum detectable activity (MDA) is (using Eq. 3):

$$\text{MDA} = \frac{28}{180 \text{ sec} \times (1.8 \times 10^{-3})} = 86 \text{ Bq} = 2.3 \text{ nCi}$$

It is also important to realize that if the patient count in a particular counting interval is less than S_{min}, it cannot be concluded that no activity is present. One can only conclude that activity was not detected in *this* particular counting interval. A longer counting interval may be able to detect the activity.

More important therefore, given a background count level, is to be able to construct a test with a desired minimal detectable activity: for example, a thyroid bioassay with a MDA of 4 nCi, or a wipe test with a MDA of 100 DPM (1.7 Bq) ($p = 0.05$).

One first performs a preliminary experiment to count background to preset counts of 300 and record time and calculate background rate (BR) in CPM. This step ensures a reasonable number of background counts.

$$\text{BR(CPM)} = \frac{300}{t(min)}$$

One then measures activity counting efficiency (eff$_a$) as described above for the probe, well counter, etc.

The desired minimal detectable count rate (MDCR) may now be calculated.

$$\text{MDCR (in CPM)} = \text{desired MDA (in DPM)} \times \text{eff}_a$$

Equation 1 is rearranged as follows:

$$z^2 = \frac{[S_{min} - (BR \times t)]^2}{S_{min} + (BR \times t)}$$

$$\text{since } S_{min} = (BR + MDCR) \times t$$

$$z^2 = \frac{(MDCR)^2 \times t}{(2 \times BR) + MDCR} \text{ and}$$

$$t = \frac{z^2}{(MDCR)^2} [(2 \times BR) + MDCR] \qquad \text{Eq. 4}$$

Using equation 4 the counting time to produce the desired MDA is obtained.

Application problem 2. At a confidence level of $p = 0.05$, how long must one count background and a thyroid gland to detect at least (MDA) 4 nCi (148 Bq or 8880 DPM) of [131]I? A background of counts (300) was acquired in 75 sec and the probe efficiency (eff$_a$) for ^{131}I is 1.8×10^{-3}.
Solution: Applying equation 4,

$$t = \frac{z^2}{(MDCR)^2} [(2 \times BR) + MDCR]$$

$$\text{MDCR} = 8880 \text{ DPM} \times 1.8 \times 10^{-3} = 16 \text{ CPM}$$

$$\text{BR} = 300 \times \frac{60}{75} = 240 \text{ CPM}$$

$$t = \frac{1.64^2}{16^2}[(2 \times 240) + 16] = 5.2 \text{ min}$$

The sample (thyroid) and background are then counted for the calculated time of 5.2 min. The minimum detectable counts, S_{min}, is calculated from equation 2:

$$S_{min} = \frac{2B + 1.64^2 + 1.64\sqrt{8B + 1.64^2}}{2}$$

If the actual sample count is greater than S_{min}, the actual detected activity (ADA) is calculated as follows:

$$ADA\ (Bq) = \frac{S_{actual} - B}{\text{counting time (sec)} \times \text{counting efficiency (eff}_a)}$$

If the actual sample count is less than S_{min} we can conclude (p = 0.05) that the patient thyroid activity is less than the specified MDA.

In the laboratory setting, if the background rate (checked daily) and the counting efficiency (checked monthly) remain stable, the periodic calculation of MDA (monthly in our clinic) will suffice for routine use.

The statistical methods presented here can be extended to any detection system used in nuclear medicine. It is not sufficient to report a subject or sample count to be equal to, or not significantly above background. One must determine statistically what, if anything, can be or has been detected. This paper is presented as an aid to the many nuclear medicine clinics not yet answering these questions correctly.

ACKNOWLEDGMENT

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