Teaching Editorial

Automatic Tuning of Scintillation Cameras: A Review

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The design changes that have been made in Anger scintillation cameras to improve spatial resolution have been acheived at the expense of field uniformity. The nonuniformities that have appeared have been essentially eliminated by the installation of energy and linearity (distortion) correction circuits. For optimal performance of these circuits, the photomultiplier tubes (PMTs) must be properly balanced (tuned). Aging and drift of electronic components, however, can cause the optimal balance to be lost. Many state-of-the-art scintillation cameras now utilize microprocessors that automatically monitor and adjust the gain of PMTs to maintain the proper PMT balance. The five methods that are currently used for performing this operation are reviewed in this article.

The desire for improved intrinsic spatial resolution has led engineers to make a number of changes in the design of Anger scintillation cameras (*1,2*). Recent developments have included: the use of more PMTs to provide finer spatial sampling, PMTs with higher quantum efficiency and a narrower range of performance specifications (*3–5*), thinner crystals (*6,7*), and reduction in thickness or elimination of the light pipe (*1*). State-of-the-art scintillation cameras have intrinsic spatial resolution full-widths-at-half-maximum ranging from 2.8–4.5 mm and are so developed that the collimator and the presence of scattering material are the limiting factors in most imaging situations (*3*). A recent study has demonstrated that when two large field-of-view cameras, which were identical except for crystal thickness and number of PMTs, were used for liver and bone imaging observers were unable to detect any significant differences in the clinical images (*8*).

The improvement in spatial resolution has been achieved at the expense of field uniformity (*3*). Nonuniformity can produce an increase in the number of false-positives in "cold" spot imaging (*9*). Therefore, it has been necessary to install special circuits (including appropriate software) to eliminate the nonuniformities that are present. State-of-the-art circuits operate primarily on two aspects of camera performance. When a gamma ray strikes the crystal at different positions relative to the center of a PMT, the photopeak may be shifted up or down along the energy axis. Energy correction circuits use special maps (sometimes called Z maps) to correct for the shift so that when the PMTs are properly balanced, the location of the photopeak relative to the energy window is independent of the X and Y location of the event (*10–13*). Linearity (distortion) correction circuits use a set of correction factors to reposition events that are incorrectly positioned by the basic position-encoding network of the Anger scintillation camera (*14–20*). These correction factors (computed from distortion maps) are prepared when the camera is first assembled and can be updated in the field if necessary. Incorporation of both of these correction circuits yield cameras that provide images with high spatial resolution and uniformity. A byproduct of these modifications has been improved ability to distinguish between photons that have been scattered and those that have not.

For those special circuits to work properly, it is imperative that the PMTs be properly balanced (tuned) and that all electronic circuits be stable with respect to time. When gains of PMTs change, nonuniformities may be introduced that are worse than if the energy and linearity correction circuits were not present. These changes in gain may be a result of PMT drift or failure or a change in PMT performance with respect to its orientation in the earth's magnetic field. Nonuniformities may also appear when the crystal deteriorates and/or there is a loss of optical coupling between the crystal and the PMTs.

If the PMT fails, or the crystal deteriorates, or there is a loss of optical coupling, components must be replaced or serviced; tuning will not solve the problem. If nonuniformities appear that are caused by PMT drift or a change in tube orientation in a magnetic field, tuning or balancing the PMTs will usually return the camera to the state that existed when the energy and linearity correction factors were first determined. Photomultiplier tube drift is generally a long-term effect that results from aging of the tube or changes in the circuits associated with the tube. These changes may be random or may show a trend toward a steady increase or decrease in gain. Change in gain with orientation in the earth's magentic field

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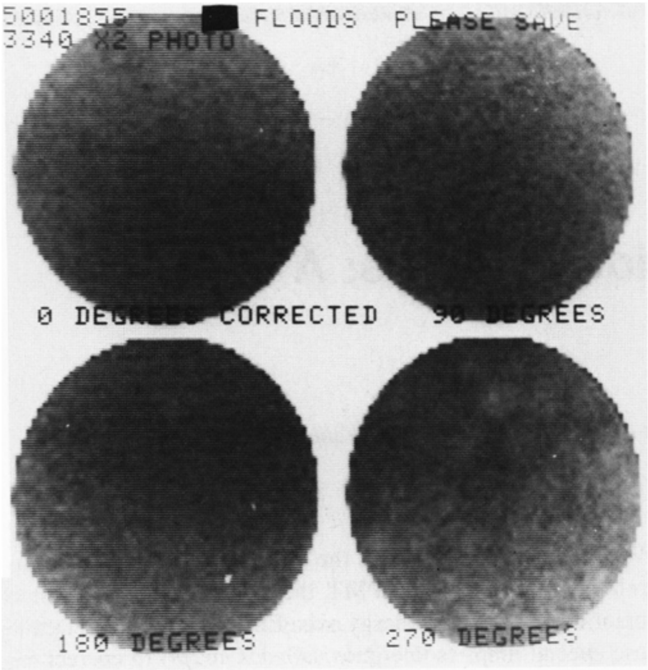

FIG. 1. Flood field images taken at 0, 90, 180, and 270 degrees with a SPECT system. The image taken at 270° shows the nonuniformity produced by magnetic fields from an isolation transformer in near proximity to the scintillation camera at that position.

was a particular problem in early work on a single-photon emission computed tomography. Uniformity changed as the camera rotated around the patient. Figure 1 illustrates the effect of a large isolation transformer and its associated magnetic field on the uniformity of a scintillation camera.

Because of the importance of maintaining proper PMT balance, some manufacturers have introduced additional circuits to monitor PMT gain and automatically "tune" the camera. The methods will be discussed in the following sections (*21*).

ON-DEMAND AUTOMATIC TUNING

Photopeak Monitoring

An approach used by one vendor* for automatic tuning is to use a source of ^{99m}Tc photons and a special mask to monitor the location of the photopeak center along the energy axis (*22*). Specific details for accomplishing this are as follows:

1. The collimator is removed and replaced with a special calibration plate that contains holes under each PMT. This plate restricts the photon flux so that it only strikes the crystal in very small regions directly under the PMTs.
2. A small vial containing 5–10 mCi of ^{99m}Tc is placed beneath the detector and exactly in the center of the field of view. A microprocessor controls the tuning operation and monitors each of the tubes in sequence.
3. Starting with Tube 1, the output of that tube is digitized to generate a spectrum.
4. The computer then calculates the centroid of the photopeak along the energy axis and compares it to a reference value in memory. The set of reference values is established at the factory when the camera is assembled.
5. If there has been a shift of more than 1% in the position of the photopeak, the preamplifier gain of that PMT is appropriately adjusted. If there is no discrepancy, or if the error is less that 1%, the microprocessor steps to the next tube, and so on, until all of the tubes have been checked.

A schematic diagram of this system is presented in Figure 2. The entire process requires ~ 30 min. The manufacturer recommends that the camera be tuned each week.

PMT Gain Monitoring With An LED

An entirely different technique† can also be used to tune a scintillation camera on-demand (i.e., when the user feels it is necessary). This method makes use of a light-emitting-diode (LED) to monitor the gain of the PMTs (*23*). As the acronym implies, a LED emits light when a current passes through it. Initially, a radioactive source is used to determine the location of the photopeak and to adjust PMT gains, similar to the technique described above. The LED is then switched on, and the individual PMT signals are measured and recorded as references for subsequent routine retuning.

When the user initiates the tuning sequence, several things occur. The first step involves the use of computer-generated pulses to check the gains and offsets of the positioning and energy determination circuits that produce the X, Y, and Z (energy) signals. This is accomplished by sending a series of computer-generated synthetic pulses to the positioning circuitry. One set mimics the signals that would be emitted by the PMTs if a gamma ray struck the crystal at the exact center of the X-Y coordinate system. Other sets are equivalent to a gamma ray striking the crystal at the edge of the field-of-view along the X- and Y-axis. The computer then checks the output of the position-encoding network to see if it accurately determined the X and Y position of these "events." If there is an error in offset or gain, a correction is made by adjusting a digital-analog-convertor. Synthetic pulses are also used to check the energy registration circuitry to see that determination of the X and Y position of an event is independent of photon energy. This entire procedure is an effective and complete way of checking the X, Y, and Z signals for both offset and gain errors. Such errors can produce a nonuniform im-

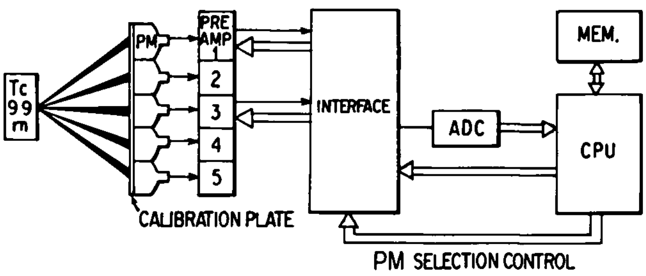

FIG. 2. Block diagram of a system that uses a point source of ^{99m}Tc and a special calibration mask for on-demand automatic tuning of photomultiplier gain under microprocessor control (*22*). See text for explanation.

age even when the PMTs are properly balanced because the energy and linearity correction maps will not accurately match the locations of the individual events. Maintaining the gains and offsets at a constant value is also important for whole-body scanning and emission-computed tomography where pixel size is a critical factor.

When Step 1 has been completed, the LED is switched on. A semi-conductor detector is then used to measure the light output of the LED to see whether or not it has changed since the previous tuning sequence. This is accomplished by comparing the measured value to a reference value. If the light output has changed, current through the LED is adjusted until the light output returns to the reference value.

In the third step of this procedure, the output of the individual PMTs is compared with predetermined reference values. Light from the LED is guided by light pipes to a set of points on the crystal that are equidistant from three tubes. Light passes through the crystal to the PMTs and each tube generates a signal. If the signals are different than the reference values, the high voltage on the individual tubes is adjusted as needed. Because proper operation of any PMT is limited to a specific dynamic range, PMT gain adjustment is not allowed to exceed $\pm$ 25% (*23*). The entire tuning sequence requires $<$ 25 sec. It is normally recommended that the camera be tuned 2–3 times each day of use.

The results of individual tuning sequences can be displayed and recorded on film if desired (*Bernstein T. personal communication, 1985*). These data can be kept as part of the quality control records and may be used by service personnel to see if an individual tube is drifting excessively.

CONTINUOUS TUNING

PMT Gain Monitoring With LEDs

Three different vendors tune their cameras on a "continuous" basis. Technically speaking, the tuning is not continuous, but it is automatically initiated on a periodic basis. One of these systems[‡] (*24*) uses LEDs as does the system that was previously described. There are, however, some significant differences. First, an LED is potted in the neck of each PMT. The LEDs are temperature compensated to maintain a constant tant light output despite temperature variations (*25*). Second, the set of LEDs are pulsed on for 1-2 μsec hundreds of times per sec (*Engdahl JC, personal communication, 1985*). Light travels down the glass of the PMT and illuminates the photocathode. Some light also enters the crystal and is reflected and distributed to the same and neighboring tubes. Because each tube has a LED, the response of a single tube to the light pulse is the sum of inputs from many LEDs, but it is most affected by seven LEDs, its own and the six nearest neighbors. The number of photoelectrons generated in the photocathode of the PMT by the LED light is markedly greater than those produced by scintillation radiation from gamma rays interacting with the crystal (by a factor of ten or more). Thus, they overwhelm any gamma events and are excluded from the image by the pulse-height analysis circuit.

The signals that are produced by the PMTs after the LEDs are flashed are fed to individual capacitors (one for each tube) with a time constant of ~ 1 sec (*Nowak DJ, personal communication, 1985*). A long time-constant is used to smooth out individual fluctuations, much like the idea of using a long time-constant on a rectilinear scanner to smooth out statistical fluctuations when peaking the instrument. A special circuit is used to compare the voltages on the capacitors to a single Zener diode stabilized reference voltage. If necessary, the gain on the PMT is adjusted. Although the LEDs are pulsed hundreds of times per second, the long time-constant dictates that significant changes in the PMT gain will occur less frequently. The essence of this technique is illustrated in Figure 3.

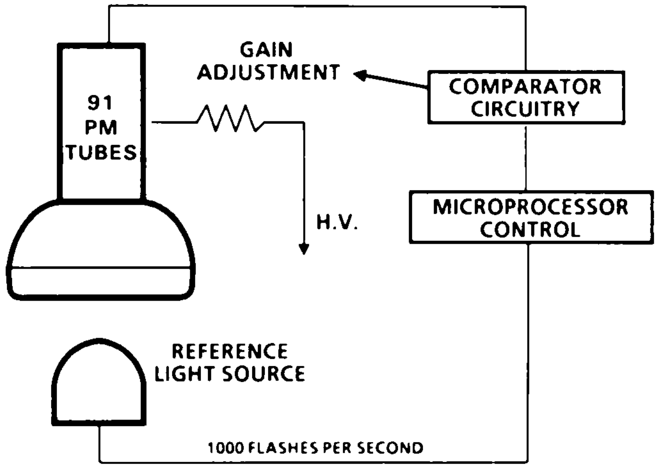

FIG. 3. Schematic diagram of a system using LEDs in each PMT for continuous monitoring and adjustment of photomultiplier gain (*24*).

This particular system also monitors the absolute gain of the individual PMTs. If the dynamic range of a PMT is exceeded, a warning light appears on the console to indicate that one of the tubes has drifted too far for the tuning circuit to work properly. Service personnel can identify the individual tube(s) and correct the problem. Because the tuning is continuous this technique was found to be particularly useful in earlier cameras that were especially sensitive to orientation in the earth's magnetic field.

Photopeak Monitoring

A still different approach used by one vendor[§] of scintillation cameras incorporates some of the features used in on-demand automatic tuning. One unique feature is that it uses radiation from the patient to provide continuous tuning (*26*). It is imperative that the PMTs be exceptionally stable from the standpoint of gain shifts at high count rates for this system to work properly. Photomultiplier tubes are carefully tested to see that they meet this criterion.

Each camera has two narrow auxiliary pulse-height analyzer (or tuning) windows associated with it. Figure 4 shows how the tuning windows are positioned for ^{99m}Tc. As illustrated in the figure, the windows are set on the high side of the photopeak so that the effects of scatter will be essentially eliminated. In addition, the size is such that when the PMTs are properly balanced, the counts in each of the tuning windows will be

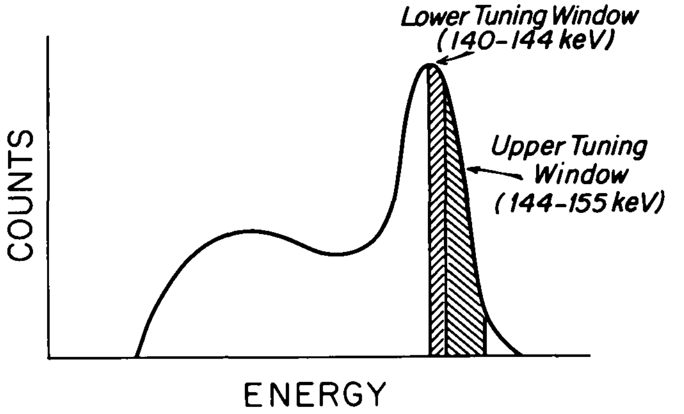

FIG. 4. Position and width of tuning windows for monitoring PMT gain shifts in a system that uses radiation from the patient for continuous automatic tuning of a scintillation camera (reprinted by courtesy of E.W. Stoub).

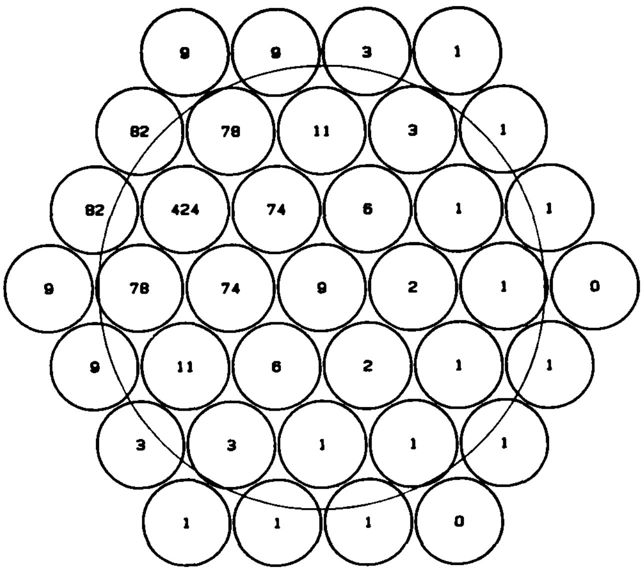

FIG. 5. Typical distribution of detected photons caused by a ^{99m}Tc photopeak event over PMT No. 11 in a 37-tube camera (reprinted by courtesy of E.W. Stoub).

equal. The positions of the tuning windows are determined by the energy set in Analyzer 1. Thus, the tuning windows for thallium are a bit different than those for ^{99m}Tc or ^{67}Ga. The microprocessor uses a lookup table to determine the actual position and width of these tuning windows. A pair of registers or memory units, used to monitor the number of counts recorded in each of the tuning windows is also associated with each PMT. The difference in counts in the register-pairs is used to monitor shifts of the photopeak. The crystal is digitally masked so that only those events which occur in the detector near the center of the PMT are recorded in the tuning windows. Approximately one-third of the gamma rays that strike the crystal are actually used for tuning. Furthermore, a special algorithm determines when tuning occurs.

Adjustment of the PMT gain may be initiated when one element of a register-pair reaches 8,000 counts. At that time, the microprocessor checks to see how many other register-pairs (tubes) have at least 2,000 counts in one element. If nine or more have at least 2,000 counts, the tuning sequence is initiated. If not, the registers are dumped (all are set to zero) and data collection is restarted. If the tuning sequence is initiated, only the tubes with register-pairs of more than 2,000 counts in one element are adjusted; all others are assumed to have no gain errors (*Stoub EW, personal communication, 1985*).

The microprocessor uses linear algebra techniques to calculate the PMT gain errors from the measured shift of the photopeak along the energy axis that is determined by the difference in counts in the register-pairs. The operation of the microprocessor can be described mathematically by the following equation:

$$\triangle Z = F_{ij} \times \triangle G,$$

where $\triangle Z$ is a column vector that is the observed shift ($\triangle$ meaning change) along the energy axis for each tube as calculated from the difference in counts recorded in the register-pairs, divided by the sum ($\triangle G$ is the gain shift vector). F_{ij} is a matrix of values that describe the proportion of photoelectrons released in PMT "j" because of a gamma or X-ray striking the crystal under PMT "i". In other words, this set of values (matrix) indicates how light is spread amongst different PMTs when a photon strikes the crystal at a specific location. These values can be determined experimentally and are relatively independent of energy and scatter conditions. (*Stoub EW, personal communication, 1985*). Figure 5 presents the data that are used to compute F_{ij}. When matrix F_{ij} is multiplied by the change in PMT gain ($\triangle G$), the product is the change in energy or the shift of the photopeak along the energy axis ($\triangle Z$). Of course, it is the shift of the photopeak that is observed, and it is the change in gain that is needed. To solve this problem in a mathematical sense, it is necessary to invert F to produce the following equation:

$$\triangle G = F_{ij}^{-1} \times \triangle Z,$$

where F_{ij}^{-1} is the inverse of the matrix F_{ij}. Once the gain shifts ($\triangle G$) have been calculated from the measured shifts of the photopeaks ($\triangle F$), the gain of the individual PMTs is adjusted. If the difference in counts is zero, there is no shift and the gain is not changed.

The automatic tuning circuit can be operated in two different modes. When the camera is first installed, or after major service, a rough tune can be performed. A point source of ^{57}Co or ^{99m}Tc is placed 1–2 meters from an uncollimated detector. Initiation of the tuning sequence brings the uniformity to within 1% of optimum PMT balance. From that point on, radiation from the patient is normally used for tuning.

Figure 6 illustrates an example of cycle-to-cycle variations in the shifts of the PMTs. Although there are some random changes, the overall variation is small. Figure 7 illustrates what happens when a camera is intentionally detuned. Within five to six tuning cycles the gains have converged so that the PMTs

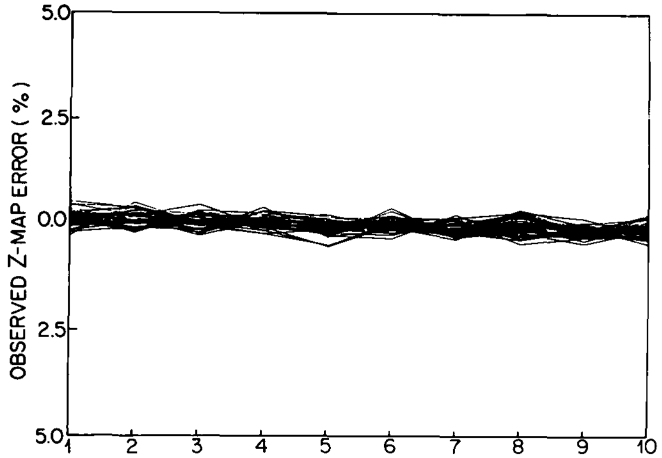

FIG. 6. Variations in Z-map errors for 10 sequential tune cycles (reprinted courtesy of E.W. Stoub).

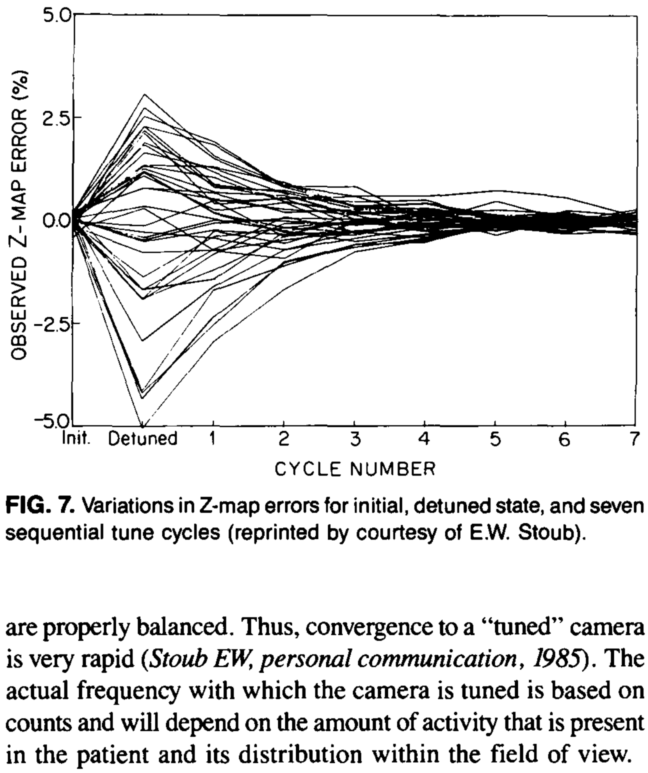

FIG. 7. Variations in Z-map errors for initial, detuned state, and seven sequential tune cycles (reprinted by courtesy of E.W. Stoub).

are properly balanced. Thus, convergence to a "tuned" camera is very rapid (*Stoub EW, personal communication, 1985*). The actual frequency with which the camera is tuned is based on counts and will depend on the amount of activity that is present in the patient and its distribution within the field of view.

This system also provides information that is useful for evaluating the overall operation of the tuning circuit. The user can see how much the gain of the individual tubes has changed and determine whether the limit of the dynamic range is being approached. Some of the other systems only signal the user when a failure has occurred.

PMT Voltage

A simpler approach, used by one vendor** to maintain PMT balance, involves the use of a microprocessor to continuously monitor voltage input to the PMTs (*Enos GW, personal communication, 1985*). As needed, the output of the digital high voltage supply is corrected to a set of reference values established when the camera is assembled. These values can also be updated by field service personnel. With the use of carefully selected PMTs, continuous monitoring, and correction of the high voltage supply, stable PMT output performance is provided (*Enos GW, personal communication, 1985*).

CONCLUSION

A number of different systems have been developed for automatic tuning of Anger scintillation cameras. These have improved system performance in clinical imaging and may reduce service costs. However, the presence of automatic tuning does not minimize the importance of careful camera operation and regular quality control procedures.

FOOTNOTES

*ADAC Laboratories, San Jose, CA.
†Elscint Inc., Boston, MA.
‡General Electric Company, Medical Systems Group, Milwaukee, WI.
§Siemens Medical Systems, Iselin, NJ.
**Raytheon Medical Systems, Melrose Park, IL.

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