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Relative calibration of energy thresholds on multi-bin spectral x-ray detectors

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ABSTRACT

Accurate and reliable energy calibration of spectral x-ray detectors used in medical imaging is essential for avoiding ring artifacts in the reconstructed images (computed tomography) and for performing accurate material basis decomposition. A simple and accurate method for relative calibration of the energy thresholds on a multi-bin spectral x-ray detector is presented. The method obtains the linear relations between all energy thresholds in a channel by scanning the thresholds with respect to each other during x-ray illumination. The method does not rely on a model of the detector's response function and does not require any identifiable features in the x-ray spectrum. Applying the same method, the offset between the thresholds can be determined also without external stimuli by utilizing the electronic noise as a source. The simplicity and accuracy of the method makes it suitable for implementation in clinical multi-bin spectral x-ray imaging systems.

1. Introduction

Spectral multi-bin detectors for medical x-ray imaging have the potential to increase the general image quality [1] and allow accurate material basis decomposition [2]. In the recent years, considerable effort has been devoted to developing spectral detectors for computed tomography (CT), predominantly using semiconductor materials such as cadmium zink telluride (CZT) and silicon [3,4].

In a multi-bin detector, photons are categorized according to their pulse amplitude (which, for a spectroscopic detector, is proportional to the energy) by a set of pulse-height comparators, or energy thresholds. Generally, the position of the thresholds is set by a digital setting (D) that has a linear relation to the pulse amplitude (A):

$$A = gD + m,$$

where g and m are referred to as the *gain* and the *offset* respectively. In order to be able to perform accurate material basis decomposition, the gain and offset have to be known with high accuracy [5]. The most common way to estimate the gain and the offset is to use a mono-energetic x-ray source or a synchrotron x-ray beam and measure the position of the peak from an s-curve (threshold scan) [6–8]. Other methods include identifying a feature in the detected spectrum [9,10], fitting a model to a measured s-curve [11] or varying the kVp and identifying the highest digital setting for which counts are registered [12]. Common for all methods in the previous art is that all thresholds within a channel are calibrated independently.

In this paper, we suggest an accurate and robust method for determining the relative gain and offset of the different thresholds within a channel. The method does not require a model of the detector's response function, or any identifiable feature in the x-ray spectrum. The proposed method can be used to increase the accuracy of the energy calibration of multi-bin detectors.

2. Method

2.1. Energy discrimination logic

When a photon interacts in a detector element on a photon-counting spectral detector, an electric pulse with pulse height proportional to the energy of the photon is created. Each individual detector element is connected to a subsequent channel in an ASIC (application specific integrated circuit). In the ASIC, a set of pulse-height comparators, also referred to as an energy thresholds, compare the pulse height to reference voltages supplied by digital-to-analog converters (DACs). Fig. 1 shows a typical example of an ASIC channel comprising a set of DACs, pulse-height comparators and corresponding digital counters. The voltage supplied by each DAC is controlled by the user via a digital setting. When the pulse amplitude from a photon interaction surpasses the reference voltage of the threshold, the threshold is “triggered”. A set of counters keep track of how many photons that surpass each threshold. The exact logic for which counter that registers the count may differ from detector to detector. In the detector that we have used

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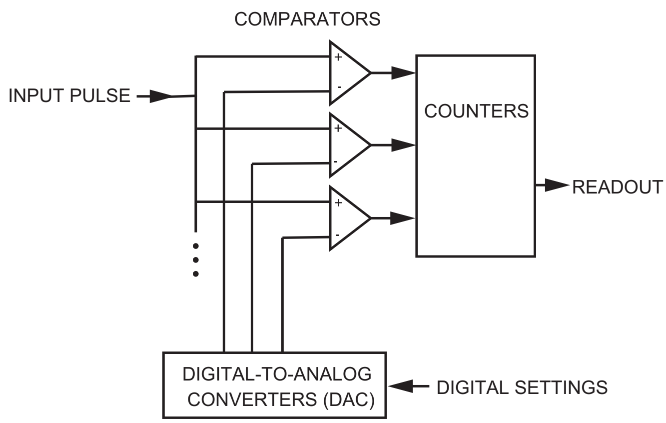

Fig. 1. Example of an energy discrimination logic in an ASIC.

in this study [6], the thresholds are numbered and the counter corresponding to the threshold with the highest number among the triggered thresholds is incremented. Due to differing electronic environments for the DACs and the comparators, the conversion between the digital setting and the pulse amplitude is individual for each threshold and channel.

2.2. Relative gain and offset

If the gain and offset of a comparator relates the digital setting to the pulse amplitude, then the *relative* gain and offset relates the digital settings of two comparators. Assume that we have two numbered comparators with digital settings D_1 and D_2 that correspond to pulse amplitudes $A_1(D_1) = g_1 D_1 + m_1$ and $A_2(D_2) = g_2 D_2 + m_2$. If the digital settings D_1^* and D_2^* set the two comparators such that they correspond to the same pulse amplitude, then

$$A_1(D_1^*) = A_2(D_2^*) \Rightarrow g_1 D_1^* + m_1 = g_2 D_2^* + m_2 \Longrightarrow$$
$$D_2^* = \frac{g_1}{g_2} D_1^* + \frac{m_1 - m_2}{g_2} \Longrightarrow D_2^* = g_{1,2} D_1^* + m_{1,2}$$

where $g_{1,2} = g_1/g_2$ and $m_{1,2} = (m_1 - m_2)/g_2$ will be referred to as the relative gain and offset between comparators 1 and 2. If we know $g_{1,2}$ and $m_{1,2}$, then we know the value of D_2^* for all values of D_1^*, and vice versa. In order to determine $g_{1,2}$ and $m_{1,2}$, we need to know D_1^* for at least two different values of D_2^*, i.e. we need to be able to find situations when we know that $A_1 = A_2$.

Now, recall that, for each photon, the counter corresponding to the threshold with the highest number among the triggered thresholds will be incremented. The counter corresponding to threshold number 1 will register all photons with amplitude $A_1 \le A \le A_2$, and the number of counts in counter number 1 will therefore be

$$N_1(D_1) = \begin{cases} \int_{A_1}^{A_2} S(A)\,dA & \text{for } A_1 < A_2 \\ 0 & \text{for } A_1 \ge A_2 \end{cases} \quad (1)$$

where $S(A)$ is the detected spectrum of pulse amplitudes. The number of counts in the first counter, N_1, should therefore become zero exactly when $A_1 = A_2$ and by measuring $N_1(D_1)$ for a fixed value of D_2^* and identifying the smallest value of D_1 for which $N_1(D_1)$ is zero, we can determine D_1^*. Unfortunately, $N_1(D_1)$ will not be exactly zero when $A_1 = A_2$ due to the finite energy resolution of the x-ray detectors. However, if the photon spectrum is approximately constant in the vicinity of A_2, then $N_1(D_1)$ will decrease linearly as A_1 approaches A_2, and the point where $A_1 = A_2$ can be estimated by linear regression. If the spectrum shape makes it difficult to find the positions where the curves $N_i(D_i)$ drop to zero (i.e. if the spectrum is very non-uniform), then other methods than linear regression will have to be used. One example could be to compare the entire shape of the $N_i(D_i)$ curves to estimate both the gain and offset between the thresholds. Although measuring D_1^* for only two different values of D_2^* is enough to determine the relative gain and offset, performing measurements at more than two points will increase the accuracy. Assume that we have N different values of D_1^* and D_2^*, then $g_{1,2}$ and $m_{1,2}$ can be estimated by solving a linear system of equations:

$$\begin{bmatrix} D_{1,1}^* & 1 \\ D_{1,2}^* & 1 \\ \vdots & \vdots \\ D_{1,N}^* & 1 \end{bmatrix} \begin{bmatrix} g_{1,2} \\ m_{1,2} \end{bmatrix} = \begin{bmatrix} D_{2,1}^* \\ D_{2,2}^* \\ \vdots \\ D_{2,N}^* \end{bmatrix}$$

The calibration relates the digital settings of a target threshold (here number 1) to the digital settings of a reference threshold with a higher number (here number 2). If the channel has more than two thresholds, the method will work for any combination of target and reference threshold as long as the thresholds that are not calibrated are positioned either below the target threshold or above the reference threshold. By choosing the threshold with the highest number as the reference threshold, we can calibrate all lower thresholds to the same reference threshold, and thereby obtain the relation between all thresholds on the channel.

2.3. Absolute gain and offset

Now assume that we have determined the (absolute) gain and offset of the n:th comparator ($A_n = g_n D_n + m_n$), and that we have determined the relative gain and offset of all other comparators with respect to the n:th comparator ($D_n = g_{i,n} D_i + m_{i,n}$), then the absolute gain and offset of the i:th comparator can be obtained by:

$$A_n = g_n D_n + m_n = g_n (g_{i,n} D_i + m_{i,n}) + m_n = g_n g_{i,n} D_i + g_n m_{i,n} + m_n \Longrightarrow$$
$$A_n = g_i D_i + m_i$$

where $g_i = g_n g_{i,n}$ and $m_i = g_n m_{i,n} + m_n$. If we know the relative gain and offsets, then it is only necessary to obtain the absolute gain and offset of one of the comparators on the channel in order to have a complete energy calibration.

3. Results

To demonstrate the method, we have performed measurements with a spectral and photon-counting silicon-strip detector currently being developed for x-ray computed tomography [3,13]. The detector has eight energy thresholds and the digital settings are integers between 1 and 255. An x-ray tube operating at 120 keV was used as a source. Fig. 2 shows the $N_i(D_i)$ curves for three different thresholds (1, 2 and 3) when using threshold number 8 as the reference threshold with $D_8^* = 50$. The curves clearly show the linear behavior predicted by an approximately constant spectrum and the positions where $N_i(D_i) \simeq 0$, are easy to find using linear regression.

The proposed method was used to estimate the relative gain and offset for thresholds from 1 to 7 on 300 channels using three different settings of the reference threshold D_8^* (50, 70, 100). To verify the method, a tungsten sheet was placed in front of the x-ray source, introducing the k-edge in the spectrum at 69.5 keV [9]. The thresholds were then scanned individually over the k-edge, producing s-curves. The k-edge is visible in the s-curves as a sudden change in the slope and the position of the k-edge was estimated using locally linear regression. An example of an s-curve with a visible k-edge is shown in Fig. 3.

If the position of the k-edge in the s-curve of the i:th threshold is $\widetilde{D}_i$, then the position of the k-edge in the s-curve of the 8: th threshold can be estimated by: $\widetilde{D}_8 = g_{i,8} \widetilde{D}_i + m_{i,8}$. If the relative gains and offsets have been determined correctly, then the estimated position of the k-edge $\widetilde{D}_8$ should coincide with the measured position of the k-edge in the s-curve of the 8: th threshold. Fig. 4 shows the normalized error distribution