Maximum-likelihood scintillation detection for EM-CCD based gamma cameras

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Abstract

Gamma cameras based on charge-coupled devices (CCDs) coupled to continuous scintillation crystals can combine a good detection efficiency with high spatial resolutions with the aid of advanced scintillation detection algorithms. A previously developed analytical multi-scale algorithm (MSA) models the depth-dependent light distribution but does not take statistics into account. Here we present and validate a novel statistical maximum-likelihood algorithm (MLA) that combines a realistic light distribution model with an experimentally validated statistical model. The MLA was tested for an electron multiplying CCD optically coupled to CsI(Tl) scintillators of different thicknesses. For $^{99m}$Tc imaging, the spatial resolution (for perpendicular and oblique incidence), energy resolution and signal-to-background counts ratio (SBR) obtained with the MLA were compared with those of the MSA. Compared to the MSA, the MLA improves the energy resolution by more than a factor of 1.6 and the SBR is enhanced by more than a factor of 1.3. For oblique incidence (approximately 45°), the depth-of-interaction corrected spatial resolution is improved by a factor of at least 1.1, while for perpendicular incidence the MLA resolution does not consistently differ significantly from the MSA result for all tested scintillator thicknesses. For the thickest scintillator (3 mm, interaction probability 66% at 141 keV) a spatial resolution (perpendicular incidence) of 147 μm full width at half maximum (FWHM) was obtained with an energy resolution of 35.2% FWHM. These results of the MLA were achieved without prior calibration of scintillations as is needed for many statistical scintillation detection algorithms. We conclude that the...
MLA significantly improves the gamma camera performance compared to the MSA.

(Some figures in this article are in colour only in the electronic version)

1. Introduction


Compact, high-resolution gamma imaging cameras are being developed by many research groups (Nagarkar et al 1996, Matteson et al 1997, Menard et al 1998, He et al 1999, Vavrík et al 2002, Fiorini et al 2003, Lees et al 2003, Miyata et al 2004, Ponchut et al 2005, Kataoka et al 2005). A subset of these gamma cameras use micro-columnar CsI(Tl) scintillators (Nagarkar et al 1998) in combination with electron multiplying charge-coupled devices (EM-CCDs) (de Vree et al 2005, Nagarkar et al 2006, Meng 2006, Miller et al 2006, Heemskerk et al 2007, Meng and Fu 2008). In such CCD based detectors individual scintillation events can be detected in photon counting mode, enabled by readout at high frame rates. This detection method greatly improves the spatial resolution compared to integration of the scintillation light signal (Beekman and de Vree 2005). The sensitivity of these detectors can be improved by using continuous instead of micro-columnar scintillators which are available in larger thicknesses (Korevaar et al 2009a, Heemskerk et al 2009). A problem of pinhole gamma cameras with continuous crystals is the degradation of spatial resolution due to the variable depth-of-interaction (DOI) for gamma photons incident at oblique angles (Hwang et al 2001, Korevaar et al 2009b). This degradation of spatial resolution can be reduced by using a detection algorithm that can detect the DOI. We have previously developed such a scintillation detection algorithm, the multi-scale algorithm (MSA), that uses an analytical model for the depth-dependent light distribution (Korevaar et al 2009a). While this algorithm already improves significantly upon an algorithm that does not use a depth-dependent light distribution model, further improvements in performance are expected by using a statistical scintillation detection algorithm.

Previously, a statistical scintillation detection algorithm using a calibration based approach was applied to an EM-CCD based gamma camera with a micro-columnar scintillator (Miller et al 2006) and to a simulation of a multi-anode photomultiplier tube-based gamma camera with a thick continuous scintillator (Hunter et al 2009). Furthermore, an excellent overview article about maximum-likelihood scintillation detection is available (Barrett et al 2009). Detection algorithms that rely on the calibration of individual scintillations have their disadvantages; given the large number of pixels of a CCD, these calibrations are often time consuming and lead to a data storage challenge.
In this paper, we present a novel statistical scintillation detection algorithm for EM-CCD-based gamma cameras with continuous scintillators. This algorithm does not require the calibration of gamma photon scintillations but instead uses analytical models for the light distribution and EM-CCD statistics. The statistical model derived in this paper is based on research into EM-CCD characteristics performed by many authors (Basden et al 2003, Plakhotnik et al 2006, Lantz et al 2008). Maximum-likelihood estimation is used to determine the scintillation position and energy of the incoming gamma photon. The performance of this maximum-likelihood algorithm (MLA) is evaluated by comparison with the MSA in terms of spatial resolution, DOI corrected spatial resolution for oblique incidence, energy resolution and the signal-to-background counts ratio (SBR).

2. Methods

2.1. EM-CCD, optical coupling and scintillator

A gamma camera consists of a CsI(Tl) SCIONIX scintillator optically coupled, by a fiber optic plate (FOP), to the E2V CCD97 EM-CCD (Hynecek 2001, Hynecek and Nishiwaki 2003, Robbins and Hadwen 2003). A schematic of the gamma camera is shown in figure 1 and is described in detail in Korevaar et al (2009a). The pixels here are binned (Westra et al 2009) on a chip of the size of 16 × 32 μm². The FOP reduces the number of optical photons that reach the EM-CCD at large oblique angles (see the appendix). The scintillator thicknesses used in this paper are 0.7, 1.5, 1.8 and 3 mm with interaction probabilities for 99mTc gamma photons (141 keV) of 20, 42, 47 and 66%, respectively.

2.2. Multi-scale algorithm

The MSA acts as a matched filter that takes the depth-dependent light distribution in the continuous scintillator into account and can therefore accurately estimate the DOI (Korevaar et al 2009a). Implicitly, the MSA uses a Gaussian light distribution model. Here we employ the MSA with a threshold on the CCD data which is at a level of 3 times the \( \sigma \) (standard deviation) above the mean dark level of the individual pixel. The pixel \( \sigma \) and the mean dark level are determined from dark CCD frames.
2.3. Maximum-likelihood algorithm

The MLA estimates the position and energy of scintillations by calculating the response of the detector for a given estimated position and energy and iteratively updating the estimate after comparison of the calculated response to the actual measurement (i.e. CCD frame). In order to accurately calculate the detector response and thus accurately determine the position and energy of scintillation events, the MLA requires advanced modeling of the detector in terms of mean scintillation photon distribution and detector statistics. The mean light distribution (figure 2(a)) and statistical model (figure 3) and their validations are discussed below.

2.3.1. Light distribution. In our gamma detector a gamma photon is absorbed in the scintillator and optical photons are generated (shown in figure 2(a)). The first step in calculating the detector response consists of estimating the mean number of scintillation photons $\lambda_i$ incident on each pixel $i$ of the detector for a given scintillation position and energy. Assuming a single interaction position and neglecting interactions of optical photons with the scintillator but taking into account Fresnel reflections and the optical properties of the FOP,
the mean light distribution can be modeled by
\[
\lambda_i(\tilde{\theta}) = \frac{\theta N \cdot f(\phi_i)}{4\pi |\tilde{p}_i - \tilde{p}_g|^3} + \theta bg,
\]
\[
\tilde{\theta} = (\tilde{\theta}_x, \tilde{\theta}_N, \theta bg) = (\theta_x, \theta_z, \theta_N, \theta bg).
\]
(1)

Here, \( \tilde{\theta} \) is the parameter vector describing the scintillation event; it contains the scintillation position \( \tilde{\theta}_\gamma \), consisting of \( \tilde{\theta}_x = (x_i, y_i) \) and \( \theta_z \), representing the \( x \), \( y \) and \( z \) coordinates of the scintillation, the number of generated optical photons \( \theta N \) and the background signal \( \theta bg \). Furthermore, \( \tilde{p}_i \) is the pixel position, consisting of the lateral pixel position \( \tilde{r}_i = (x_i, y_i) \) and \( z \)-position \( z_i \), \( A \) is the area of an EM-CCD pixel, \( \epsilon \) is an efficiency factor and the function \( f(\phi_i) \) describes the Fresnel reflections and transmission of the FOP as a function of the angle \( \phi_i \) of the photon with the fiber axis for pixel \( i \) (see the appendix). The \( z \)-axis is chosen perpendicular to the scintillator plane with zero at the scintillator bottom (see figure 1(b)). To obtain a simple expression for the mean light distribution, we have approximated (1) by a Gaussian with a cutoff at an angle \( \phi_{cutoff} \):
\[
\lambda_i(\tilde{\theta}) = H \left[ \phi_{cutoff} - \arctan \left( \frac{|\tilde{r}_i - \tilde{\theta}_i|}{\theta_z} \right) \right] \frac{\theta N \cdot f(\phi_i)}{2\pi \sigma_{DOF}(\theta_z)} \cdot \exp \left[ -\frac{|\tilde{r}_i - \tilde{\theta}_i|^2}{2\sigma_{DOF}^2(\theta_z)} \right] + \theta bg.
\]
(2)

Here \( H \) is the Heaviside step function and \( \sigma_{DOF}(\theta_z) \) describes the width of the light distribution which depends on the scintillation \( z \)-position \( \theta_z \).

### 2.3.2. Statistical model

The role of the statistical model (figure 3) is to provide a complete distribution of the detector output for a mean photon distribution described by the light distribution model. The number of optical photons generated is not a Poisson random variable (Dorenbos et al. 1995, Kupinski and Barrett 2005), however, through rarity, the optical photons incident on one pixel of the EM-CCD are Poisson distributed (Barrett and Myers 2004a, Barrett et al. 2009). An optical photon incident on the EM-CCD can reflect at different boundaries (scintillator-optical coupling, optical coupling-FOP, etc) before reaching the EM-CCD and an optical photon reaching the EM-CCD can generate an electron-hole pair or not. Both these processes are binomial selections whereby the Poisson distribution is retained and only its mean changes (Barrett and Myers 2004b). Besides these electrons generated by photons, also noise-induced electrons can be present in a pixel of the EM-CCD. The main noise sources for electrons are dark current noise and CIC noise (Basden et al. 2003, Plakhotnik et al. 2006, Lantz et al. 2008), shown in figure 3. These noise-induced electrons are Poisson distributed. The sum of the photon generated electrons and noise-induced electrons in one pixel is again a Poisson random variable
\[
pr_{EM}(n|\tilde{n}) = \frac{\tilde{n}^n \exp (-\tilde{n})}{n!}
\]
\[
\tilde{n} = n_p + \tilde{n}_n,
\]
(3)

where \( n \) is the number of electrons in the pixel and \( \tilde{n} \) the mean number of electrons in the pixel consisting of the mean number of photon-generated electrons \( \tilde{n}_p \) and the mean number of noise-induced electrons \( \tilde{n}_n \). The electrons are amplified in the electron multiplication (EM) register, and the conditional probability \( pr_{EM}(g|n) \) for \( g \) electrons at the EM register output given \( n \) electrons in a pixel is, similar to Basden et al. (2003), given by
\[
pr_{EM}(g|n) = H(g) \frac{g^{n-1} \exp \left( -\frac{\tilde{n}}{\text{gain}} \right)}{\text{gain}^n (n-1)!} + \delta_{gn} \delta(g).
\]
(4)
Here $H(g)$ is the Heaviside step function, $\delta_{0i}$ is the Kronecker delta and $\delta(g)$ is the Dirac delta function. We describe the number of electrons at the EM register output by a continuous variable $n$, which is allowed because gain $\gg 1$. The distribution $p_{\text{FEM}}(g|n)$ is normalized for integration over $g$ for any given $n$. Combining distributions (3) and (4) yields the conditional probability $p_{\text{outputEM}}(g|\bar{n})$ of the number of electrons at the EM register output given a mean number of electrons in a pixel,

$$p_{\text{outputEM}}(g|\bar{n}) = \sum_{n=0}^{\infty} p_{\text{FEM}}(g|n) \cdot p_{\text{rel}}(n|\bar{n})$$

$$= H(g) \exp\left(-\bar{n} - \frac{g}{\text{gain}}\right) \sqrt{\frac{\bar{n}}{g \cdot \text{gain}}} I_1 \left(2 \sqrt{\frac{\bar{n}g}{\text{gain}}}\right) + \exp(-\bar{n}) \delta(g). \quad (5)$$

Here $I_1$ is the modified Bessel function of the first kind and the Dirac delta function $\delta(g)$ describes the case of zero electrons at the input of the EM register.

Subsequently, the electrons at the output of the EM register are converted to a voltage in the charge-to-voltage amplifier. This conversion and other electronic noise in the analog electronics add readout noise which has a Gaussian distribution. The output is a convolution of a Gaussian with the output signal (Lantz et al 2008), but can be approximated by a convolution with the Dirac delta function in (5) only (Plakhotnik et al 2006). Applying this to the distribution in (5) results in

$$p_{\text{output}}(g|\bar{n}) = H(g) \exp\left(-\bar{n} - \frac{g}{\text{gain}}\right) \sqrt{\frac{\bar{n}}{g \cdot \text{gain}}} I_1 \left(2 \sqrt{\frac{\bar{n}g}{\text{gain}}}\right) + \exp(-\bar{n}) \frac{1}{\sqrt{2\pi\sigma}} \exp\left(-\frac{g^2}{2\sigma^2}\right). \quad (6)$$

where $\sigma$ is the standard deviation of the Gaussian readout noise. The distribution is normalized for integration over $g$ from $-\infty$ to $+\infty$. Equation (6) is the conditional probability to measure $g$ electrons at the output given $\bar{n}$. Since we want to estimate $\bar{n}$ given a certain output $g$, we need the conditional probability $p_{\text{output}}(\bar{n}|g)$. We have no prior knowledge of $\bar{n}$ and therefore assume that $p_r(\bar{n})$ is constant for non-negative $\bar{n}$ and zero for negative $\bar{n}$ as is typical in ML methods (Barrett et al 2009). In that case Bayes rule (Barrett and Myers 2004c) reduces to

$$p_{\text{output}}(\bar{n}|g) = \int_0^{\infty} \frac{p_{\text{output}}(g|\bar{n})}{p_{\text{output}}(g|\bar{n})} d\bar{n}. \quad (7)$$

Applying this to the approximation above results in a normalization of (6) for $\bar{n}$:

$$p_{\text{output}}(\bar{n}|g) = \left[H(g)\text{gain}^{-1} + \exp\left(-\frac{g^2}{2\sigma^2}\right)(\sqrt{2\pi\sigma})^{-1}\right]^{-1} p_{\text{output}}(g|\bar{n}). \quad (8)$$

2.3.3. Maximum-likelihood estimation. Combining the light distribution model (1) and the noise $\bar{n}_i$ with the normalized conditional probability (8) and multiplying over all pixels $i$, the conditional probability for a scintillation described by vector $\theta$ given the measured pixel values $\vec{g}$ is

$$p_{\text{output}}(\theta|\vec{g}) = \prod_i p_{\text{output}}(\lambda_i(\vec{\theta}) + (\bar{n}_i)|g_i), \quad (9)$$

where $\vec{\theta}$ is the vector describing the scintillation position, the number of generated optical photons and the background signal defined in (1). The maximum-likelihood estimate is obtained by maximizing (9) or its logarithm.
2.3.4. Implementation of MLA. For the ML algorithm, the CCD frame is thresholded at a level of 3 times the Gaussian readout noise and the data are binned from $16 \times 32$ to $64 \times 64$ $\mu$m pixels by digital summation. The threshold on the data was necessary due to a low amplitude drift in the CCD frame data. To obtain starting values for the vector $\vec{\theta}$ (see (1)), the CCD frame is initially searched with the MSA algorithm and the outcome is used as a first estimate. The starting value for $\theta_{bg}$ is set at $\bar{n}_n$, obtained from a measurement of the noise. Subsequently, a taxi-cab type search algorithm maximizes the log of the likelihood (9). This search algorithm, which is a simple version of the Powell method (Powell 1964) and similar to a previously published work (Hunter et al 2007, Hesterman et al 2010), evaluates $\log[pr_{output}(\vec{\theta}, \vec{g})]$ by varying only one of the elements of the vector $\vec{\theta}$ at a time. The value that maximizes an arithmetic mean of the likelihood (9) is chosen as the new estimate of $\vec{\theta}$. This taxi-cab type algorithm performs the same search for all elements in vector $\vec{\theta}$ and this five-element search is repeated for 40 iterations.

2.4. Validation methods

2.4.1. Validation of the statistical model. To validate the probability distribution (6) that was derived in this paper and that forms the basis of the MLA, a series of measurements was performed. The pixel values $\vec{g}$ of the EM-CCD were measured as a function of the mean number of incident photons. To this end we irradiated the EM-CCD with a light source with varying intensities and measured its response. The measurements were fitted with (6) with gain, $\bar{n}$ and $\sigma$ as fit parameters.

2.4.2. Scintillation light distribution on the detector. The mean light distribution of optical photons on the EM-CCD as a function of the depth of the scintillation events ($\theta_z$) was measured. The setup for this measurement consisted of a slit at an angle of approximately $45^\circ$ as shown in figure 2(b). The scintillations at a certain depth ($\theta_z$) can be selected by combination of the detected position ($\theta_x, \theta_y$) with the known thickness of the scintillator. Scintillations detected at the same depth ($\theta_z$) were summed to obtain mean scintillation light distributions as a function of depth. These mean light distributions at 15 different depths were fitted with (1) where the fit parameters were $\theta_x, \theta_N, \theta_{bg}$ and the reflectivity (see the appendix). $\theta_c$ was set to the value of the known depth. The light distributions were fitted again with (1) with constant reflectivity (obtained from the previous fit) and with the Gaussian given by (2) with fit parameters $\theta_z, \theta_x, \theta_N$ and $\theta_{bg}$. The value of $\phi_{cutoff}$ in (2) was chosen at $37^\circ$. The linear relation between $\sigma_{DQI}$ and ($\theta_z$) was determined from the latter fit.

2.5. Algorithm comparison

As a measure of performance of the statistical algorithm, its spatial resolution, energy resolution, SBR and linearity of response with energy are compared with the values obtained by the MSA. In the MSA the slices are selected in such a way that every slice corresponds to a depth in the scintillator of approximately 300 $\mu$m. However, in the case of oblique incidence more slices were chosen (approximately 70 $\mu$m per slice) to rule out any spatial resolution degradation due to a limited number of slices. To determine the spatial resolution, a line pattern from a $^{99m}$Tc source (141 keV), projecting through a slit onto the scintillator, is acquired (illustrated in figure 2(a)). The spatial resolution is defined as the full width at half maximum (FWHM) of the line spread function of the radioactive source without correction for the width of the gamma photon beam. In our experiments we have investigated both perpendicular incidence (figure 2(a)) and incidence at an angle of approximately $45^\circ$.
Figure 4. Measured distribution for a signal level and a fit with (6) for (a) 3.2 detected photons per pixel, (b) 6.6 detected photons per pixel and (c) no photons incident on the CCD ($\bar{n} = 0.1$ due to noise).

(figure 2(b)). The FWHM energy resolution is obtained by determining the FWHM of the $^{99m}$Tc photo-peak for the scintillations in an area around the slit (with a width of 260 pixels). The energy in the energy spectra is calibrated by using the photo-peak of $^{99m}$Tc at 141 keV. The SBR is defined as in Korevaar et al (2009a). The uncertainties in the SBR, spatial and energy resolution measurement were determined using the bootstrap method (Efron 1979) and are expressed as a standard deviation. Comparison of the spatial resolution and SBR of the two algorithms is always done for an equal number of net signal counts. This is accomplished by setting an energy window for the MSA and the MLA. The linearity of response with energy of the MLA is investigated using a $^{99m}$Tc, $^{241}$Am and $^{125}$I source after which the measured relative photo-peak energy is compared with the known relative photo-peak energies of these isotopes.

3. Results

3.1. Validation of the statistical model

The output distribution of a single pixel was measured as a function of the mean number of detected photons per pixel and fitted using (6). The plots, shown in figure 4, show a fairly good fit indicating that the statistical model gives an adequate description of the large noise and signal components.
3.2. Scintillation light distribution on the detector

The measured mean light distribution of scintillations on the detector pixels is shown in figure 5(a). The mean reflectivity obtained from the fit was $0.9976 \pm 0.0004$. The profiles and the fit results are shown in figures 5(b) and (c) for depths of approximately 0.4 and 1.3 mm. The measurements and fits show that both the model (1) and the Gaussian (2) can describe the mean light distribution accurately.

3.3. Spatial resolution for perpendicular incidence

The influence of the algorithm on the spatial resolution is investigated using the line pattern measurement of $^{99m}$Tc (as shown in figure 2(a)) consisting of 100,000 CCD frames for the 3 mm thick scintillator and 50,000 CCD frames for the 1.8 mm thick scintillator. For the 3 mm thick scintillator, the profiles of the line patterns obtained with the MLA and the MSA are shown in figure 6. Both profiles are approximately the same. For the 1.8 mm thick scintillator the results are shown in table 1. The FWHM spatial resolution for the MLA is slightly smaller than for the MSA, but only significantly for the 1.8 mm thick scintillator. The spatial resolution for the 3 mm scintillator was $150 \mu m$ for the MSA, a factor 1.02 $\pm$ 0.03 from the $147 \mu m$ for the MLA. The spatial resolution for the 1.8 mm scintillator was $125 \mu m$ for the MSA, a factor 1.10 $\pm$ 0.04 from the $114 \mu m$ for the MLA. All results and errors are summarized in table 1.
Table 1. Spatial resolution, energy resolution (FWHM) and SBR for the MLA and MSA.

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>MSA</th>
<th>MLA</th>
<th>Improvement factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy resolution (%)</td>
<td>1.5</td>
<td>53.3 ± 1.4</td>
<td>32.7 ± 0.8</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>65.3 ± 2.9</td>
<td>35.2 ± 0.7</td>
</tr>
<tr>
<td>Spatial resolution Δx (μm)</td>
<td>1.8</td>
<td>125 ± 2</td>
<td>114 ± 3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>150 ± 3</td>
<td>147 ± 2</td>
</tr>
<tr>
<td>Spatial resolution Δx (μm)</td>
<td>1.5</td>
<td>306 ± 4</td>
<td>273 ± 4</td>
</tr>
<tr>
<td>at oblique incidence (45°)</td>
<td>3</td>
<td>495 ± 12</td>
<td>437 ± 9</td>
</tr>
<tr>
<td>SBR</td>
<td>1.5</td>
<td>87 ± 4</td>
<td>133 ± 7</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>130 ± 7</td>
<td>178 ± 11</td>
</tr>
</tbody>
</table>

3.4. DOI detection and correction

Figure 7 illustrates the capability of our algorithm to estimate the z-coordinate of the interaction for the 3 mm thick scintillator. A density plot is shown in figure 7(a) with the gray scale representing the number of detected scintillation events as a function of x- and z-position, when the gamma photons of the $^{99m}$Tc source are incident under an angle of approximately 45°. As expected, the scintillation events are distributed along a line having a slope of approximately 45° with respect to the scintillator surface plane. Figure 7(b) shows the spatial profile of the density plot in (a). It can be clearly seen that the intensity of the detected gamma beam is reduced by interactions of photons with the scintillator, as would be expected. For the 3 mm thick scintillator, the MLA is slightly more efficient at detecting scintillations far from the detector (at $z \approx 3$ mm or $x \approx 6$ mm) compared with the MSA (remember that the profiles are shown with an equal total number of counts). In figure 7(c), the profile corrected for the DOI is plotted. Compared with the MSA, the MLA improves the DOI corrected spatial resolution by a factor of 1.13 ± 0.04 (from 495 to 437 μm FWHM) for the 3 mm thick scintillator and by a factor of 1.12 ± 0.02 (from 306 to 273 μm FWHM) for the 1.5 mm thick scintillator (see table 1). The measurements contain 100 000 (1.5 mm) and 75 000 (3 mm) CCD frames.
3.5. Energy resolution and SBR

The energy spectra for the MLA and MSA, shown in figure 8, consist of 100,000 CCD frames for the 1.5 mm scintillator and 95,000 frames for the 3 mm scintillator. For both scintillator thicknesses the MLA significantly improves upon the energy resolution obtained with the MSA. For the 1.5 mm thick scintillator the energy resolution improves from 53.3 to 32.7% by a factor of 1.63 ± 0.06, and for the 3 mm thick scintillator the energy resolution improves from 65.3 to 35.2% by a factor of 1.85 ± 0.09. Compared with the MSA, the MLA improves the SBR from 87 to 133 by a factor of 1.54 ± 0.10 (1.5 mm) and from 130 to 178 by a factor of 1.37 ± 0.11 (3 mm).

3.6. Linearity of response with energy

The energy spectra of $^{99m}$Tc and $^{241}$Am for the 1.5 mm thick scintillators are shown in figure 9(a). The high-energy tail of the $^{241}$Am spectrum is probably due to the high count rate during the measurement which resulted in pile-up. The same measurement for $^{99m}$Tc and $^{125}$I was performed on a 0.7 mm thick scintillator. In figure 9(b), the measured relative energy peak for $^{125}$I, $^{241}$Am and $^{99m}$Tc (with respect to the $^{99m}$Tc energy peak position) for the MLA and MSA are plotted versus the known isotope gamma energies. The responses with energy for the MLA and the MSA are approximately equal and linear.
4. Discussion

The MLA presented in this paper uses a validated statistical model of the EM-CCD, based on the work by Basden et al. (2003), Lantz et al. (2008), Plakhotnik et al. (2006) and a Gaussian approximation to a realistic light distribution model. The results in this paper show that the use of a statistical model in a scintillation detection algorithm improves the performance. The MLA outperforms the previously developed MSA which, like the MLA, uses a Gaussian depth-dependent light distribution model but no statistical model for detector response and noise. The aspect that benefits the most from the statistical approach is the energy resolution; a significant improvement of more than a factor 1.6 is found for scintillator thicknesses of 1.5 mm and 3 mm. Furthermore, the MLA improves the SBR by factors of 1.37–1.54, depending on the scintillator thickness, and the DOI corrected spatial resolution for oblique incidence by factors of 1.12 (1.5 mm thick scintillator) and 1.13 (3 mm). For the latter measurement, we chose to use many slices in the MSA (with a single slice corresponding to 70 μm instead of 300 μm in depth) to rule out any degradation of the MSA result due to too few slices. The spatial resolution for perpendicular incidence was, within uncertainty, the same with the 3 mm thick scintillator for both algorithms. However, for the 1.8 mm
thick scintillator, the improvement for the MLA is small but significant. Furthermore, it was shown that the responses with energy for the MLA and MSA are approximately linear by a measurement for $^{99m}$Tc and $^{241}$Am with a 1.5 mm thick scintillator and for $^{99m}$Tc and $^{125}$I with a 0.7 mm scintillator. These measurements with $^{241}$Am and $^{125}$I were performed on rather thin scintillators because thick scintillators (3 mm) would make detection of these low energies very difficult.

The MLA, unlike many statistical scintillation detection algorithms, does not require calibration of individual scintillations for different scintillation positions and energies. Although calibration could improve performance close to the edges of the camera, it requires a recurring large experimental effort to obtain the calibration data and it also requires a large amount of data storage for detectors with many pixels such as CCDs.

Using the MLA, our gamma camera reaches a spatial resolution of $147 \pm 2 \ \mu m$ FWHM with an energy resolution of $35.2 \pm 0.8\%$ for $^{99m}$Tc for the 3 mm thick scintillator (interaction probability 67% at 141 keV). While the spatial resolution is much better than the spatial resolution of clinical gamma cameras (typically 3–4 mm), the energy resolution is not yet as good. However, this is not so important for animal imaging as scatter rejection is often not required due to the relatively low amount of scatter in animals compared to humans.

Furthermore, we expect to further improve the detector performance by combining the advantages of silicon photo multipliers (SiPM) with those of EM-CCDs using SiPM side detection (Heemskerk et al. 2010). Moreover, we expect that further reduction of the noise in the EM-CCD, for instance by using an advanced CCD controller (Daigle et al. 2009), can improve the energy resolution. To accurately determine how much a given reduction of noise will improve the performance of the EM-CCD based gamma camera a simulation study would be beneficial.

5. Conclusion

In this paper we have presented a statistical maximum-likelihood scintillation detection algorithm. The statistical model and light distribution model employed in the algorithm have been validated experimentally. We have compared the statistical scintillation detection algorithm with a previously presented analytical multi-scale algorithm and found that the use of a statistical instead of an analytical algorithm significantly improves the energy resolution, the spatial resolution for oblique incidence and the SBR.

Acknowledgments

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Appendix

The optical light distribution is determined by the various optical components of the detector (shown in figure A1). The optical system consists of the scintillator which absorbs gamma photons and emits optical photons. These optical photons can travel through the thin layer of optical grease (Bicron 630) to the fiber optic plate (FOP) with angle $\phi_i$ with the fiber axis. The FOP restricts lateral spreading of optical photons. An optical epoxy (Epotec 301-2 with refractive index $n_s = 1.53$ (Epoxy-Technology 2010)) connects the FOP optically to
the EM-CCD. To accurately model the light distribution of a scintillation as detected on an EM-CCD, we use a model that describes the different optical components. The FOP is the most complicated part of the optical system. The Anteryon FOP core is made of FOC-1 glass ($n_3 = 1.805$) and the cladding is made of 8250 Scott glass ($n_4 = 1.487$). These refractive indices result in a critical angle $\phi_c$ of $34.5^\circ$ with the fiber axis. The FOP is 3 mm thick and consists of fibers with a diameter of 5.4 $\mu$m. In order to take the transmission of skew rays (Snyder et al 1973) above the critical angle into account, the fibers are assumed to be cylindrical. The main causes of attenuation in the FOP are Fresnel reflections at the faces, an internal reflectivity less than 1 and absorption within the material of the fiber (Potter 1961). The Fresnel reflections at the faces of the FOP and at the CsI(Tl) scintillator ($n_1 = 1.79$ (Saint-Gobain-Crystals 2007)) to optical grease (Bicron 630, $n_2 = 1.47$ (Braem et al 2007)) interface are taken into account. The internal reflectivity is assumed to be less than 1 and the equation given by Mildner and Chen (1994) is used. Given the relatively small thickness of the FOP, the absorption within the material is neglected. We neglect the small difference in refractive indices between $n_1$ (1.79) and $n_3$ (1.805) and between $n_2$ (1.47) and $n_5$ (1.53) which simplifies the expression for the Fresnel transmission. Furthermore, the angle of a photon with the scintillator surface is approximated by the angle with the fiber axis, denoted by $\phi_i$. $f(\phi_i)$ from (1) can then be described by

$$f(\phi_i) = \left[ \frac{1}{2} (T_s(\phi_i) + T_p(\phi_i)) \right]^3 R^{n(\phi_i)l} \left\{ 1 - \frac{2}{\pi} \left[ \arccos \left( \frac{\alpha(\phi_i) - 1}{\alpha(\phi_i)} \right) + \alpha(\phi_i)^{-1} \left( 1 - \alpha(\phi_i)^{-2} \right)^{1/2} \right] \right\}. \tag{A.1}$$

Here the first term with coefficients $T_s$ and $T_p$ describe the Fresnel transmission (Hecht 1987) of the scintillator to the optical grease interface and the FOP top and bottom interfaces, $R$ is the reflectivity, $n(\phi_i)$ is the number of reflections per unit length inside the FOP as a function of the angle with the fiber axis $\phi_i$, $l$ is the length of the fibers and $\alpha(\phi_i)$ is given by (Snyder et al 1973)

$$\alpha(\phi_i) = \frac{n_3 \sin (\phi_i)}{\sqrt{n_3^2 + n_4^2}}. \tag{A.2}$$
The table below shows the refractive indices of various materials:

<table>
<thead>
<tr>
<th>Material</th>
<th>Refractive index</th>
</tr>
</thead>
<tbody>
<tr>
<td>CsI(Tl)</td>
<td>1.79</td>
</tr>
<tr>
<td>Bicron 630</td>
<td>1.47</td>
</tr>
<tr>
<td>FOP core</td>
<td>1.487</td>
</tr>
<tr>
<td>FOP cladding</td>
<td>1.805</td>
</tr>
<tr>
<td>Epotec 301-2</td>
<td>1.53</td>
</tr>
</tbody>
</table>

The angle with the fiber axis $\phi_i$ (in figure A1) can be approximated by

$$\phi_i = \arcsin \left( \frac{n_1 |\vec{r}_i - \hat{r}_i|}{n_3 |\vec{\rho}_i - \hat{\rho}_i|} \right) \approx \arcsin \left( \frac{|\vec{r}_i - \hat{r}_i|}{|\vec{\rho}_i - \hat{\rho}_i|} \right).$$

The number of reflections $n(\phi_i)$ per unit length (Mildner and Chen 1994) is given by

$$n(\phi_i) = \frac{\phi_i}{R} \left[ \left( 1 - \frac{\phi_c}{\phi_i} \right) \left( \frac{\phi_i^2}{\phi_c^2} - 1 \right)^{\frac{1}{2}} \right] \sec \csc \left( \frac{\phi_i}{\phi_c} \right) \left( \frac{\phi_c^2}{\phi_i^2} - 1 \right)^{\frac{1}{2}} \quad \phi_i > \phi_c$$

$$n(\phi_i) = \frac{2\phi_i}{\pi R} \quad \phi_i \leq \phi_c,$$

with $R$ being the radius of the fiber.

References


Hecbt E. 1987 *Optics* (Reading, MA: Addison-Wesley).


Saint-Gobain-Crystals 2007 CsI(Na) and CsI(Tl) Material Product Data Sheet http://www.detectors.saint-gobain.com/CsI(Tl).aspx