Development of component-based normalization correction for the Clear-PEM system

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***Abstract*–We are developing a component-based normalization correction for the Clear-PEM positron emission mammography system. This system consists of two opposing parallel planar detectors that rotate around the breast. The distance between detector plates can vary to adapt to the patient and scintillation light is read at two ends of the crystals for Depth of Interaction (DOI) information. The normalization model currently accounts for intrinsic and geometric efficiencies using new methods specifically developed for this purpose. Both efficiencies are calculated from data obtained with a planar source that is parallel to the two detector plates. Support for other components (deadtime and DOI) is currently being developed. The whole normalization scheme is in the process of being assessed with real data using planar and cylindrical sources.**

I. INTRODUCTION

We present the development of a model-based scheme to normalize the efficiency of the Clear-PEM scanner [1], a system under development by the PEM Consortium in the framework of the Crystal Clear Collaboration at CERN. This system is dedicated to breast and axilla imaging using Positron Emission Tomography. The Clear-PEM system has two planar detectors of 129.0 mm × 173.5 mm that can rotate in a given radius around the breast, with the possibility of switching to a secondary position to image the axilla region. Each detector head is organized into 4 super-modules which are further subdivided into 2 half super-modules that have 2×6 modules each (Fig. 1). Module are arrays of 4×8 LYSO:Ce pixelized crystals of 2×2×20 mm^3 optically coupled on both ends to two 4×8 avalanche photo-diodes arrays (APDs) to account for Depth Of Interaction. Each detector head thus has 12×8 modules or 48×64 crystals, corresponding to a total of 9 437 184 Lines Of Response (LORs) whose different efficiency has to be compensated.

The direct normalization method can be used to compensate for variations of LOR efficiency, by illuminating each LOR with a known activity source (usually with a simple geometry, cylindrical or planar) and by measuring the fraction of detected coincidences for each individual LOR. The inverse of this fraction provides a normalization factor that multiplies the number of counts measured in a given LOR during a specific study, to compensate for the spatial variations of efficiency.

The ClearPEM system has been using a normalization correction based on the direct method. However, direct normalization has the disadvantage of requiring long acquisitions in order to accumulate a sufficient number of counts in all LORs. Since these normalization factors change in time, this measurement has to be repeated periodically, thus becoming less practical. Furthermore, since in the ClearPEM system the distance between detector plates may vary to accommodate for the axilla region and different breast sizes, the normalization measurement has to be repeated for each distance between plates, imposing a significant increase in the total acquisition time necessary and a need to limit the number of possible detector positions. One solution to avoid this problem could be to measure normalization factors for a limited set of positions (for example, three distances between plates) and then interpolate them for other intermediate positions. However, some normalization factors may change rapidly with the distance between plates, again requiring many measurements with different distances between plates and long acquisition times or a less accurate correction.

For these reasons we are developing a component-based normalization method that in principle could reduce the number and duration of the periodic acquisitions needed for normalization correction. Component-based normalization correction [2] relies on modeling the efficiency of a given LOR as the product of several efficiency factors that can be measured independently with good accuracy. The duration of the acquisitions can be reduced by exploiting the periodicity and symmetry of the elements of the detection system, by adding together LORs in equivalent conditions regarding a specific component of the normalization model.

The model used for normalization correction is currently being assessed using data acquired using a planar source placed at the center of the Field Of View, parallel to both detector plates. The model includes components that take into account the intrinsic efficiency of individual crystals, ε_{ij}, the efficiency of rows of crystals, η_j, (corresponding to ring efficiency in a cylindrical scanner), geometric interference, g_{ij}, dead time, t_{ij}, and depth of interaction, d_{ij}. The geometric interference is further decomposed into a set of factors corresponding to the modular organization of the detection system. Thus, $g_{ij} = \chi_c \chi_m \chi_h \chi_s$, where χ_c, χ_m, χ_h and χ_s are geometric interference factors between crystals, modules, half super-modules and super-modules, respectively,

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calculated for the indexed position *i,j* of each crystal in the detector head (*i*=0,1,…,47 and *j*=0,1,…,63) and taking into account eventual symmetries of the detection system.

The product of all these factors aims to reflect the efficiency variations of the scanner due to the different effects, allowing the calculation of the efficiency of any given LOR between two crystals in different detector heads.

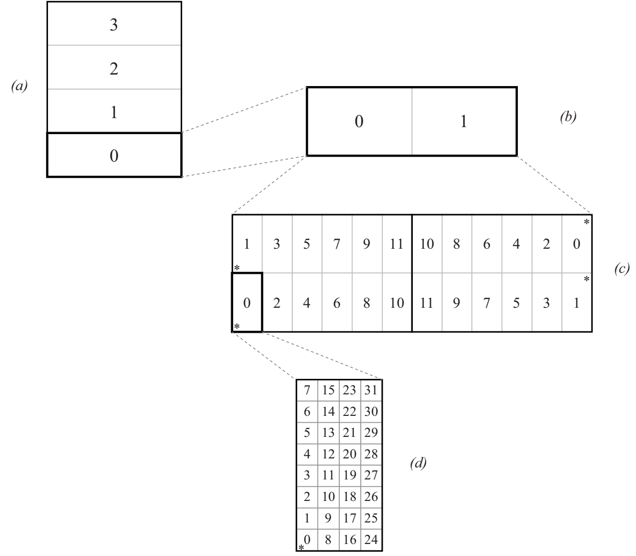


Fig. 1 – Organization of a detector head of the Clear-PEM scanner. a) super-modules; b) half super-modules; c) modules; d) individual crystals.

The different factors are usually normalized to a mean of 1 and their inversion corresponds to the normalization correction factor (NC) that needs to be applied to compensate for that particular efficiency dependence. The NCs that compensate for the efficiency variations of any given LOR between crystal (i_1, j_1) and crystal (i_2, j_2) on different detector heads are given by:

$$NC = NC(\text{intrinsic}).NC(\text{geometric}).NC(\text{dead time}).NC(\text{DOI})$$

The intrinsic term corresponds to the correction due to both the ε_{ij} and η_j factors. The following section details the measurement and calculation of some of these factors.

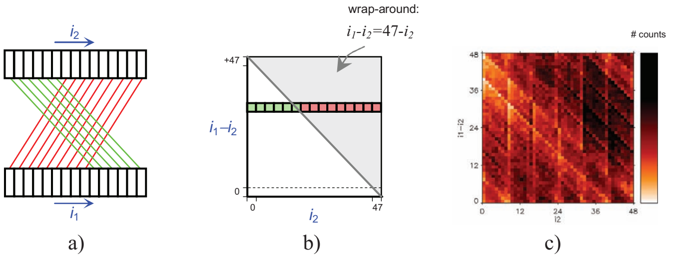
II. CALCULATION OF THE MODEL COMPONENTS

A. Measurement using a planar source

The calculation of the normalization factors is based on the acquisition of coincidence data using a planar ^{68}Ge source slightly larger than the size of the detector heads (160.0 mm × 180.3 mm), positioned halfway between the heads and parallel to them. This illuminates all the crystals regularly (but not exactly uniformly), in a way independent of the angle of rotation of the heads.

B. Data organization

Real data was acquired in list-mode and organized into a set of native planograms, i.e., histograms of the number of counts in LORs specified by the indexes of individual crystals. Since the used system had only 75% of the crystals, corresponding to 48x48 crystals on each detector head, the set of native planograms had 48^4 elements. This organization facilitated the calculation of the different normalization components: for example, the LORs where a given crystal participates were located along vertical or diagonal lines, as shown in Fig. 2.



a) b) c)

Fig. 2 – Organization of the data used for the calculation of normalization components. a) A group of LORs. b) The corresponding elements of the native planogram. c) Example of a native planogram.

C. Intrinsic efficiency

This component is calculated using an adaptation of the fan-sum method [3], which estimates efficiencies based on the variations of the number of counts registered in fans defined by crystals equally exposed to activity. With planar geometry, the crystals are not equally illuminated by the planar source and the fans are not geometrically equivalent, as seen in Fig. 3 (one dimensional fans are shown for clarity of exposure). To calculate the crystal efficiencies, some LORs are used twice while others where the crystal participates are not used at all, in order to assure that they are geometrically equivalent, as shown in Fig. 4.

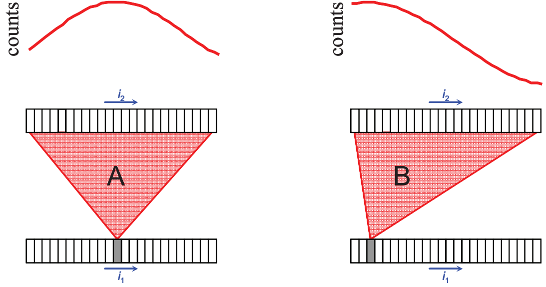


Figure 3 – Non-equivalence of the counts in crystal fans (red regions) with the planar geometry. Fans A and B would have different number of counts due to geometry (red line).

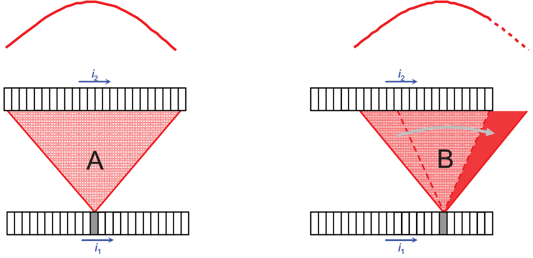


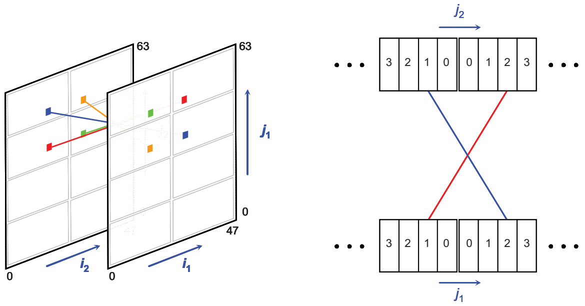
Figure 4 – Geometrically equivalent fans are used in our model, by discarding some of the counts in fan B and adding the number of counts of the dark red region of fan B, estimated from the counts on the symmetrical part of the fan.

The total counts in each crystal fan are calculated using two-dimensional fans to include the largest number of LORs possible: the sum of counts in each fan is calculated for each crystal and then divided by the average of all fan-sums [3], giving the ε_{ij} factors. The efficiency of a row of crystals, η_j, is also calculated for all rows and divided by its mean. The total efficiency of a crystal, ε_{ij}^{total}, is assumed to be equal to $\varepsilon_{ij}\eta_j$ and the corresponding normalization factor of a LOR becomes:

$$NC_{i_1 j_1 i_2 j_2}(\text{intrinsic}) = \frac{1}{\varepsilon_{i_1 j_1}^{total}\varepsilon_{i_2 j_2}^{total}}.$$

D. Geometric interference factors

These factors take into account efficiency variations that modulate the total LOR efficiency and that are due to the position of a crystal in a given level of modularity of the detection system. To maximize the accuracy of this calculation, the counts in all geometrically equivalent LORs are used, taking into account the symmetries available. For this purpose, crystals, modules, half super-modules and super-modules are assigned a number according to the position of that structuring element relative to the remaining elements of the same modularity level. Using this information facilitates the determination of the sums of LORs that are necessary to calculate each interference factor χ_c, χ_m, χ_h and χ_s : all the LORs joining 2 elements with the same combination of numbers can be summed in the same group (Fig. 5).



(a) (b)

Figure 5 – Calculation of geometric interference factors (example for χ_c using combination of assigned numbers 1-2). a) the 4 LORs joining the 8 crystals shown can be summed in the same LOR group to calculate the interference factor. b) two of the LORs shown in a) with the corresponding numbers assigned to the crystals (combination 1-2): the assigned numbers take into account the relative position of the crystal in the module and the possible symmetries.

E. Other factors

The dead time and DOI factors are also included in the model. The DOI factors are being modeled from the DOI data acquired with the planar source acquired with high counting statistics.

III. VALIDATION OF THE MODEL COMPONENTS

Monte Carlo simulations were used to assess the software, which was implemented in IDL (ITT Visual Information Solutions). The simulations were produced using a tool developed for that purpose which reproduced the detector's geometry and simplified detection criteria, and which also allowed to set randomly chosen values for the intrinsic crystal efficiencies. The assessment focused on the comparison between the calculated values for the intrinsic efficiencies and the previously set values, and estimating the typical statistical precision of the calculated intrinsic efficiencies, as well as the typical magnitude of geometrical correction factors.

It was found that the crystal efficiency correction is intrinsically limited by the variability of actual crystal efficiency values, i.e. that even with a virtually unlimited number of counts the exact efficiencies are not recovered with full exactness. With a moderate variability of simulated efficiencies, bound to reproduce satisfactorily the expected variability in real conditions, that limit seems to be attained slightly above a total number of around 10^9 events. At this count number, the statistical precision is about 2%, matching a level which would require 10 times more counts if one would choose to use a direct normalization model. Also with this number of events, it was seen that no significant changes in the exactness and precision of the intrinsic efficiency estimates existed as a function of the distance between detector planes, indicating that the smallest distance possible may be used to determine those efficiencies. A similar precision was also observed for the geometrical correction factors, which were furthermore seen to have an apparently small impact on the correction of the LOR counts.

Real data acquired with planar and cylindrical sources in the Clear-PEM tomograph is currently being used to assess the normalization model. One of the final goals of this work is to reach an accurate normalization correction for different distances between detector heads, in order to accommodate breasts with different sizes with optimized sensitivity. Another goal is to develop a correction that determines accurate efficiencies for any given LOR, allowing the use of different LOR specification schemes for image reconstruction.

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