Development of Intraoperative Beta Probes based on Silicon Photomultipliers

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Introduction

Inside body delineation of tumor boundaries labeled with positron emitters opens up new prospective to help surgeons to discriminate with higher sensitivity malignant tissues from surrounding normal tissues [1,2]. Among the alternative photosensors that have been developed and implemented during the last ten years, Silicon Photomultipliers (SiPM) have the potential to notably impact the performances of future intraoperative devices [3].

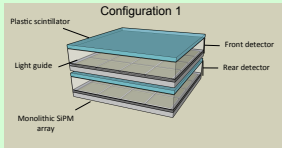
The key features when trying to localize small amount of tumor tissue labeled with positron are the sensitivity, γ ray rejection efficiency and compactness. To achieve efficient rejection of the background noise coming from the high flux of 511keV annihilation γ rays while maintaining the small overall dimensions of the probes, we chose to implement real-time subtraction schemes: gamma contamination is estimated by a detector shielded to beta particles and then subtracted from the count rate measured by the beta-sensitive detector (after being scaled by a suitable weighting factor) to obtain an estimate of the pure beta signal.

We present here our first results on the development of two different intraoperative beta probes based on SiPM:

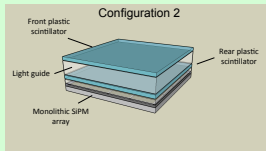
- A light imaging device with a small field of view (~5cm²) to perform tumor localization and post-operative control of the surgical cavity.
- A miniaturized counting probe to guide in real time the excision of the tumor lesion. To facilitate a more complete and accurate excision of tumor tissue, the counting probe will be especially built to be directly coupled to an excision tool (ultrasonic aspirator or electrocautery).

The imaging probe: architecture

- Two background subtraction schemes are investigated, based on the use of one or two read-out detectors.
- For both configurations, two 0.5 mm-thick plastic scintillators are used for detection : the front detector is for beta particles detection and the rear detector is for the estimation of the background gamma noise.
- Light measurement is made by one or two photodetection SiPM-module based on four 16-channel monolithic SiPM arrays composed of 3 x 3mm² elements (Hamamatsu. S11828-3344M)

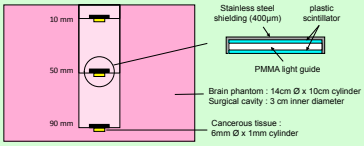


One SiPM array for each scintillator



One SiPM array for both scintillator. Events originating from the two layers are discriminated from the analysis of the width of the light distribution on the photosensor.

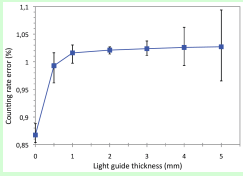
Simulation study: Gamma ray rejection efficiency



Two steps simulation:

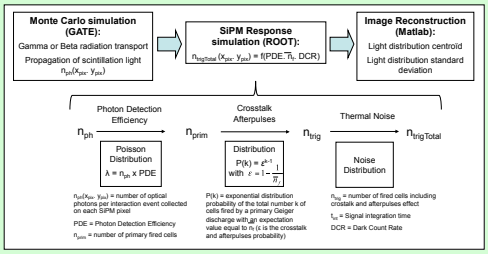
- Brain phantom emits 511keV gamma rays. The count ratio between the two scintillators gives the weighting factor.
- Cancerous tissues emits ^{18}F positrons.

After subtraction of the estimated gamma contamination, error on the true positron counting rate is calculated for each tumor depth.



- Error bars represent the maximum variation of the counting rate measured for different background gamma ray source distributions.
- Rejection efficiency close to 98 % can be achieved when the gap between the front and the rear detector is between 0.5 and 4 mm.
- The subtraction method is nearly insensitive to the variation in the background γ ray distribution.

Simulation study: Imaging performances



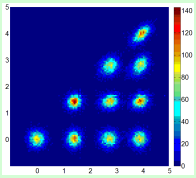
Simulation parameters :

- 16-channel SiPM array (13x13 mm² field of view)
- Diffusing optical coating on the top of the front scintillator and black absorbant coating on the edges of the scintillators and light guides
- SiPM intrinsic parameters set according to measurements at 20°C and V_{diode} = 71V [1] : PDE = 0.25, $\bar{n}_T$= 1.14, t_{int} = 150 ns, DCR = 270 kHz

Configuration	Light guide thickness (mm)	FWHM (mm) [min-max]	Bias (mm) [min-max]
1	0	0.4 [0.27-0.57]	0.3 [0-0.64]
1	0.5	0.44 [0.37-0.51]	0.38 [0-0.93]
1	1	0.45 [0.43-0.49]	0.52 [0-1.23]
1	2	0.51 [0.47-0.55]	0.83 [0.1-1.81]
2	0.5	0.45 [0.41-0.49]	0.51 [0.1-1.22]
2	1	0.5 [0.45-0.57]	0.63 [0-1.45]
2	2	0.53 [0.46-0.59]	0.95 [0-2.04]
2	3	0.6 [0.51-0.71]	1.18 [0.1-2.48]
2	4	0.63 [0.52-0.73]	1.4 [0.1-2.84]

Average spatial resolution (FWHM) and bias on the estimation of the X/Y position for the two configurations of the imaging probe. The spatial performances are given for the top scintillator.

Configuration 1 (0.5mm thick light guide)



Configuration 2 (2mm-thick light guide)

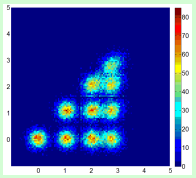
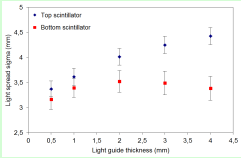
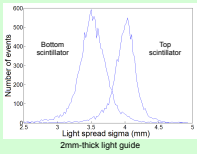


Image of a matrix of ten pinpoints 511keV gamma source with normal incidence photon fluxes. Pinpoint sources are spaced apart from 1.6 mm along the X and Y axes to within 1.5 mm of the detector edge (only one eighth of the field of view was simulated).

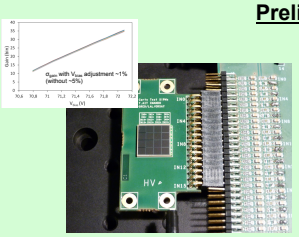




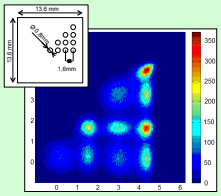
2mm-thick light guide

- Light distribution standard deviation for 511 keV gamma ray events interacting at the centre of each scintillator (error bars represent the FWHM of each light spread)
- Events originating from the two layers can be identified when the light guide thickness is larger than 2 mm.
- For a 2mm-thick light guide, the identification error is around 12% with a mean value of 16% on the whole field of view.

Preliminary experimental results



- 16-channel SiPM array
- Electronic read-out based on a front-end chip composed of a 32-channel ASIC (EASIROC, LAL) with individual trigger and charge measurement
- 8-bit input DAC allowing individual adjustment of the bias voltage in order to improve the response uniformity

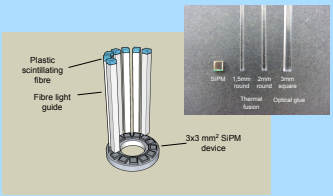


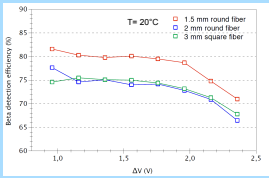
Preliminary images of collimated ^{204}Tl irradiation spots obtained with a 0.5mm-thick plastic scintillator (BC400, Bicron) covered by a sheet of specular reflector (ESR, 3M) and a 1mm-thick PMMA light guide.

Mean FWHM
0.85 mm [0.47-1.33]
Mean bias 0.32 mm [0-0.68]

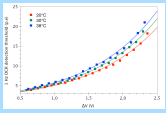
The counting probe

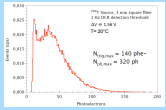
- Detection elements composed of 0.5mm-thick piece of scintillating fiber fused to a 10cm-long clear fiber.
- Detection elements held around the excision tool in a close packed annular arrangement.
- Each detection element is individually optically coupled to a 3x3 mm² SiPM device (S10362-11, Hamamatsu).
- Gamma contamination is measured by one or two fibres shielded to beta particles with a thin sheet of stainless steel.





- Detection threshold to achieve a 1Hz Dark count rate strongly dependent on the level of the correlated noise (crosstalk and afterpulses)
- Beta detection efficiency up to 80 % can be obtained despite the high thermal and correlated noises of SiPM devices
- Optimal beta detection efficiency reached for low ΔV





Conclusion and perspectives

- Different designs of a positron imaging probe using SiPM photosensors were simulated.
- First configuration based on the stack of two SiPM arrays offers very good imaging performances and gamma ray rejection ability.
- Second configuration allows to reduce the size and the cost of the probe but further optimizations are necessary to improve the trade-off between the accuracy on the layer identification and the spatial performances
- Further optimizations will include the use of new position algorithms and optical coatings
- First measurements on scintillating fibre-SIPM assembly show that for a beta counting probe, good detection efficiency can be achieved

[1] Bogalhas F et al., *Phys. Med. Biol.*, vol. 54, 2009. [2] Garcia-Parra R et al., *Ann. Nucl. Med.*, vol. 25, 2011.
[3] Hudin N et al., *Nucl. Instr. and Meth.*,