Wearable Positron Emission Tomography, WPET

John Allison[1,2], Paweł Antkowiak[3], Nada Bellam[4], Filipe Castro[5,6], Lingyi Chen[4], Pedro Correia[5,6], Pedro Encarnação[5,6], João Veloso[5,6], Cinzia Da Via[2], Erica Fanchini[7], Ferdinando Giordano[7], Alessandro Iovene[7], Aleksandra Kowalczyk[3], Patryk Mięsak[3] , Massimo Morichi[7], Zhuoying Ren[4], Sini Simpura[4], Eero Suhonen[4], Yuri Venturini[7], Raimo Vepsäläinen[4], Stephen Watts[2*]

[1]Geant4 Associates International Ltd., Hebden Bridge, HX7 7BT, UK; [2]Department of Physics and Astronomy, The University of Manchester, Oxford Road, Manchester, M13 9PL, UK; [3]Warsaw University of Technology, plac Politechniki 1, 00-661, Warszawa, Poland; [4]Aalto University, PO Box 11000, FI-00076 Aalto, Finland; [5]RI-TE Radiation Imaging Technologies, Lda, UA Incubator, PCI Creative Science Park, 3830-352, Ílhavo, Portugal; [6]I3N - Universidade de Aveiro, Departamento de Física, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal; [7]CAEN S.p.A., Via Vetraia, 11, 55049, Viareggio (LU), Italy.

*Corresponding author: Stephen.Watts@manchester.ac.uk

ABSTRACT

We discuss how modern technology allows the manufacturing of Wearable PET systems for cancer preventive screening. Using simulation and tests with single modules we conclude that the fabrication and use of a WPET system is feasible. The key to feasibility is scalability, miniaturization, data storage and handling and precise position monitoring. With current technology, WPET can detect tumours as small as 2 mm with a 10 kg system in 6 hours, using the same tracer dose as conventional clinical PET. Other scientific and medical fields could also benefit: space missions; homeland security; radiation environment monitoring; and evaluating COVID-19 lung infection.

Keywords: Positron Emission Tomography, PET, micro-systems, wearable electronics.

1. INTRODUCTION

Positron Emission Tomography or PET is a very precise imaging modality commonly used in hospital oncology units to test patients with cancer to establish possible metastasis or other complex diseases difficult to diagnose with traditional methodologies. In PET a radioactive positron emitter is injected into the patient's body, typically a radiolabelled glucose solution (18F-FDG). Sugar is especially attracted by infected human cells and cancer cells, which therefore accumulate the positron emitter. When emitted, positrons annihilate when they meet electrons and, in a large proportion of cases, form ortho-positronium, which produces two high energy gamma rays back to back that can be detected outside the human body.

- Traditional PET systems are expensive and massive and can only be used for a limited number of tests daily.
- WPET would allow one to use this modality for routine screening for a large fraction of the population at risk, improving early stage detection.
- We have proved the feasibility of a wearable PET system with Geant4 simulations. With current technology a WPET system weighing about 10 kg would be capable of identifying lesions as small as 2 mm in 6 hours with a normal radiolabelled glucose dose.

The technology to miniaturise the detector and electronics components as well as controls, alignment, batteries, connectors, data storage and data transmission already exist. The construction of a full-scale wearable PET system would proceed in two stages:

- Full system with existing components and validation in a medical environment.
- Design and optimization of a more compact, wearable system.

2. STATE OF THE ART

The latest advances in PET imaging instrumentation have been enabled mainly by the rapid development and optimization of silicon photomultipliers (SiPMs), which has allowed substantial improvements in compactness and timing resolution, as well as photon detection efficiency, with practically all manufacturers shifting to SiPMs in modern time-of-flight scanners. To maximize detection efficiency and reduce scan time or radiation dose, there has been a trend to build clinical PET scanners with an extended axial field of view (FoV), with over 100 cm and up to 195 cm in the case of the EXPLORER total-body PET scanner [1] (vs. 20-25 cm of typical whole-body clinical scanners), at the expense of much heavier equipment and higher costs. On the other hand, there is a trend to reduce costs, increase mobility and image specific organs with dedicated scanners (e.g. breast, brain) [2], aiming at high resolution and sensitivity, although often compromising the latter. New concepts of wearable PET scanners have been proposed for neuroimaging [3, 4], allowing brain imaging during movement and in an upright position, making it easier to study brain function during different tasks. The design of a wearable PET scanner needs to balance trade-offs between a lower weight, higher mobility, more affordable device and a heavier, more costly system with greater sensitivity or wider body coverage.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

The WPET project aims at building a wearable PET scanner with a modular, flexible design, able to image different body parts according to specific needs, as well as to track detector motion and correct its effects in real-time. This is made possible not only by lighter and compact LYSO-SiPM detector modules, but also by accompanying developments in miniaturized readout electronics, battery technology, wearable sensors, wireless data transmission and fast PET image reconstruction algorithms. PET and WPET are compared in Tab.1. The cost of a WPET system will be substantially lower than PET, but an estimate needs further work. WPET brings superior detection of cancer to screening rather than diagnosis. WPET requires a novel system design to combine wearable electronics with novel materials, controls, batteries and data transmission components to be hosted in a comfortable wearable support. Storage, handling and visualization are also part of the package on the medical side for an easy diagnosis of the collected data.

Tab. 1. Comparison of PET and WPET

Feature	PET	WPET
Size	Fixed PET system 2x4 m^2	Human Torso ~90x50x30 cm^3
Weight	1000 kg	~10kg
Cost	~1-2 million Euro	TBD. See text.
Other	Often combined with CT or MR. Fixed installation.	Portable.

4. PROJECT RESULTS

This section focuses on key results including simulation and data reconstruction of the WPET system which is compared to a full size hospital PET system.

4.1 WPET computer modelling and simulation

The main purpose of computer modelling and simulation is to demonstrate that we can identify cancerous tissue (hotspots) with sufficient spatial accuracy and sufficient sensitivity with a patient dose not exceeding standard PET. Compared to conventional PET, WPET has the advantage that data-taking can extend over a longer period of time and detectors can be closer to the body. Its disadvantage arises from smaller solid angle coverage due to the limitations of mechanical support and detector mass. We have chosen a "light-weight" configuration of 14,336 LYSO crystals with dimensions 3x3x10 mm^3, weighing just 10 kg with minimal structural support (Fig. 1). This has been evaluated and compared to a conventional PET scanner with 150,453 crystals of 3x3x20 mm^3 (a ring of 70 cm diameter and 70 cm axial) weighing 214 kg and requiring a massive support structure. We have assumed that detector positions are surveyed and known to a precision better than a millimetre. The spatial resolution of hotspots is then limited by detector element size, positron range and positron annihilation non-collinearity. All these effects are simulated using the Geant4 [5, 6] software toolkit.

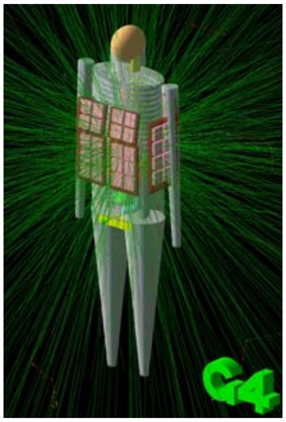

Fig. 1. A "light-weight" configuration of LYSO crystals around the upper torso modelled in Geant4.

4.2 Image reconstruction

A dedicated GPU-based List-mode Maximum Likelihood Expectation Maximization [7, 8] Ordered-Subset Expectation Maximization [9, 10] (LM-MLEM/OSEM) algorithm was developed and implemented using a NVidia Geforce GTX 1060 and an Intel Core i7 (8700). The method uses list-mode data rather than histogram projection data since this preserves the spatial sampling accuracy, which allows superior resolution, contrast and noise properties. List mode offers further advantages over histogram mode such as convenience and accuracy of motion correction, the straightforward use of time-of-flight (TOF) information to improve reconstruction accuracy and the possibility of using temporal basis functions to improve 4D image reconstructions [10]. The method’s performance is highly dependent on a correct system modelling, which includes geometric factors, detector sensitivity, subject attenuation, positron range corrections, photon pair non-collinearity modelling, inter-crystal phenomena and depth of interaction. So far, only geometric and detector sensitivity corrections were taken into account. The geometric factors were calculated on-the-fly with a ray-driven approach where the maximum probability of detection is the centre of the tube of response (ToR) between two detectors.

To determine the spatial sensitivity a source of ^{18}F uniform over the trunk of the body was simulated in Geant4 for the "conventional" system and our chosen "light-weight" system. Similarly, six "test" sources - spheres of radius 10, 8, 6, 4, 2 and 1 mm - were simulated and analysed. Five of the six sources are clearly visible for both configurations, the 1 mm source escaping detection with our statistics (Fig. 2).

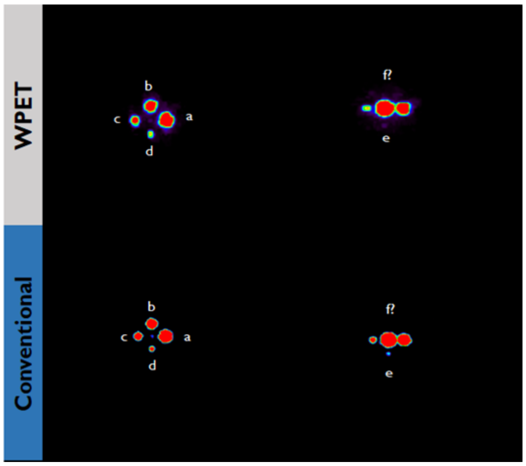

Fig. 2 Image reconstruction of a simulation of six FDG spherical sources with radius of 10, 8, 6, 4, 2 and 1 mm (a to f, respectively). MLEM was performed with a voxel size of 27 mm^3 and 40 iterations.

4.3 WPET hardware setup

The proof-of-concept setup we developed for the WPET project emulates a simple PET system and it is based on two SiPM-based Gamma sensors read-out by a CAEN DT5550W board, Fig. 3. The CAEN DT5550W is equipped with four CITIROC1A ASICs by WeeROC (www.weeroc.com) and is capable of bias and read-out of up to 128 SiPMs providing 2D-image reconstruction and high energy resolution spectrum. The prototype detectors are two Hamamatsu S13900-9990 light-tight assemblies, each including a 64-channel SiPM matrix coupled to a segmented LYSO crystal with a total active volume of 24.8 x 24.8 x 10 mm^3. The sensors are connected to the DT5550W through 2-meters long micro-coaxial cables, allowing for remote control as well as arranging them in different geometries.

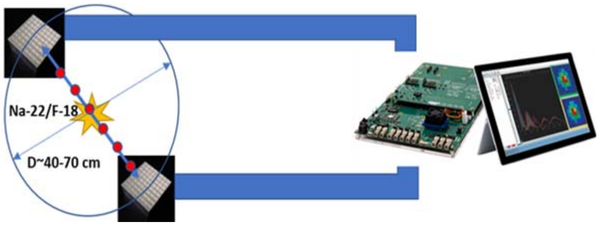

Fig. 3. Setup of the prototype system. CAEN DT5550W is used to readout LYSO-coupled SiPM matrices.

The system is used to perform a PET analysis: the two sensors are located 180° apart, detecting coincidences from a ^{22}Na source placed along their conjunction line, and are spaced 40-70 cm apart, to emulate the dimensions of a human chest. The CAEN DAQ software is able to acquire coincidence events between the two sensors and reconstruct the instantaneous and cumulative 2D-image of the source, from which it is possible to evaluate the spatial resolution of the system. Due to COVID-19 laboratory access restrictions, in Fig. 4 we show results for an earlier system using similar technology.

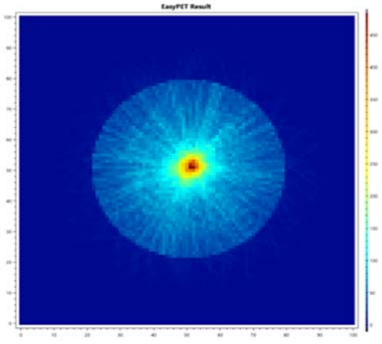

Fig. 4. 2.5 hour of measurements with 400 kBq Na-22 source, 6/7 mm source hot spot. The image has a 100x100 mm^2 area.

5. FUTURE PROJECT VISION

The WPET feasibility demonstration (TRL3/4) is a key step towards the fabrication of a full size prototype and its validation in a medical environment. A prototype is the next key stage to prove that a full body wearable detection system can be manufactured and used for routine cancer screening. The key components required to assemble a full size WPET system are; modular detector units, jacket design, control and data processing, and a data reconstruction and visualization unit. Several hardware components are already available on the market. However, many will need to be custom designed and manufactured. Software development is required for front-end data selection, data transfer, image reconstruction and display.

5.1. Technology Scaling

Usability requires that the weight, volume and power consumption of the system must be significantly reduced. This objective can be achieved by increased integration of electronics and detector elements. As a first step we plan to replace the current electronics with a scalable readout system based on small electronic modules with a daisy-chained readout (CAEN FERS platform, Fig. 5); this would allow us to build a full-size demonstrator with a reasonable size/weight (quasi-wearable) to demonstrate the technology in a relevant environment (TRL 6).

Fig. 5. A CAEN FERS unit (A5202) implementing the WeeROC CITIROC 1A ASIC.

Once this milestone is achieved, the second step will be to develop a fully integrated sensor read-out in a SoC package in collaboration with WeeROC. This integration would reduce dramatically the size and weight of the system allowing a real wearable full-size demonstrator ready for an operational test campaign (TRL 7).

5.2. Project Synergies and Outreach

The WPET consortium, which performed this feasibility study, will require enlargement to add further expertise to perform the tasks described in Section 5. The current consortium of four partners includes expertise in detector systems, simulation, data acquisition, reconstruction and display. Contacts have already been made with groups with expertise in system design, medical physics and clinical validation. This would enlarge the consortium to 6-7 members.

Public dissemination of the results and activities during ATTRACT Phase 2 would be performed by the creation of a website to showcase achieved milestones and results. Furthermore, the consortium would present the results at international conferences and workshops.

5.3. Technology application and demonstration cases

WPET is primarily being developed for early cancer screening and therefore benefits the European Society's challenge on *Health, demographic change and wellbeing.* However, other areas could benefit from this technology. The system could be used to image radiation from the external environment and therefore establish the dose to a person wearing the jacket. This could be useful for personnel in radiation environments such as nuclear plants, radioactive waste sites, particle physics and nuclear facilities, and astronauts in space. These applications benefit the *nuclear and space Research Infrastructure in Europe*. WPET could also be used in radiotherapy, in particular for dosimetry where on-body measurements could be of great use in determining the delivered dose and consequent treatment planning. Recent results from PET imaging of symptomatic and non-symptomatic patients [11,12] with COVID-19 may also encourage interest in WPET.

5.4. Technology commercialization

The next phase will be to build a Minimum Viable Product (MVP) and create a spin-out company to hold the underlying intellectual property and supply Original Equipment Manufacturer (OEM) components. Investors and medical equipment providers in specific geographic regions with local knowledge and supply networks will be sought in the next year. It is also vital that the MVP is tested in a clinical environment and collaboration with suitable medical facilities is actively being sought. Outline costs including risk mitigation considerations are given in Tab. 2.

Tab. 2. OverView of Phase 2 Costs

Item	Cost (k€)	Comment
Specialist Staff	600	Especially System Engineering
Jacket Detectors and Electronics	500	Miniaturisation of electronics, crystals, mechanics, etc.
External electronics and control systems	300	Wireless data transmission, storage etc.
Image processing	200	Fast processing unit + code
Vest Alignment and Tracking	250	Motion capture (e.g. Lidar) and on-board sensors.
Other	100	Travel, meetings, publicity, industrialisation.
Total	**1950**	

5.5. Envisioned risks

The feasibility study performed during Phase 1 was critical in demonstrating with some confidence that it is possible to reconstruct back-to-back emitted 511 keV gammas with multiple matrices of 6-10 mm LYSO crystals and SiPMs positioned around the human torso in close proximity. The scaling from two modules to a full-scale prototype has been successfully simulated, however risks R are identified with a mitigations strategy M:

R1 Medium. Controlling the relative position of the modules during long data taking.

M1 This risk is mitigated by the use of motion capture measurements with a lidar system, or real-time measurement of movement using position sensitive stretching material (see Section 5.6)

R2 Difficulty reducing the overall weight below 10kg with existing components.

M2 Proceed with the construction of a standing WPET as an intermediate stage, which could be used in the hospital to validate the system while smaller and lighter components would be sought.

5.6. Liaison with Student Teams and Socio-Economic Study

A Masters Level student team from Aalto University Finland and Warsaw University of Technology, Poland studied by testing how the wearable PET could be made. The multidisciplinary team included mechanical engineering, electrical engineering, chemical and process engineering, design and fashion students.

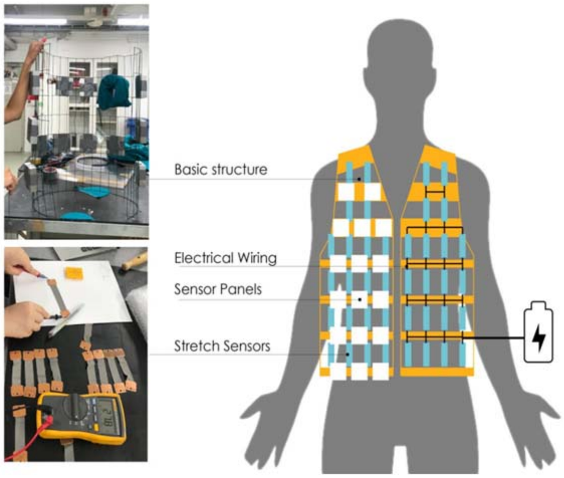

Fig. 6. Concept for a wearable PET assembly

The team tackled key challenges; how to make the jacket lightweight, comfortable, modular for different size patients, and how to track detector positions in time. The team made many prototypes, and tested how it felt to wear a 10kg vest for some hours. They also tested different methods for tracking detector placement and wireless transmission of motion data in real time. The final concept is shown in Fig. 6. The jacket has a strong, grid-type modular structure to hold the detectors, battery, stretching sensors and other electronics. A textile cover-up would add cushioning and ensure the jacket looked normal.

It has been rewarding for everyone integrating Masters students into the WPET team. We are happy to continue this collaboration and also participate in a social-economic study of the ATTRACT initiative through interviews and technology impact references.

6. ACKNOWLEDGEMENT

Authors thank the academic supervisors working at the Design Factory, University of Aalto, supporting the MSc project team. This project has received funding from the ATTRACT project funded by the EC under Grant Agreement 777222.

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