MEMS Gating: A new dual gating technique for eliminating motion-related inaccuracies in PET imaging

Mojtaba Jafari Tadi, Jarmo Teuho, Eero Lehtonen, Antti Saraste, Tero Koivisto, Mikko Pänkäälä and Mika Teräs

Abstract—**Respiratory and cardiac motions may cause quantitative inaccuracies and hinder visual interpretation in positron emission tomography (PET) imaging. In practice, concurrent respiratory and cardiac gating is required to reliably image and identify small structures such as vulnerable coronary plaques. This study proposes a new microelectromechanical sensor (MEMS)-based gating method for eliminating motion-related artefacts. We used joint miniaturized tri-axial accelerometer and gyroscope sensors attached to the patients' chests to extract seismocardiographic (SCG) and gyrocardiographic (GCG) signals. Dual gating in cardiac patients was performed using 18F-fluorodeoxyglucose (FDG) as a tracer. The MEMS dual gating was configured and studied parallel to clinically approved methods for cardiac and respiratory gating: electrocardiography (ECG) and Real-time Position Management (RPM) systems, in PET acquisition of two atherosclerosis patients. Moreover, the radiopacity of the sensor readout-electronics was tested using a Ge-68 phantom before the clinical examinations. Accordingly, no metal artifacts were detected either in CT or PET images due to the motion sensor board, as investigated by two independent operators. Therefore, the MEMS gating board does not contain materials that could affect the visual or quantitative accuracy of PET images or CT-based attenuation correction (CTAC). Dual gated PET images were successfully reconstructed by using only cardiac and respiratory signals derived by MEMS sensors. The MEMS-gated images from the patient study were quantitatively compared to non-gated and gated images that were obtained with the reference methods. In conclusion, these results from the small patient group first imply that implementation of the MEMS gating approach is applicable in dual gated PET imaging and secondly show both qualitative and quantitative improvements in the obtained images. Thus, the first clinical experiences using MEMS cardiac-respiratory dual gating were promising and warrant for further investigations in PET imaging studies.**

I. Introduction

Motion artifacts decrease the image quality and quantitative accuracy of the nuclear medicine imaging which may lead to incorrect diagnosis, unnecessary treatment and insufficient therapy [1], [2]. More precisely, respiratory and heart induced motions in positron emission tomography/computed tomography (PET/CT) are the major cause of blurring, artifacts and inaccuracies in image quantification in cardiac and oncology imaging [3]. For dealing with these motion-related issues, respiratory and cardiac gating methods are the most common approaches used for motion correction in nuclear imaging and radiation therapy. Gating in a simple definition means dividing the PET data into individual bins that correlate to phases of respiratory and/or cardiac motion by overlaying corresponding time-stamped data [4]. In practice, gating enhances the effective spatial resolution of reconstructed images by reduction of partial volume effects (PVE) due to motion blurring [5].

For cardiac gating, electrocardiography (ECG) is considered as the gold standard. However, ECG can only detect the electrical states of the heart functionality and thus fails to give any information about its mechanical activity. For respiratory gating, various methods have been implemented, such as elastic respiration belts, pressure sensors, and infrared camera tracking. A recent review regarding various gating techniques was given in [6]. In general, infrared-based monitoring systems are regularly used in clinical practice but are limited e.g. due to inaccuracies in the marker block placement, thus reducing the quality of the respiratory signal recording and affecting the visual and quantitative accuracy of gated PET images. Moreover, camera-based methods for decomposing surface chest motions have limitations to the respiratory cycle change and breathing irregularities [5]. In addition, tracking the external surface chest motion might not be a sufficient surrogate for internal motion and mechanical anatomical deformations of the heart due to respiration. Therefore, novel gating methods for deriving accurate cardiac and respiratory signals which have high internal and mechanical motion correlation need to be investigated. Recently, novel simultaneous cardiac-respiratory gating methods for cardiac PET/CT imaging have been proposed for PET dual gating. Such methods are bioimpedance [7] and accelerometer [8] based gating.

This study was conducted to investigate the feasibility of a new micro electromechanical (MEMS) based approach in dual gated PET imaging. We consider the use of two tri-axial MEMS sensors, namely the gyroscope and the accelerometer, for gating applications, as these two sensors are able to yield mechanical information of the cardiorespiratory function. The ultimate objective of this study is to develop new gating methods to reduce quantification errors as well as PVE in PET images due to cardiac and respiration motion blurring. To this end, we propose a MEMS-only sensor based gating solution for eliminating motion-related inaccuracies.

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II. Methods and Materials

A. MEMS Dual Gating

Dual gated PET has been introduced to minimize motion-related inaccuracies [9]. Current dual gating systems apply ECG and respiratory trigger events on PET list mode (LM) data. Two independent triggers are transmitted periodically into LM data based on respiratory and ECG cycles. In this study, we employ an inertial measurement unit (IMU) which consists of a tri-axial MEMS accelerometer and a gyroscope sensor. The accelerometer-based seismocardiography (SCG) measures the linear motions of the chest wall, while the gyrocardiography (GCG) measures the angular motions [10].

Hence, the IMU based measurements provide 6-axis cardiomechanical information suitable for cardiac gating. Additionally, the IMU is able to track the chest movements so that respiratory signals can be extracted. These cardiac and respiratory signals can be employed for dual gating applications.

B. Data Acquisition and Signal Processing

The data acquisition involved concurrent measurement of cardiac motion using a miniaturized tri-axial gyroscope (MAX21000 from Maxim Integrated), a tri-axial accelerometer (MMA8451Q from Freescale Semiconductor), a standard two lead electrocardiogram (ECG) (ADS1293 from Texas Instruments). All the recordings were acquired simultaneously with a sampling frequency of f_s=800 Hz. A 4^{th}order Butterworth IIR filter with bandpass 1-20 Hz, 4-40 Hz, and 1-45 Hz was respectively applied on the GCG, SCG, and ECG signals, allowing the removal of white noise and signals offset. ECG was recorded in this study only for reference purposes, and was not used in the computation of the gating triggers. The MEMS cardiac signals were processed based upon [11], so that the cardiac cycle intervals were estimated and segmented accordingly. In addition to cardiac signals, the respiration waveforms due to the longitudinal displacements of the chest were extracted using a brick-wall bandpass filter [0.1-1 Hz], down sampled to 25 Hz, smoothed using a moving average filter. Subsequently, the gyroscope derived respiration (GDR) signal were integrated so that chest longitudinal displacement was achieved and normalized based upon successive mean quantization transform [12]. Fig. 1 shows fixed-time gated cardiac MEMS – SCG and GCG signals – and respiratory GDR signals gated by amplitude- and phase-base gating methods according to [7] for different respiratory gating schemes.

C. PET Phantom Imaging for Radiopacity Test

The radiopacity of the sensor readout-electronics was tested to ensure that the placement of the IMU to the patient's chest will not result in artifacts in PET/CT images. A cylindrical PET quality control phantom consisting of Ge-68 in epoxy resin was used for the phantom study. The phantom was scanned in a PET/CT acquisition over one bed position covering the motion sensor with a duration of 15 minutes. For attenuation correction, a standard low-dose CT scan was collected, using a tube voltage of 120 kV and tube current of

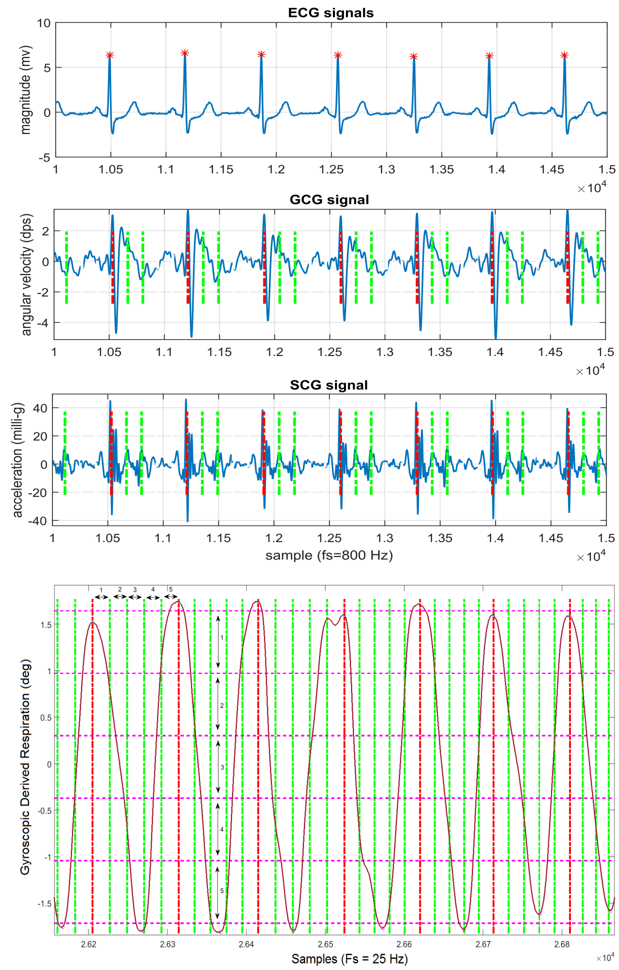

Fig. 1. Seismocardiography (Z-axis) and gyrocardiography (Y-axis) cardiac signals with time-stamped bins (n=3) against ECG measurement (upper inset). The bottom panel shows gyroscopic derived respiration and time-stamped bins (n=5) for both amplitude and phase based gating. Gating bins for respiration signals were calculated based on [7].

20 mAs. The phantom PET images were reconstructed using a 3D-OSEM algorithm using 3 iterations and 24 subsets, with an image matrix size of 256 x 256 x 47 with a pixel size of 1.37 mm x 1.37 mm x 3.27 mm and a field of view (FOV) of 350 x 350 mm with 5 mm Gaussian post-filtering. In addition, PET images with 10 iterations and 24 subsets using 2 mm Gaussian post-filtering were reconstructed (data not shown). Afterwards, the CT and PET images were investigated by two independent operators for image artifacts.

D. PET Patient Study

Two atherosclerosis patients (one male and one female) were examined in this study. Table I shows the patients demographics information as well as PET scan details. The clinical study was performed in the Turku PET Center, Turku University Hospital, Finland, by using the measurement set up described in [13]. The research protocol was approved by the Ethical Committee of the Hospital District of the South-Western Finland. In this study, we assessed the capability of MEMS motion sensor -based measurements in parallel to the Real-time Position Management (RPM) system (from

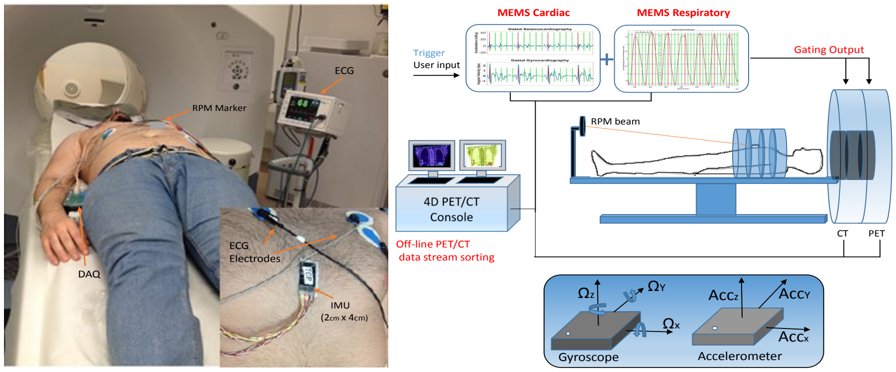

Fig. 2. Left: General measurement set up including data acquisition (DAQ) unit, the IMU, the RPM marker block, and ECG electrodes are attached to the subject's upper chest. Right: A simplified block diagram of 6-axis MEMS dual gating system for PET/CT imaging. Arrows show orientation of sensitivity and the polarity of 6-axis accelerometer and gyroscope sensors.

Varian Medical Systems, Palo Alto, CA, USA) and ECG. Fig. 2 shows the diagram of MEMS dual gating method. Dual gated PET imaging of the subjects was performed using ^{18}F-FDG as a tracer. We first performed a computed tomography attenuation correction (CTAC) scan with a tube voltage of 120 kV and a tube current of 30 mAs, followed by an 24 minute dual gated cardiac PET study. The MEMS cardiorespiratory motion data was recorded in line with the RPM and ECG. The PET/CT scan was performed with Discovery D690 PET/CT scanner (GE Medical Systems, Milwaukee, WI, USA). The PET/CT system has an axial and transaxial FOV of 157 mm and 700 mm and contains a 64-slice CT. The PET performance of the system is described in detail in [14].

E. PET Image Reconstruction

Both ECG and MEMS cardiac signals were gated with three bins while RPM and MEMS respiration signals were gated by five bins. Fixed-time gating was used for ECG cardiac gating for separating the diastolic phase while amplitude gating was used for the RPM respiratory gating to separate the end-expiratory phase. Similarly, fixed-time gating was used for gyrocardiographic and seismocardiographic gating and respiratory signals were gated by amplitude-based gating method to separate the diastolic and end-expiratory phases, respectively. Finally, non-gated images from the whole PET scan duration were reconstructed for comparison.

Dual gated PET images were reconstructed using a 3D-OSEM algorithm using 2 iterations and 24 subsets, with an image matrix size of 256 x 256 x 47 and a FOV of 350 x 350 mm with 6 mm Gaussian post-filtering. Attenuation correction for dual gated PET images was performed using a respiratory-averaged cinematic CT (CINECT) over the whole respiratory period. All image reconstructions were done by off-line reconstruction software provided by GE Healthcare (Research Gating Tool, RGT) including all corrections for image quantification such as detector normalization, dead-time, randoms, scatter and attenuation.

TABLE I
PATIENT DEMOGRAPHICS AND PET ACQUISITION DETAILS

ID	Age (years)	Weight (kg)	Dose (MBq)	Heart Rate (bpm)	Respiratory Cycle Length (sec)
Patient 1	59	69	301	74	6.86
Patient 2	57	116	313	59	4.27

F. Analysis of PET Images

Gating statistics preserved by respiratory, cardiac and dual gating for each method were calculated for evaluation of the image quality and noise. The amount of PET data in percentage units preserved in the best gates is reported, where the non-gated image is assumed to benefit 100% of the PET data. The dual gated and non-gated images were inspected visually as well for assessing image noise and reduction of motion blurring due to gating.

Quantitative analysis of the PET images was performed to assess whether MEMS gating can improve motion-related inaccuracies or not. We considered two image quantification metrics, the signal-to-noise ratio (SNR) and target-to-background ratio (TBR) to evaluate MEMS gating against RPM and ECG gating techniques. SNR was defined as target (myocardium) mean standard uptake value (SUV) divided by the background (liver) SUV standard deviation (SD). TBR was defined as myocardium mean SUV over the liver mean SUV.

III. RESULTS

A. Phantom Study

No image artifacts were detected either in CT or PET images due to the motion sensor board, as investigated by two independent operators. The MEMS gating sensor is of small size and is constructed from a small amount of low-density materials, which did not cause any visually detectable artifcats in the CTAC or PET image of the phantom (Fig. 3).

B. Gating Statistics

Table II indicates gating statistics for ECG- and RPM-based cardiac, respiratory and dual gating with MEMS-only based cardiac, respiratory and dual gating. Accordingly, the results in Table II confirm that the MEMS gating method preserved more data in the best gates while significantly less data was maintained with the ECG- and RPM-based methods.

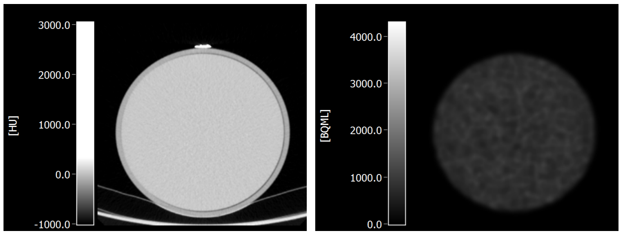

Fig. 3. Radiopacity test using a Ge-68 phantom with CT (left) and PET (right) scans. There are no visually detectable artifcats in either the CT or PET images due to IMU placement on the surface of the phantom.

C. Quantitative Analysis of PET Images

Table III shows the SNR and TBR for none-gated, ECG- and RPM-gated, and MEMS-only gated images. The MEMS-only method has a higher SNR as compared to the ECG- and RPM-gated techniques, in accordance to Table II. However, TBR shows slightly higher values for the ECG- and RPM-gating methods, although the difference to MEMS-only method can be considered to be very small.

D. Qualitative Analysis of PET Images

Finally, qualitative evaluations in Fig. 4 demonstrate that the myocardium shape is less blurred in both ECG-RPM and MEMS gated images as compared to non-gated images, indicating a reduction of motion-induced PVE.

IV. Discussion

In general, the achieved results imply that MEMS gating may improve quantitative accuracy of PET imaging and is applicable for dual gated cardiac PET imaging. MEMS-only gating allowed a comparable preservation of count statistics, SNR and TBR compared to ECG-RPM dual gating. Furthermore, no artifacts were detected in the phantom study due to the sensor board.

Although, the primary PET image dual gating and reconstruction process for MEMS gating method is not yet fully optimized, Fig. 4 shows that the PET images dervied by MEMS-only dual gating are well comparable to ECG-RPM-gated images. Additionally, MEMS-only dual gated images appear less noisy, probably due to optimized selection of cardiac and respiratory quiescent phases provided by the mechanical sensors.

Nevertheless, further investigations, optimizations on both the mechanical signal processing and PET image reconstruction methods are essentially required to enhance the applicability of MEMS gating. Thus, these preliminary results warrant further investigations with larger clinical populations for cardiac PET imaging.

TABLE II
Gating statistics, indicating the percentage of data saved compared to non-gated PET.

Subject	RPM Respiration	ECG Cardiac	ECG-RPM Dual	MEMS Respiration	MEMS Cardiac	MEMS Dual
Patient 1 (m)	14.1 %	31.8 %	3.9 %	17.4 %	60.0 %	10.4 %
Patient 2 (f)	21.3 %	45.8 %	10.4 %	26.0 %	59.4 %	15.4 %

TABLE III
Quantitative analysis of PET images.

Subject		No Gating	ECG-RPM	MEMS
Patient 1 (m)	SNR	24.91	7.85	12.93
	TBR	1.57	1.78	1.75
Patient 2 (f)	SNR	23.72	11.57	12.43
	TBR	1.75	2.43	2.33

V. Conclusion

The preliminary clinical experiences using MEMS gating are encouraging. We implemented a fully MEMS-based gating scheme and reconstructed dual gated PET images by using cardiac and respiratory signals derived by MEMS gating alone for the very first time. Our observations, both quantitatively and qualitatively, show that MEMS gating method is applicable for reducing motion-related inaccuracies in cardiac PET imaging.

Acknowledgements

The study was conducted within the Finnish Center of Excellence in Molecular Imaging in Cardiovascular and Metabolic Research supported by the Academy of Finland, University of Turku, Turku University Hospital and Åbo Akademi University. The authors thank GE Healthcare for providing offline reconstruction software (Research Gating Tool, RGT) for PET gating. The authors would also like to thank clinical nurses at Turku PET center for their excellent assistance during the experiments in this work. This work was supported in part by the University of Turku Graduate School (UTUGS), Academy of Finland under Grant 277383, and by Tekes (Finnish funding agency for innovation).

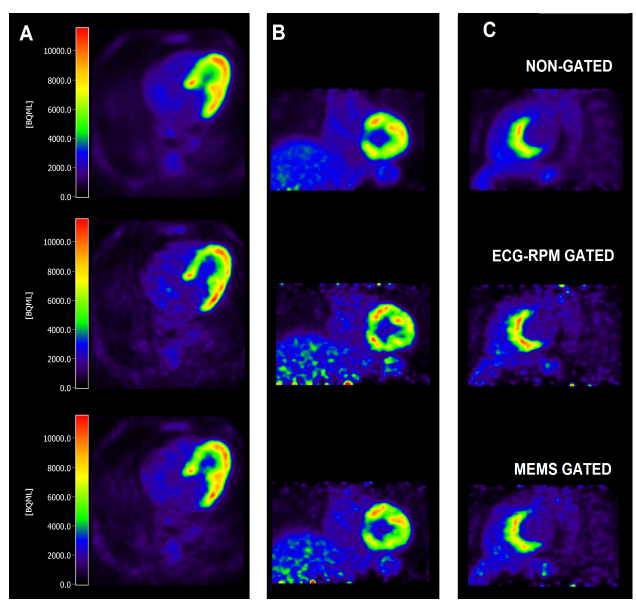

Fig. 4. Transaxial (A), coronal (B), and sagittal (C) views of non-gated (upper row) and dual gated cardiac PET images obtained via ECG-RPM (middle row) and MEMS gating (bottom row) for patient 2. Notable blurring in the myocardium is visible in non-gated images which is reduced by both dual gating methods.

REFERENCES

[1] M. Teräs, T. Kokki, N. Durand-Schaefer, T. Noponen, M. Pietilä, J. Kiss, E. Hoppela, H. T. Sipilä, and J. Knuuti, "Dual-gated cardiac pet–clinical feasibility study," *European Journal of Nuclear Medicine and Molecular Imaging*, vol. 37, no. 3, pp. 505–516, 2009.

[2] T. Koivumäki, M. Vauhkonen, J. T. Kuikka, and M. A. Hakulinen, "Bioimpedance-based measurement method for simultaneous acquisition of respiratory and cardiac gating signals," *Physiological Measurement*, vol. 33, no. 8, p. 1323, 2012.

[3] S. J. McQuaid and B. F. Hutton, "Sources of attenuation-correction artefacts in cardiac pet/ct and spect/ct," *European Journal of Nuclear Medicine and Molecular Imaging*, vol. 35, no. 6, pp. 1117–1123, 2008.

[4] S. A. Nehmeh, Y. E. Erdi, C. C. Ling, K. E. Rosenzweig, O. D. Squire, L. E. Braban, E. Ford, K. Sidhu, G. S. Mageras, S. M. Larson, and J. L. Humm, "Effect of respiratory gating on reducing lung motion artifacts in pet imaging of lung cancer," *Medical Physics*, vol. 29, no. 3, 2002.

[5] T. Kokki, H. T. Sipilä, M. Teräs, T. Noponen, N. Durand-Schaefer, R. Klén, and J. Knuuti, "Dual gated pet/ct imaging of small targets of the heart: Method description and testing with a dynamic heart phantom," *Journal of Nuclear Cardiology*, vol. 17, no. 1, pp. 71–84, 2009.

[6] P. J. Slomka, T. Pan, and G. Germano, "Recent advances and future progress in PET instrumentation," *Seminars in Nuclear Medicine*, vol. 46, no. 1, pp. 5 – 19, 2016, recent Advances and Future Perspectives in Nuclear Medicine.

[7] T. Koivumäki, S. G. Nekolla, S. Fürst, S. Loher, M. Vauhkonen, M. Schwaiger, and M. A. Hakulinen, "An integrated bioimpedance-ECG gating technique for respiratory and cardiac motion compensation in cardiac pet," *Physics in Medicine and Biology*, vol. 59, no. 21, p. 6373, 2014. [Online]. Available: http://stacks.iop.org/0031-9155/59/i=21/a=6373

[8] M. Jafari Tadi, T. Koivisto, M. Pänkäälä, and A. Paasio, "Accelerometer-based method for extracting respiratory and cardiac gating information for dual gating during nuclear medicine imaging," *International Journal of Biomedical Imaging*, vol. 2014, no. 690124, pp. 1–11, 2014.

[9] G. J. Klein, B. W. Reutter, and R. H. Huesman, "Non-rigid summing of gated PET via optical flow," in *Nuclear Science Symposium, 1996. Conference Record., 1996 IEEE*, vol. 2, Nov 1996, pp. 1339–1342 vol.2.

[10] M. J. Tadi, E. Lehtonen, M. Pänkäälä, A. Saraste, T. Vasankari, M. Teräs, and T. Koivisto, "Gyrocardiography: A new non-invasive approach in the study of mechanical motions of the heart. concept, method and initial observations," in *2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, Aug 2016, pp. 2034–2037.

[11] M. J. Tadi, E. Lehtonen, T. Hurnanen, J. Koskinen, J. Eriksson, M. Pänkäälä, M. Teräs, and T. Koivisto, "A real-time approach for heart rate monitoring using a Hilbert transform in seismocardiograms," *Physiological Measurement*, vol. 37, no. 11, p. 1885, 2016.

[12] M. Nilsson, M. Dahl, and I. Claesson, "The successive mean quantization transform," in *Acoustics, Speech, and Signal Processing, 2005. Proceedings. (ICASSP '05). IEEE International Conference on*, vol. 4, March 2005, pp. iv/429–iv/432 Vol. 4.

[13] M. J. Tadi, E. Lehtonen, J. Teuho, A. Saraste, M. Pänkäälä, M. Teräs, and T. Koivisto, "A miniaturized MEMS motion processing system for nuclear medicine imaging applications," in *Computing in Cardiology, 2016*, 2016, pp. 1–4.

[14] V. Bettinardi, L. Presotto, E. Rapisarda, M. Picchio, L. Gianolli, and M. C. Gilardi, "Physical performance of the new hybrid pet/ct discovery-690," *Medical Physics*, vol. 38, no. 10, 2011.