# The long fight against motion artifacts in cardiac PET

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Controlling and managing cardiac motion is likely one of the most long running issue in Positron Emission Tomography. Hoffman began studying the impact of cardiac motion on image blurring in 1979[1] while Ter-Pogossian wrote an article about the impact of combined respiratory and cardiac motion already in 1982.[2] During the cardiac cycle, the base moves toward the apex by 9 to 14 mm and the wall of a normal heart thickens from 10 to 15 mm or more.[3] This movement is not only greater than PET resolution, but also of the cardiac wall itself. However, the resulting blurring effect does not necessarily limit interpretation accuracy. When images are read, the wall is interpreted as mono-dimensional, therefore a uniform blurring results in a partial volume effect (PVE) that is consistent everywhere. Instead, respiration is more critical. It is concentrated mostly in the cranio-caudal direction; therefore, PVE is larger in the anterior and inferior areas than in the other segments, causing artifacts in the final image, due to the localized activity reductions. This might cause reductions in accuracy. Furthermore, motion in this direction can cause attenuation correction issues. Gould and colleagues found PET/CT misalignment artifacts in 40% of patients in their sample; in 23% of all patients the artifacts were judged as ''marked'' to ''severe.''[4] Indeed, the range of motion in the cranio-caudal direction has been reported to be on average larger than 10 mm, but highly varying between patients, reaching up to 20 mm. Algorithms to address this issue have long been proposed, and we refer to the review by Rahmim[5] for an in-depth analysis. In his paper dozens of algorithms, used to try performing motion-corrected cardiac PET reconstruction, are listed and analyzed. The simplest algorithms reconstruct images at different frames and realign them afterward. More robust and advanced ones perform the motion correction directly within the reconstruction scheme. This is definitely the best choice, but two factors limit their applicability: the quality of the motion estimate and the computational complexity of the algorithm. The first one is the most complex to solve as all external respiratory motion trackers can measure only a surrogate of respiration.[6] They are very effective in finding the phase of the respiratory cycle in case of regular respiration; however, this seldom happens in cardiac stress studies. Under stress conditions, most patterns are irregular and furthermore ''cardiac creep'' is often observed. This is probably caused by a change in the respiration that shifts the heart upwards as the examination progresses. It was first intensely explored by Loghin et al. who reported a diaphragm shift of 7 mm on average in patients, with a standard deviation between subjects of 8 mm.[7] This paper is still now of interest thanks to its in-depth investigation of the different sources of motions that add up, especially during stress conditions, to the plain respiration cycle. More recent studies confirmed the large impact of ''cardiac creep.'' Koenders and colleagues reported it in 52% of their sample of 112 patients,[8] when using regadenoson as a stressor. Another study by Memmott[9] found that this motion is even of larger magnitude, on average, when using adenosine. Correcting this cardiac motion is complex, as the deformation that heart and surrounding organs undergo is not rigid. Such deformations are mathematically complex and, even if they could be estimated robustly, computationally it is too complex to insert them within the reconstruction scheme.

In this issue of the Journal of Nuclear Cardiology, Armstrong and colleagues propose and test an algorithm that aims at robustly addressing all heart motion unrelated

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to its beating (i.e., both the respiration, even if non-regular, and the creep). Two independent steps are used to achieve this: a motion estimation step and a motion correction one. The authors model only a rigid motion, estimating it in a data-driven way. Their technique, conceptually, is not different from the ''center of mass'' ones previously proposed by many (see the review by Rahmim);[5] however, the novelty of the work is in the availability of a high temporal resolution time-of-flight (TOF). The effective TOF resolution of their tomograph corresponds to a spatial resolution of less than 4 cm; therefore, it can be reasonably expected that it allows the successful separation of the signal of the left ventricle from all the other organs. This way, TOF not only reduces noise but it also allows isolating the motion of the heart alone, instead of providing an average signal that is influenced by all high uptake structures (e.g., liver).

The authors decided to model cardiac motion only as a linear shift in the cranio-caudal direction. This model is relatively crude, as we know that not only the heart has a complex non-rigid motion, but also that other organs generally deform much less. Nonetheless, this simple model might have the advantage of robustness. The data-driven estimation of motion is a crucial step in allowing an effective motion correction. Their observations are similar to what reported by previous studies that uncovered that almost half of their patients to have signs of baseline drift. It happens in just the 3 minutes used to produce the static image for an $^{82}$Rb study. Also, half of the patients exhibited an irregular respiration pattern, confirming the necessity of tracking cardiac motion in a way that is more complete than the one using external trackers.

A limitation of this study is common to all projects that try to assess the quality of motion correction: there is no gold standard comparison, because it is intrinsically unknown. The authors here choose to evaluate the performance using a dedicated phantom. While this would highlight macroscopic problems, it does still not fully describe the complex motion of the heart and the more complex background that surrounds it, that are partially decoupled in the human body, and that might make motion detection less precise. They asked physicians to qualitatively evaluate the amount of motion and the image quality, as compared to the state-of-the-art reconstruction. They reported a very consistent improvement of image quality and reduction in perceived motion artifacts. Repositioning the heart in the cranio-caudal direction also ensures that the attenuation correction map is aligned, therefore removing this frequent source of errors in cardiac PET. This approach is in fact imperfect, as it might misalign some other distant organs that follow different motion patterns. However, most attenuation correction errors result only in local artifacts. Furthermore, TOF makes reconstructions intrinsically robust to inconsistent data in the attenuation map.[10]

The second issue that comes into play is the computational complexity of the algorithm. Most algorithms that correct motion within the reconstruction scheme are extremely computationally burdensome.[11] For this reason, their translation to the clinical routine never materialized. Using a simple approximation, instead, that models only displacement along $z$, they can just use the same tools used for continuous bed motion, allowing a reconstruction without increased complexity.

We hope that these factors will ease the implementation of this development to the clinical routine, which is something that plagued most of the previous developments in motion correction. As we previously stated, validation of these algorithms is tricky due to the lack of a gold standard. If the solution proposed by the authors can be easily and automatically applied to hundreds of consecutive exams, a clinical trial could be effortlessly designed. It would compare the diagnostic and prognostic accuracy of their proposed strategy, and its design could result simpler.

This study was performed on $^{82}$Rb PET. It can be reasonably expected that the performance of the motion detection part depends mainly on how much the heart contrasts with the other structures in the field of view. Therefore, we expect performances to be similar for all perfusion tracers, and probably also for $^{18}$F-FDG viability studies. With such tracers, the increased resolution allowed by motion correction should be even more welcome, given the small positron range of these nuclides (and their longer acquisition time). However, this motion detection algorithm would still be not ideal for studies where the myocardial uptake is suppressed (e.g., inflammation studies)

In summary, we are very optimistic about the possibilities introduced by this algorithm, and we hope to see in the near future a testing of its performance on a widespread set of patients.

## Disclosures

*No potential conflict of interest to declare.*

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