Sign Determination Methods for the Respiratory Signal in Data-Driven PET Gating

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***Abstract*—Respiratory motion correction in PET imaging is of crucial importance in the thorax. On current scanners, respiratory gating is performed based on the signal of an external device. Recent methods extract a respiratory signal from raw PET data exploiting data driven (DD) methods, avoiding the use of external equipment and having potential increased fidelity to internal motion. However, many of these DD methods determine the signal up to an arbitrary scale factor: it is not known if maxima and minima in the signal are related to end-inspiration or end-expiration states, possibly causing inaccurate motion correction. The aim of this work is to propose methods based on PCA and compare their performance on clinical data with other existing methods based on registration of reconstructed gates.**

***Index Terms*—PET, respiratory motion, data driven gating, PCA.**

I. Introduction

RESPIRATORY gating, i.e. grouping the data into (nearly) motion free gates, is needed to reduce the effects of breathing motion. In order to select the data depending on the breathing state a respiratory signal is required. On current scanners respiratory gating is performed based on the signal of an external device, whereas data driven (DD) methods obtain the signal directly from the raw data, thus avoiding the use of external equipment, having the advantage of patient and operator convenience and also potential increased fidelity to the internal movement. Various data driven methods have been proposed, which make use of the intrinsic motion information present in the raw data and can run without any impact on image acquisition protocols [1]. The PCA-based method [2] and SAM [3] showed promising results, however the respiratory signal is in both cases determined up to an arbitrary scale factor. The uncertainty on the direction of motion could therefore cause inaccurate motion correction especially with multiple bed positions.

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The issue of sign determination of respiratory signal for PET gating has been addressed in [4] and [5] related to the use of PCA-based method and SAM. In this work we propose two methods that determine the direction of motion by comparing similarities between the respiratory Principal Component (PC) and the gradient of the data in the axial direction. Their performance will be compared with the method in [4] and a variation of it [5].

II. Methods

The method presented in [4] (referred to as *MIP*) detects the direction of motion by registering the maximum intensity projections of reconstructed gates in the z-direction. In [5] a variation of *MIP* is implemented (referred to as *SUM*, registering the sum of the projections).

The methods we present in this work rely, as the registration-based ones, on the assumption that the biggest change in the data related to the chest area is due to respiratory motion in the axial direction, causing an "up and down" motion of the internal organs. As we expect PCA to return a PC that is related to the changes in the data caused by respiratory motion, a potential strategy to fix its sign is to compare the respiratory PC with a template of a component representing motion along the z-direction. We then define the gradient sinogram (*GradSino*) as the sinogram obtained by evaluating the temporal mean of the dynamic data and then applying the gradient in the z direction to it. Defining the raw listmode data as the 4-dimensional vector $p(r, z, \theta, t)$, the temporal mean sinogram is defined as:

$$Mean(r, z, \theta) = \frac{\sum_{t=1}^{T} p(r, z, \theta, t)}{T}$$

where T equals the number of time frames, hence the *GradSino* is obtained from the following:

$$GradSino(r, z, \theta) = Mean(r, z + 1, \theta) - Mean(r, z - 1, \theta)$$

Considering the *GradSino* as a mask to be applied to the dynamic data $p(r, z, \theta, t)$ (the areas where there is no "up and down" motion should be approximately zero after the gradient is applied), a signal can be obtained by evaluating the inner product with the data:

$$w_t = GradSino(r, z, \theta) \cdot p(r, z, \theta, t)$$

therefore obtaining a signal related to the extent of the similarity between the data in time and the *GradSino*, see Fig.1.

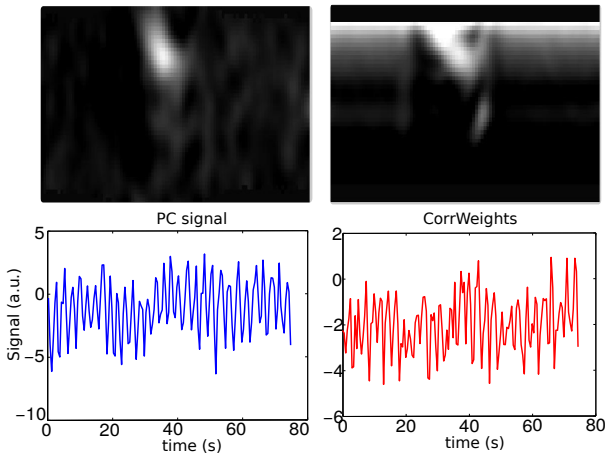

Fig. 1: Left: respiratory PC and corresponding signal (r_t); right: *GradSino* and corresponding signal (w_t).

Since the direction of motion related to *GradSino* is known by construction, its weight w represents a signal where an increase relates to a motion towards the head ("up") while a decrease relates to a motion towards the feet ("down"), thus maxima will correspond to end expiration states and minima to end inspiration states.

The comparison between the *GradSino* and the respiratory PC can be performed both in the sinogram space and in the signal space. If the correlation between the two sinograms is negative it is a symptom that the PC represents a motion in the opposite direction compared to the motion related to *GradSino*, thus the sign of the weight corresponding to the PC (i.e. the respiratory signal used for gating, defined as r_t) has to be reversed. This method is referred to as *CorrSino* (also presented in [5]).

Similarly the correlation between the *GradSino* weight w_t and the PC weight r_t should tell us the degree of agreement between the two traces. If the correlation is negative, the sign of the PCA signal has to be reversed. This method is referred to as *CorrWeights*.

Both *CorrSino* and *CorrWeights* are performed on the raw data (and for this reason will be referred to as sinogram-based methods), thus avoiding the time consuming reconstruction step required by the registration-based methods.

III. Results

We have tested the methods on 37 FDG oncology patient datasets acquired in 3D list mode on GE Discovery STE and GE Discovery 690 scanners, using activity levels according to routine clinical protocols. We selected the bed positions corresponding to the chest. The acquisitions were monitored by the Varian® Real-time Position Management™ (RPM) device, whose signal was then utilized as the comparative standard. The respiratory signal was obtained applying PCA on the PET raw data and its sign was then determined using four different methods: *MIP* and *SUM* [4] [5], *CorrSino* [5] and *CorrWeights*. For each patient, independent time intervals of different duration (50, 100, 200 and 300 s) were selected from the total acquisition. The four methods were applied on each of the selected intervals and their outcome compared to the corresponding RPM trace by evaluating the correlation between the signals: for negative correlations the method was considered to have failed. Table I shows the percentage of failures for the four methods relative to the duration of the intervals taken into account.

TABLE I: Failure rates (%) for all patient datasets with respect to interval duration. In brackets the amount of intervals for each duration.

Duration (s)	CorrSino	CorrWeights	MIP	SUM
50 s (242)	8.6	4.9	23.1	16.9
100 s (113)	7	4.4	15.9	14.1
200 s (44)	9	4.5	9	9
300 s (32)	12.5	3	15	9
All (431)	8.4	4.5	18.9	14.8

The failure rates show the methods' ability to detect the correct direction of motion with respect to decreasing frame duration is more stable for the sinogram-based ones, that show approximately stationary results for all cases, whereas the registration-based methods show higher failure rates for the 50s intervals. This is presumably due to the smaller amount of utilized data and to the consequent higher level of noise, that result in poorer quality of the reconstructed gates hindering the registration process.

To examine the failure rates in more detail, we partitioned the evaluated intervals based on the correlation coefficient between the PCA and RPM signals, considering high correlation values as evidence of good "respiratory-like" PCA traces. The analysis resulted in 91.8% of the cases (396 intervals of the total 431) showing correlation values higher than 0.75, and the remaining 8.2% (35 intervals) being poorly correlated to the external device signal. The failure rates corresponding to the two sets of traces are reported in Table II.

TABLE II: Failure rates (%) for all patient datasets wrt to the correlation between the PCA trace and the RPM. In brackets the amount of intervals in each group.

Correl. range	CorrSino	CorrWeights	MIP	SUM
$[0 - 0.75]$ (35)	46	29	29	46
$[0.75 - 1.00]$ (396)	5.3	2.5	16.4	9.8

IV. Discussion

Following the results obtained by the application of the four methods on the available patient datasets, *CorrSino* and *CorrWeights* proved to be more efficient compared to *SUM* and *MIP* in detecting the correct sign of the respiratory signal. The former two methods also have the advantage of avoiding the reconstruction step. Failure rates for the registration-based methods increase as frame time decreases: the registration process required by *MIP* and *SUM* is more likely to fail as a consequence of the increased noise of the reconstructed gates, whereas *CorrSino* and *CorrWeights* show a more stable behaviour.

When analyzing the PCA respiratory traces with respect to their similarity to the external device signal, it is possible to see that in most cases (91.8%) the PCA signal has high agreement with the RPM (higher than 0.75) and that in those cases CorrWeights largely outperforms all the other methods (2.5% failures). However, when the PCA and RPM signals are poorly correlated (8.2% of the cases), all methods are more likely to fail, although there is insufficient data to draw statistically significant conclusions about which method is best in these cases. Initial evidence suggests that patient movement (as opposed to respiratory motion) is the most probable cause for failures.

V. Conclusion

Two new sign determination methods, that only require PET raw data, have been proposed and implemented. Their performance has been evaluated on patient data and compared to two image-registration-based methods. *CorrWeights* showed very promising results, providing the lowest failure rate and proving to be the best choice out of the analyzed methods. When the PCA signal is highly correlated with the true motion (that in our work is represented by the RPM signal), *CorrWeights* fails in only 2.5% of the cases. Its simple implementation makes it easily applicable in clinical applications and no reconstruction is needed. Patient bulk motion might be one of the causes for the method failures and requires further investigation.

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