Cardiac Motion Estimation from Intracardiac Electrical Mapping Data: Identifying a Septal Flash in Heart Failure

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Abstract. In this paper, we present a methodology to estimate cardiac motion directly from the high resolution temporal data provided by an intra-cavity electrical mapping system (CARTO). These data consist in intracardiac electrical measurements, obtained invasively through the contact of a catheter with the endocardial wall at different locations, with simultaneous recording of the position of the measuring catheter over time. The 3D displacement fields between the different timepoints obtained from the position measurements are projected onto the vector pointing from the CARTO points to the centroid of the CARTO cloud, giving a very intuitive vectorial coarse representation of the diastolic and systolic motion. Furthermore, scalar projection 1D curves can be used to identify specific motion patterns. We have applied the proposed methodology to the CARTO acquisitions of nine candidates to cardiac resynchronization therapy, identifying the specific sequence of motion and deformation (septal flash) found in LBBB, which was confirmed by visual inspection of the corresponding MR and 3D-US images.

Keywords: Electrical mapping, CARTO, septal flash, cardiac motion, left bundle branch block, cardiac resynchronization therapy.

1 Introduction

Estimation of cardiac motion is crucial for a complete understanding of cardiac (dys-)function in a wide range of cardiovascular pathologies such as left bundle

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branch block (LBBB) and for the optimization of related clinical procedures such as cardiac resynchronization therapy (CRT). CRT is an innovative treatment for congestive heart failure aiming at synchronizing the electrical activation of the left ventricle (LV) in order to better coordinate its contraction, thus assuring the generation of enough force to push blood through the body. However, up to a third of the patients who are treated with CRT do not show any response to this very expensive therapy. Therefore, the development of new patient selection indices would lead to better success rates of CRT. For instance, a fast motion pattern called septal flash [1], a mechanical consequence of dyssynchronous contraction which occurs in some LBBB patients at early systole, has been related to a high probability of response to the CRT therapy.

In general, this type of motion information is obtained by applying post-processing techniques either to gray-scale images [2,3,4,5] or to acquired velocity data [6]. On the other hand, detailed electrophysiological data on the LV is also critical for a better planning of clinical procedures and patient's follow-up. However, it can only be measured invasively, using either endocardial contact mapping (CARTO, Biosense, Cordis Webster, Marlton, NJ) or non-contact mapping (Ensite, Endocardial Solutions, Saint Paul, MN) systems, or with a sock of epicardial electrodes to record epicardial electropotential data [7].

Automatic combination of the electrophysiological data given by these invasive systems with cardiac motion estimates or geometrical information obtained from medical images is not straightforward due to the different nature of the acquisitions and the use of different spatial reference systems. Registration techniques applied on data acquired in a XMR system [8] can partially solve this problem, but it is a relatively expensive solution. Another issue is that abnormal motion patterns specific to known cardiac pathologies require rich data with high spatial and/or temporal resolution to be identified. For instance, fast events such as a septal flash would be better captured with Doppler Myocardial Imaging than with MRI due to its higher frame-rate.

In this paper, we propose to estimate cardiac motion directly from the data provided by a CARTO system. Along with electrical measurements defined at a given number of acquisition points at the endocardium, a CARTO system provides, for every acquired point, the 3D spatial location of the measuring catheter over time at a high acquisition rate (100Hz). The catheter's spatial location obviously follows the motion undergone by the corresponding heart segment. Consequently, we compute a 4D displacement field from the time-varying spatial location of the catheter. The computed 3D displacement vector of every CARTO acquired point is then projected onto the vector that goes from this point to the centroid of the CARTO cloud of points, giving a very intuitive vectorial coarse representation of the diastolic and systolic motion. The associated scalar projection can be plotted over time to identify specific motion patterns.

We have applied the proposed methodology to the CARTO data of nine CRT candidates with and without a septal flash. The scalar projection curves showed significant peaks within the ECG interval defined between the contraction onsets of the earliest (septum) and latest (lateral wall) activated CARTO points in four patients, which were confirmed by visual inspection of corresponding MR and US images.

2 Intracardiac Electrical Mapping Acquisitions

For the present study data from 9 patients showing heart failure (age 65 ± 10 years) was collected. The study protocol was accepted by the Hospital Clínic's ethics committee and written informed consent was obtained from all patients. All the patients were candidates for CRT, according to current recommendations based on the NYHA classification, the ejection fraction (EF) and the QRS length. Details about the characteristics of each patient and these indices are given in Table 1.

Table 1. Clinical Data

ID	Age	NYHA	EF [%]	QRS [ms]
1	75	II	50.9	200
2	71	III	22.8	160
3	68	III	26.2	120
4	80	III	25	200
5	66	III	25	200
6	58	III	27	200
7	55	II	24.8	120
8	68	III	9	140
9	65	III	26	120

Data of these patients consisted of endocardial electroanatomic contact mapping (CARTO, Biosense, Webster), a system that basically consist of a low-intensity magnetic field generated by a location pad under the bed of the patient, two catheters instrumented with a sensor and a graphic computer.

CARTO maps are composed by a set of intracardiac samples that contain electrical signals (recorded at $1kHz$) and position of the catheter (recorded at $100Hz$) over $2500ms$ so that ECG and trajectory data can be derived. The absolute positions of the catheter tip are given in millimeters. The electrical measurements consist of uni- and bipolar voltages where the unipolar peak-to-peak voltage refers to the potential difference between the catheter tip and a reference electrode, whereas the bipolar voltage is the potential difference between the 2 electrodes within the catheter (Ring-Tip).

For each patient, a number of point measurements ranging from 32 to 83 (mean of 49.6) were obtained. Points were taken from different areas of the LV endocardium so that the approximate geometry could be recovered. As the samples are obtained sequentially, the system uses a common reference point in the surface ECG (R wave) to start recording the electrical signals. In that way, we are able to recover and align electrical signals and to calculate the local activation maps. Analysis of the mapping data was carried out for patients in sinus rhythm.

3 Septal Flash

The identification of dyssynchrony indexes, to identify patients that could benefit from CRT, has been an issue of debate over the last years. Some simple indexes measured from echocardiographic data [9,10] have proven to have a poor prediction capability of CRT success. Recently, a fast motion pattern, called *septal flash*, which occurs in some LBBB patients at early systole, has been related to a high probability of response to the CRT therapy.

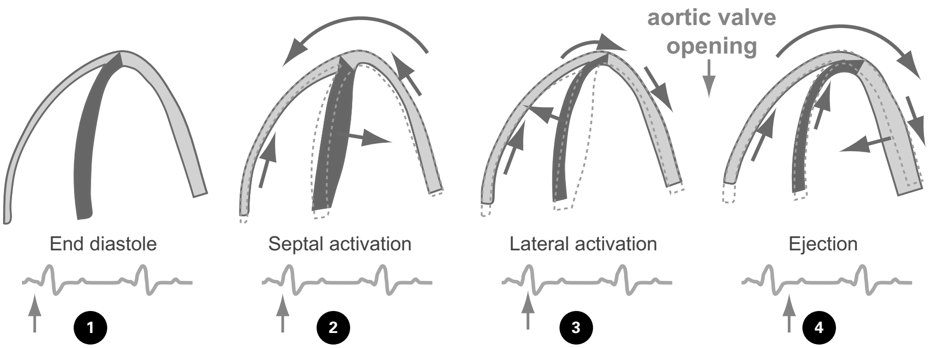

Fig. 1. Diagram showing the septal flash motion

A septal flash can be explained by unbalanced forces appearing in the septum due to a conduction delay between the activation of the septum and the lateral wall. In a normal left ventricle, all segments are activated almost simultaneously and thus deform in synchrony. In this case, the contraction that the septum exerts on the lateral wall while contracting is balanced by the symmetric contraction exerted by the lateral walls towards the septum. Because of this balance, the motion of the septum is mostly longitudinal and the apex remains stationary.

In the case of a conduction delay between the septum and the lateral wall, the interaction between the walls changes significantly. Indeed, the septum in this case contracts while the contralateral wall does not. This provokes a faster and inward motion of the septum stretching the lateral wall. Once the lateral wall is activated, it will in turn start stretching the septum which makes the septum going in the outward direction. This quick succession of inward and outward motion of the septum, happening within the (wide) QRS complex and the isovolumetric contraction time (IVCT), is illustrated in Fig. 1. The quick reversal in the septal displacement direction for the LBBB patient is the septal flash that we want to identify from CARTO data in this paper.

4 Cardiac Motion Estimation from CARTO Data

The proposed methodology for the estimation of cardiac motion from CARTO data can be divided in the following stages:

1. computation of the 4D displacement field;
2. filtering out outliers and temporal smoothing of the 4D displacement field;
3. projection of the 4D displacement field onto the unit vector pointing to the centroid of the CARTO cloud of points;
4. temporal analysis of the vector projection and the 1D scalar projection curves.

The first stage of the methodology is the estimation of the trajectory of each CARTO point over time, i.e. the computation of the 4D displacement field. For doing so, we made use of the spatial locations of the measuring catheter at consecutive timepoints, which are available every 10ms.

The resulting displacement field is quite noisy, in particular for timepoints far away from the trigger point (R peak of the last heart cycle). This is due to the uncertainty in the spatial location of the catheter when it is not in contact with the endocardium wall but rambling in the bloodstream. Nevertheless, it must be pointed out that the CARTO system provide visual signs alerting when the catheter is in contact with the wall and thus the acquisition of electrical and catheter spatial location measurements is more accurate (trigger point). In order to reduce the noise of the 4D displacement field, CARTO points are defined as outliers if they have spatial displacements in their catheter's trajectory larger than 2cm, indicating timepoints far away from the trigger point (it is always at 2000ms of the acquired 2500ms) where the catheter is not in contact with the wall. The mean and standard deviation of the percentage of outliers rejected in this filtering out stage for the nine patients are $21.34\% \pm 12.21\%$. Moreover, we applied a temporal smoothing to the remaining CARTO points, based on a binomial filter using the previous and following points in the trajectory.

The next step in the proposed methodology consisted in projecting the displacement vector of each CARTO point onto the unit vector going from its spatial location to the centroid of the cloud of CARTO points, at each timepoint of the sequence. The scalar projection (or scalar resolute), $sp_{\boldsymbol{a}}\boldsymbol{b}$, of the displacement vector $\boldsymbol{a}$ onto the centroid unit vector $\boldsymbol{b}$ is obtained as follows:

$$sp_{\boldsymbol{a}}\boldsymbol{b} = \frac{\boldsymbol{a} \cdot \boldsymbol{b}}{\mid \boldsymbol{a} \mid}. \tag{1}$$

The scalar projection of a given CARTO point will be positive when its displacement vector points towards the centroid (contraction), and is negative when moving away from the centroid (dilation). The vector projection (or vector resolute) can then be found by multiplying the scalar resolute by $\boldsymbol{b}$, resulting in a very intuitive and normalized vectorial coarse representation of the diastolic and systolic cardiac motion. The scalar resolute values can be plotted over time, deriving 1D curves with information that can be used to identify particular motion patterns for some CARTO points.

5 Identifying the Septal Flash

In this paper, we analyzed these 1D curves and the corresponding vectorial representation to identify septal flash motion. For doing so, we selected the

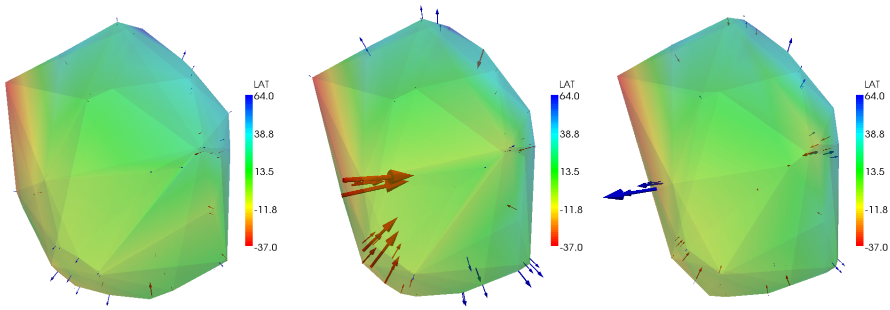

Fig. 2. Delaunay triangulations of CARTO points, colored according to the LATs (red: earliest LATs; blue: latest LATs.), together with vector projection displacements (arrows). From left to right, three different frames within the septal flash interval.

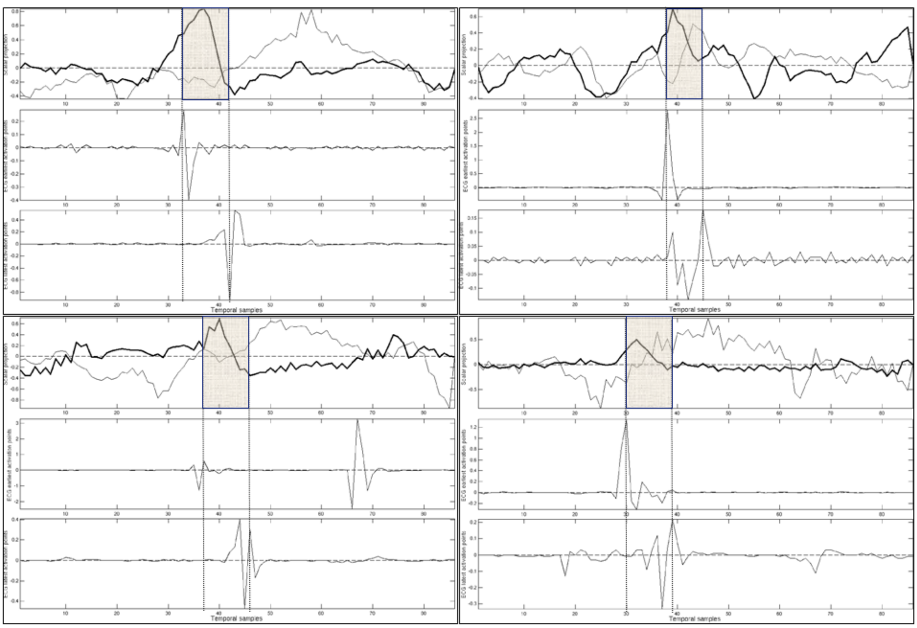

Fig. 3. Scalar projection curves (top in each subplot) and ECGs of CP_{elat} (middle in each subplot) and CP_{llat} (bottom in each subplot) for four cases with septal flash. The darker and thinner lines in the scalar projection curves corresponds to the septal and lateral wall points, respectively. The dashed markers limit the septal flash interval (shady in the scalar projection curves).

CARTO point with the earliest local activation time (LAT), CP_{elat}, and the one with the latest LAT, CP_{llat}. In LBBB patients, it is quite likely that CP_{elat} would be located at the septal wall and CP_{llat} at the lateral wall. The individual ECGs (unipolar and bipolar voltages) corresponding to CP_{elat} and CP_{llat} gave

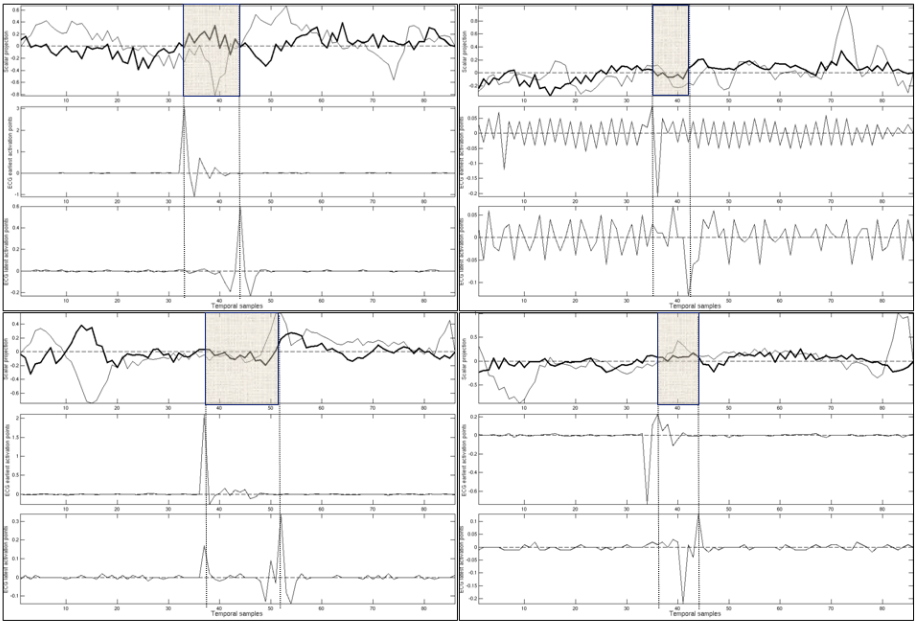

Fig. 4. Scalar projection curves (top in each subplot) and ECGs of CP_{elat} (middle in each subplot) and CP_{llat} (bottom in each subplot) for four of the five cases without septal flash. The darker and thinner lines in the scalar projection curves corresponds to the septal and lateral wall points, respectively. The dashed markers limit the septal flash interval (shady in the scalar projection curves).

us the time interval where, if present, the septal flash must occur, specifically between the R peaks of CP_{elat} and CP_{llat}. Within this septal flash interval (see shady region in Fig. 3 and Fig. 4), an abnormally large peak would show up in the scalar projection 1D curve of the CP_{elat} if a septal flash appears, representing the sudden contraction and relaxation of the septum. In other heart regions (e.g., CP_{llat}) or in patients without septal flash, no significant peaks should be present in the same time interval.

Fig. 2 shows the Delaunay triangulations of the CARTO points for three different frames within the septal flash interval for one patient having septal flash, together with the arrow representation of the vector projection. For the CARTO data displayed in Fig. 2, one can easily observe the presence of large arrows pointing towards and then going away from the centroid in some points of the septal wall, representing a fast motion that corresponds to a septal flash.

Fig. 3 and Fig. 4 show the scalar projection curves and the ECGs for patients with (four cases) and without (four of the five cases are shown for space reasons) septal flash, respectively. For each case, the top subplot presents the scalar projection curves for the CARTO points with the earliest (septum, thicker line) and latest (lateral wall, thinner line) LATs. The middle and bottom subplots correspond to the individual ECGs (bipolar voltage) of the CP_{elat} and the CP_{elat}, respectively. It is straightforward to distinguish septal flash from not septal flash cases by visual inspection of the scalar projection curves of the septal wall points within the septal flash interval. In the cases illustrated in Fig. 3, a substantial peak appears just after the activation of CP_{llat}, while no considerable event develops in cases displayed in Fig. 4. The same classification of septal/no septal flash cases was obtained by visual inspection of the corresponding MRI (including tMRI, cine MRI, delay-enhancement MR) and 3D-US data by an expert cardiologist.

6 Conclusions

To the best of our knowledge, this is the first time CARTO data is used for cardiac motion analysis, making its comparison with electrophysiological data trivial, without needing complex or manual registration techniques. Furthermore, the high acquisition rate and the 3D nature of the CARTO data (one frame each 10ms) has allowed to identify fast 3D events such as septal flash motion with simple post-processing techniques of the catheter's trajectories. Future work will be focused on automating the procedure with simple signal processing algorithms and on quantitatively comparing these results with indices provided by registration techniques applied to medical images.

Acknowledgments

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References

1. Parsai, C., Bijnens, B., Sutherland, G., Baltavaeva, A., Claus, P., Marciniak, M., Paul, V., Scheffer, M., Donal, E., Derumeaux, G., Anderson, L.: Toward understanding response to cardiac resynchronization therapy: left ventricular dissynchrony is only one of multiple mechanisms. European Heart Journal (2008) (in press)
2. Perk, G., Tunick, P., Kronzon, I.: Non-doppler two-dimensional strain imaging by echocardiography–from technical considerations to clinical applications. Journal of the American Society of Echocardiography 20, 234–243 (2007)
3. Axel, L., Montillo, A., Kim, D.: Tagged magnetic resonance imaging of the heart: a survey. Medical Image Analysis 9(4), 376–393 (2005)
4. Ledesma-Carbayo, M., Kybic, J., Desco, M., Santos, A., Suhling, M., Hunziker, P., Unser, M.: Spatio-temporal nonrigid registration for ultrasound cardiac motion estimation. IEEE Transactions on Medical Imaging 24(9), 1113–1126 (2005)

5. Elen, A., Choi, H., Loeckx, D., Gao, H., Claus, P., Suetens, P., Maes, F., D'Hooge, J.: Three-dimensional cardiac strain estimation using spatio-temporal elastic registration of ultrasound images: a feasibility study. IEEE Transactions on Medical Imaging 27(11), 1580–1591 (2008)
6. Bijnens, B., Cikes, M., Claus, P., Sutherland, G.: Velocity and deformation imaging for the assessment of myocardial disfunction. European Journal of Echocardiography (in press, 2009)
7. Nash, M., Mourad, A., Clayton, R., Sutton, P., Bradley, C., Hayward, M.: Evidence for multiple mechanisms in human ventricular fibrillation. Circulation 114, 536–542 (2006)
8. Rhode, K., Sermesant, M., Brogan, d., Hegde, S., Hipwell, J., Lambiase, P., Rosenthal, E., Bucknall, C., Qureshi, S., Gill, J., Razavi, R., Hill, D.: A system for real-time XMR guided cardiovascular intervention. IEEE Transactions on Medical Imaging 24(11), 1428–1440 (2005)
9. Yu, C., Abraham, W., Bax, J., Chung, E., Fedewa, M., Ghio, S., Leclercq, C., León, A., Merlino, J., Nihoyannopoulos, P., et al.: Predictors of response to cardiac resynchronization therapy (PROSPECT)–study design. American Heart Journal 149(4), 600–605 (2005)
10. Chung, E., Leon, A., Tavazzi, L., Sun, J., Nihoyannopoulos, P., Merlino, J., Abraham, W., Ghio, S., Leclercq, C., Bax, J., et al.: Results of the Predictors of Response to CRT (PROSPECT) Trial. Circulation 117(20), 2608 (2008)