Estimating Septum Rotation to Improve Accuracy of Cardiac Biventricular Bullseye Representation Using the UNISYS Algorithm

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Abstract

Visualizing and comparing electrophysiological data obtained from the whole heart's surface in a standardized fashion can be challenging and has led to the development of tools such as the UNISYS algorithm. However, this representation is sensitive to septal rotation, complicating the localization of regions of interest.

This study introduces a novel method for correcting septal rotation to improve interpretability of bullseye plots. Different techniques have been tested to determine the best way of choosing construction points and all of them significantly brought the septum closer to the vertical delineation of the bullseye, especially near the apex. Moreover, results generated by this method are not significantly impacted by inter-user variability, making it a reliable improvement to the original algorithm.

1. Introduction

Because the heart's shape is complex and varies between individuals, representing electrophysiological data from the heart surface in a single and standardized image can prove difficult. Regional comparisons between patients or experiments can therefore be challenging, which led to the development of the bullseye representation [1]. This method allows for a standardized visualization of the left ventricle (LV) by drawing a circle whose center is the apex and whose circumference is the ventricle's base. While widely used in clinical practice, the biggest downside of this representation is the absence of the right ventricle (RV), despite its significant role in arrhythmia triggering [2]. Thus, the bullseye principle has been adapted to biventricular epicardial visualization with an open-source MATLAB® algorithm called UNISYS [3].

This algorithm retains the initial concept of the bullseye but uses the vertical line in the centre of the circle to separate the ventricles, i.e., the septum. It is therefore necessary to define the septum location to generate a bullseye representation with a correct lateral separation. In the current implementation, this is achieved by fitting a plane through three user-defined points; at the apex and at the anterior and inferior base respectively. However, in reality the septum cannot be accurately estimated using a plane due to its rotation from base to apex (see Figure 1).

The aim of this work was therefore to develop a method to integrate into the UNISYS bullseye representation, improving the delimitation of the ventricles by correcting for the rotation of the septum.

2. Methods

2.1. UNISYS algorithm principle

The UNISYS algorithm has previously been described in [3] and its principle is illustrated in Figure 1. In brief, the algorithm requires vertices of the cardiac shape as an input, all of them defined by a 3D position and a value (e.g., activation time). After fitting a plane to three user-defined points marking the septum, the heart is transformed into a cone by converting the cartesian coordinates to polar coordinates. This cone is then visualized from the top to obtain a 2D circle representing the whole heart with the apex on the centre. This bullseye plot is composed of different colors showing the initial values assigned to each vertex and is split in 20 segments.

2.2. Experimental data

Three-dimensional rotational fluoroscopy (Artis; Siemens, Munich, Germany) was performed on male pig

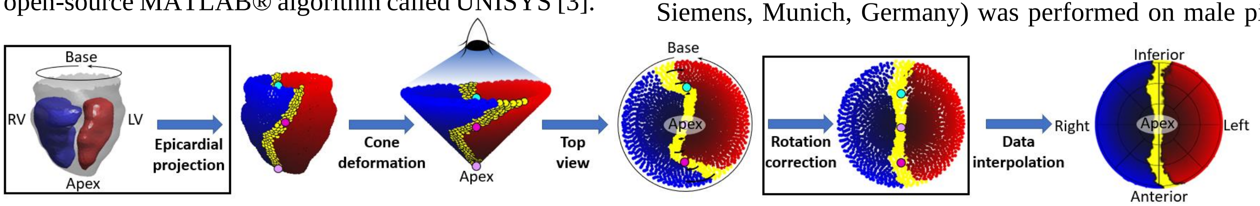


Figure 1: Pipeline of the modified UNISYS algorithm, with the new steps indicated by black boxes. The septum is represented in yellow and its rotation across the heart's height can be seen in every step before its correction. Please note that for the sake of visualization, the rotation correction step has been represented on the bullseye plot while its implementation in the algorithm is actually before the cone deformation.

hearts (n = 4; 35-45 kg) after various *ex vivo* experiments. Based on these images, the epicardium has been segmented and used as a reference for bullseye transformation. An iodinated contrast agent infused in the aorta allowed visualization of the coronary arteries and cavities.

2.3. Septum tracking processing

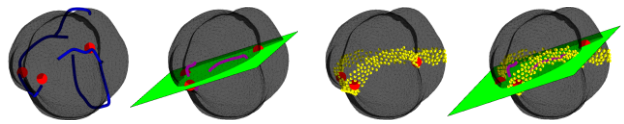
On fluoroscopic imaging, the right ventricular side of the septum was the most consistently visible part and was therefore used to track two apico-basal lines (an anterior border and an inferior border), defining the septal orientation. Both borders were smoothed with a moving average filter and resampled to be composed of 100 points, defining septal orientation as 100 vectors between the anterior and inferior borders. Near the base and the apex, where the septum was no longer visible in imaging data, the vectors were extrapolated to cross the epicardium in all directions.

2.4. Septal points selection

Since this bullseye transformation is based on a selection of 3 points, different techniques have been tested to determine the best way of choosing them (see Figure 2). Firstly, an "Initial technique" (IT) where using the coronary arteries (left anterior descending artery and posterior descending artery) to estimate the epicardial location of the septum. The second technique uses an "Optimal plane" (OP) that has been automatically defined to fit the septal tracking as best as possible. The 3 points have then been chosen at the intersection of the epicardial mesh with this virtual plane (regardless of the real septum location on their vicinity). The third approach uses the septal tracking to choose the epicardial points on both the apex and the base that are as close as possible to the real septum, and is later referred as "Apical and basal septum" (A&BS). The last technique uses the same apical point as A&BS, then calculates the plane that best fits the septal tracking while still going through this apical point. The basal points have been chosen on this plane and this technique has therefore been called "Apical septum and optimal base" (AS&OB).

2.5. Septum rotation correction

To correct for the septal rotation, the angle between the anatomical septum and the plane separating left and right on the bullseye plot is first estimated. For each point selection method, this septal angle was calculated using the 100 orientation vectors defined by fluoroscopy. This angle has then been used to correct each vertex's polar position by the septal rotation at the corresponding height. The heart shape is therefore deformed to compensate for the septal rotation. Because the "Initial technique" is not based on septal tracking, the rotation has neither been estimated nor corrected. As a consequence, this technique is used as a reference to assess the improvement brought by the other approaches and their septal correction.



IT OP A&BS AS&OB

Figure 2: Illustration of points selection techniques on an apical view of a porcine heart (LV is on top). Red dots are selected points, blue lines are coronary arteries, yellow dots are the septal tracking projected to the epicardium, purple lines are septum edges and the green plane is the best fit to septum edges.

2.6. Bullseye quality assessment

To evaluate the impact of the modifications made to the algorithm, 4 pig hearts have been used to generate bullseyes. Each heart has undergone a septal tracking by 2 different users, repeated 3 times, and the 3 new points selection approaches have been performed for each tracking. The IT and coronary arteries segmentation have also been repeated 3 times by 2 different users. This protocol generated a total of 96 bullseyes.

Because the main aim of this work was to improve the bullseye by ensuring a left/right separation that matches the anatomical septum, the main evaluation criterion was the closeness of the true septum to the y-axis of the bullseye. To assess this proximity, epicardial points < 5 mm from the septal tracking have been considered as on the septum. The bullseyes have then been split into 100 horizontal slices and the mean abscissa of the epicardial points on the septum has been calculated for each of these slices. The bullseye structure (100 concentric circles of 360 points each) means the density of points is inversely proportional to the circle radius, thus each point has been weighted by its distance to the bullseye's center. The absolute mean of the abscissas on all of the slices has then been calculated for each bullseye to assess septum deviation across the whole plot. Means have also been calculated for the inferior basal part (30 highest slices), the apical part (40 central slices) and anterior basal part (30 lowest slices) to determine if regional deviations in the septum occur.

The reproducibility of the representation was assessed by comparing intra- and inter-user septal trackings and bullseyes for each heart. The trackings were compared in pairs, using percent agreement (ratio of points with identical results over total number of points) and F1 score.

The bullseyes' reproducibility was assessed by calculating the percent agreement of the 20 bullseye segments in the 3D heart space (see Figure 3). They have therefore been compared in pairs across different techniques and users in order to determine their respective impact on the final visualization.

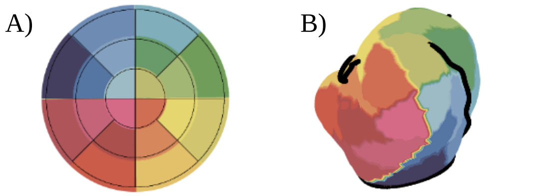


Figure 3: Bullseye segmentation. Each segment delimited in A) is associated with a color that is applied on the 3D heart's vertices on B) to associate epicardial vertices with bullseye's segments.

2.7. Statistics

All statistical tests have been performed with GraphPad Prism® using 1-, 2- or 3-way ANOVA tests with repeated measures between the point selection techniques, except for tracking comparisons which was non-repeated. When a factor had neither significant effect nor interaction with the other factors, data have been regrouped to perform another ANOVA without this factor. Statistical significance was defined as $p < 0.05$.

3. Results

3.1. Septum rotation correction

The 3 new techniques generated bullseyes with a visible improvement over the reference, as illustrated in Figure 4.

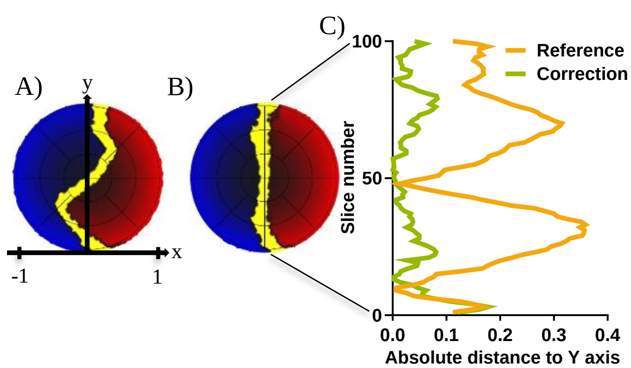


Figure 4: Example of bullseyes' septum centering from the same heart and tracking, generated with either A) IT or B) AS&OB technique. C) Septum deviation quantification over the bullseyes' 100 slices.

In terms of distance between the septum and the y-axis, both users had comparable results (not shown) and have therefore been regrouped. A 1-way repeated measures ANOVA has been carried out on 24 pairs of heart and tracking, each using 4 points selection techniques for a total of 96 bullseyes. The 3 approaches using a correction generated a significant improvement over the Initial Technique (IT) in terms of absolute mean distance to the y-axis over the whole bullseye (OP: 0.049 ± 0.021; A&BS: 0.064 ± 0.031; AS&OB: 0.051 ± 0.024; IT: 0.166 ± 0.036; $p < 0.0001$), and the only significant difference among them was between OP and A&BS ($p < 0.05$). These results are shown in Figure 5A.

When separating septum deviation between the different regions, users had no effect again and both basal regions (inferior and anterior) had similar results (not shown). Data have therefore been regrouped to perform a 2-way repeated measures ANOVA and results are shown in Figure 5B. Briefly, the 3 new techniques reduced septum deviation on the basal regions by a factor of 2 or 3 ($p < 0.0001$) and on the apical region by a factor of roughly 5 ($p < 0.0001$) compared to IT. For each of these 3 techniques, apical deviation was smaller than basal deviation by a factor of 2 or 3 ($p < 0.0001$) while the IT had a similar deviation between both apical and basal regions. Additionally, the A&BS approach performed slightly less well than OP ($p < 0.01$) and AS&OB ($p < 0.05$) with a basal deviation 30-40% higher.

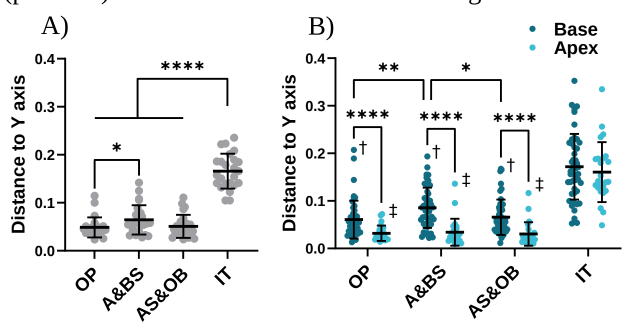


Figure 5: Comparison of bullseyes' septum centering between different point selection techniques: OP, A&BS, AS&OB and IT. A) Mean septum absolute deviation across the whole bullseye. B) Mean septum absolute deviation depending on the bullseye's region. Values presented as mean and standard deviation. (*) indicates $p < 0.05$, (**) indicates $p < 0.01$ and (****) indicates $p < 0.0001$. (†) indicates $p < 0.0001$ VS Base of IT and (‡) indicates $p < 0.0001$ VS Apex of IT.

3.2. Reproducibility

To assess reproducibility, manual septal trackings have been compared in pairs and their percent agreement (PA) are shown in Figure 6A. A 1-way ANOVA identified a statistically significant though non-substantial decrease between intra-user 2 PA and inter-user PA (approximately 2.5%; $p < 0.05$). Because most of the epicardial points are far away from the septum and therefore systematically identified correctly, we also calculated F1 scores to limit the impact of those true negative points and results are depicted in Figure 6B. Again, a difference has been found between intra-user 2 and inter-user ($p < 0.05$) with a 13% decrease in F1 score. Inter-user reproducibility remained satisfying with an average F1 score of 0.75 and only 2 of

36 values below 0.5.

In terms of epicardial segmentation, different users had slightly different results depending on the techniques (not shown): user 1 had inferior results with IT than with OP while user 2 had better results with IT and OP than with the other 2, and inter-user results were similar across techniques with only OP above IT and A&BS. Thus, reproducibility of a technique may vary depending on the user. To determine if one method is best across users, their data have been regrouped. Results are shown in Figure 6C and all techniques generated satisfying results, with OP being slightly more reproducible (0.83) than the other techniques (between 0.76 and 0.79).

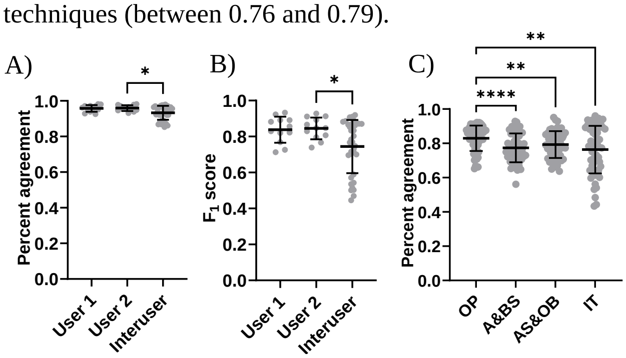


Figure 6: Reproducibility assessment. A) Percent agreement (PA) of manual septum trackings comparison in pairs. B) F_1 score of manual septum trackings comparison in pairs. C) PA of epicardial segmentation across different points selection techniques: OP, A&BS, AS&OB and IT. Values and p-values are presented as in Figure 5.

4. Discussion

UNISYS is an existing algorithm that allows an easy 2D visualization of cardiac electrical or mechanical data. This study has improved the algorithm by ensuring a better interpretability in terms of signal localization. To do so, the septum has been tracked using fluoroscopic imaging and its rotation has been calculated and corrected so as to ensure the septum is straight on the bullseye plot, correctly separating LV and RV.

Three different variants of the algorithm have been tested and all of them resulted in a satisfactory improvement in terms of septum centering compared to the reference technique, especially near the apex. They also came with a good reproducibility (comparable to that of IT, but with less outliers), even between different users. Indeed, although septal tracking varied slightly between users, it did not negatively impact the other parameters (i.e., septum centering and epicardial segmentation reproducibility). The resulting bullseye plot is therefore not impacted greatly by inter-user variability.

Even though all 3 new techniques performed well, we would recommend the AS&OB technique. This method outperforms the AB&S, and although it is marginally less reproducible than the OP, it ensures that the apical point is truly on the septum and not solely on a "virtual" plane.

This study was performed on pig hearts with fluoroscopic imaging, but the same algorithm could be used on humans or with a different imaging modality as long as both the epicardium and the septum can be visualized. The main strength of this method is to represent and divide data into meaningful areas, making regional studies easier from a statistical point of view.

Finally, it should be kept in mind that a 2D representation of a complex form such as a heart's shape is first and foremost a distortion. It can be very practical for interpretation but cannot perfectly retain the whole initial complexity.

In conclusion, this study introduces a new approach to improve standardized visualization of biventricular data on a 2D bullseye. By correcting septum rotation along the heart's height, it has been possible to significantly reduce septal deviation on the final bullseye plot. This reproducible method therefore ensures that both sides are well defined, facilitating areas of interest's localization. The algorithm will be available shortly on Job Stoks's GitHub: https://github.com/jobstoks/UNISYS.

Acknowledgments

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References

[1] M. D. Cerqueira *et al.*, « Standardized myocardial segmentation and nomenclature for tomographic imaging of the heart. A statement for healthcare professionals from the Cardiac Imaging Committee of the Council on Clinical Cardiology of the American Heart Association », *Circulation*, vol. 105, nº 4, p. 539-542, janv. 2002, doi: 10.1161/hc0402.102975.

[2] L. Capulzini, P. Brugada, J. Brugada, et R. Brugada, « Arrhythmia and right heart disease: from genetic basis to clinical practice », *Rev. Esp. Cardiol.*, vol. 63, nº 8, p. 963-983, août 2010, doi: 10.1016/s1885-5857(10)70190-0.

[3] J. Stoks, U. C. Nguyen, R. Peeters, P. G. Volders, et M. J. Cluitmans, « An Open-Source Algorithm for Standardized Bullseye Visualization of High-Resolution Cardiac Ventricular Data: UNISYS », in *2020 Computing in Cardiology*, sept. 2020, p. 1-4. doi: 10.22489/CinC.2020.160.

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