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Angaben zur Veröffentlichung / Publication details:

Zaunseder, Sebastian, Martin Schmidt, Hagen Malberg, and Mathias Baumert. 2014. "Measurement of QT variability by two-dimensional warping." In *8th Conference of the European Study Group on Cardiovascular Oscillations (ESGCO), 25-28 May 2014, Trento, Italy*, edited by Vlasta Bari, Tito Bassani, Luca Faes, Michela Masè, Elisa Morganti, and Flavia Ravelli, 163–64. Piscataway, NJ: IEEE. https://doi.org/10.1109/esgco.2014.6847570.

Measurement of QT Variability by Two-Dimensional Warping

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***Abstract*—This contribution presents a novel warping method, two-dimensional signal warping (2DSW), for tracking beat-to-beat changes in time intervals from electrocardiograms. To evaluate the efficiency of 2DSW to capture subtle changes in the QT interval we apply 2DSW to the Physionet QT database. It is shown that 2DSW allows highly accurate tracking of QRS-onset and T-end, which renders the method useful for future clinical applications, in particular beat-to-beat variability analysis of ECG features.**

I. INTRODUCTION

QT variability was shown to be a strong predictor of cardiac mortality. A major concern regarding QT variability analysis is the correct identification of subtle QT interval changes between beats. Amongst the most powerful methods to extract the QT interval on a beat-to-beat basis are template-based methods. Such methods typically rely on shifting and/or homogeneous stretching [1] of signal excerpts to optimize the similarity between a beat under consideration and a QT template. After manually or semiautomatically defining the QT interval borders in the template, the QT interval can be deduced from the optimal stretching/shifting factors. Although template stretching has proven its clinical applicability, it might not be able to capture the details of morphological changes within the QT interval. To account for more complex modifications and extract changes in the QT interval from long-term ECG, we recently introduced a method referred to as *2-dimensional signal warping* (2DSW) [3]. 2DSW allows for inhomogeneous deformation of patterns by introducing horizontal and vertical segmentation and adaptation. This contribution applies 2DSW to a standard ECG database. We compare 2DSW's efficiency to track changes in the QT interval on a beat-to-beat basis to previously described methods.

II. MATERIALS AND METHODS

Data: We used the QT database (QTDB) [4] which is freely available from Physionet [5]. The database was designed for the evaluation of algorithms dedicated to the measurement of QT and other time intervals in the ECG. The QTDB consists of 105 fifteen-minute excerpts of two-channel ECG Holter recordings. The recordings include a broad variety of QRS and ST-T morphologies. Each recording contains reference annotations for at least 30 heart cycles.

Concept of 2DSW: Extending the template stretching algorithm by Berger et al. [2] 2DSW employs a beat template. Using a grid of N_c columns and N_r rows this template is segmented into so-called *warping areas*. To delineate a beat under consideration the template is adapted to minimize the normalized Euclidean distance between the template and that beat (see Fig. 1). Adaptation is accomplished by shifting the intersection points, so-called *warping points*, and deforming the adjacent warping areas. Signal portions are deformed relatively to the deformation of the warping area they belong to. Similar to [2], the QT interval is identified by automatically or semiautomatically defining the QT interval borders in the template and subsequently evaluating the position of the borders after deforming the template. Details on 2DSW (concept, mathematical consideration, algorithmic implementation) are given in [3]. Parameterization and application of 2DSW: The template beat was constructed from 30 beats detected before the first reference annotation. To construct the template we used time delay estimation by Improved Woody's Method for temporal alignment and median filtering for outlier removal. The warping grid consisted of $N_c = 7$ columns and $N_r = 4$ rows. The segment borders were positioned with respect to the derivative of the template. The QT interval in the template was automatically derived from three reference annotations of the annotated beats that resemble the template most closely. Beats for which the adaptation by 2DSW did not yield satisfactory quality, i.e. the normalized Manhattan distance between the deformed template and the beat exceeded a predefined threshold, were excluded from the further analysis.

Performance assessment: Strategies for the measurement of time intervals and its evaluation using the QTDB differ between methods and researchers. Algorithmic measurements most often make use of a single lead only, whereas the reference annotation of the QTDB bases on two leads. One commonly used procedure performs the delineation in a single

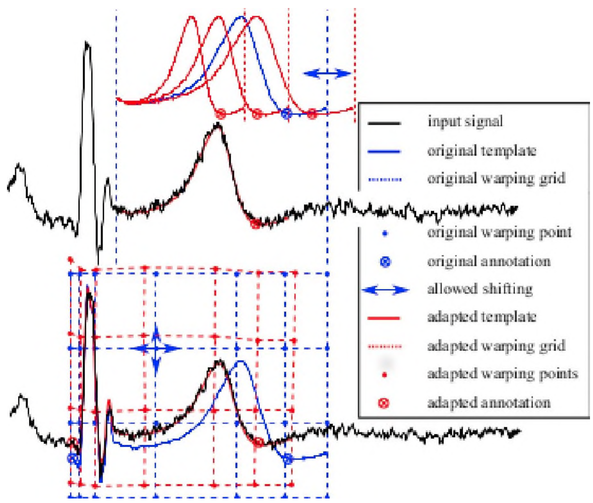

Fig. 1. Concept of homogeneous stretching and 2DSW. 2DSW allows for segmented horizontal and vertical adaptation by shifting of warping points.

Research supported by DAAD and the Group of Eight.

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TABLE I
RESULTS OF ALGORITHMIC MEASUREMENTS.

Method (used lead)	Q Se*	Q mean	Q std	T-end Se*	T-end mean	T-end std
single lead evaluation						
Zifan [7] (2)	74.8	-5.22	3.60	63.4	6.72	33.5
Vullings [8] (1)	81.5	-0.8	10.6	79.4	9.4	49.0
Dubois [9] (1)	n.a.	n.a.	n.a.	82.1	45.0	38.6
Dubois [9] (2)	n.a.	n.a.	n.a.	81.6	42.8	40.3
Rincon [10] (1)	99.6	5.4	8.4	99.3	-5.3	22.7
Rincon [10] (2)	99.7	8.6	12.6	99.2	-4.6	27.2
2DSW (1)	88.6	-4.0	7.0	90.7	-6.6	15.4
2DSW (2)	88.7	-6.8	8.0	90.8	-7.1	16.7
supervised two lead evaluation						
Martinez [6]	100	4.6	7.7	99.8	-1.6	18.1
Laguna [6]**	99.9	-3.6	8.6	99.0	13.5	27.0
Dubois [9]	n.a.	n.a.	n.a.	93.6	34.8	30.3
Rincon [10]	100	3.4	7.0	100	-2.4	16.9
2DSW	92.8	-3.2	6.2	94.9	-4.5	13.1

*Se in % is the sensitivity, i.e. the percentage of evaluated beats. For 2DSW all QRS reference annotations were considered. A beat was rejected, thus degrading Se, if 2DSW failed to adapt the template closely to that beat.
**Numerical results taken from [6] where the method of Laguna was applied.

channel and compares the algorithmic results to the reference (*single lead evaluation*). Another strategy performs the delineation in the two leads independently and incorporates the reference annotation to select the algorithmic annotation that best matches the reference annotation for each beat (*supervised two lead evaluation*) [6].

III. RESULTS

Table I compares the results regarding the extraction of QRS-onset and T-end by using 2DSW to the results obtained by other methods. Mean errors and standard deviations of 2DSW were computed by averaging the intrarecording mean errors and standard deviations, respectively. The underlying distributions of delineation errors for all beats are shown in Fig. 2. 2DSW is directed at capturing beat-to-beat changes, not to derive an absolute delineation. Thus, the algorithmic capacity is assessed best by the standard deviation, whereas the mean deviation is of minor interest. Regarding the standard deviation, our results are in all settings below the standard deviations of most other algorithms while the number of evaluated beats compares to the average usage rate.

IV. DISCUSSION AND CONCLUSION

The results obtained by 2DSW using the QTDB compete with the most accurate results that have been published. Importantly, we did not train the algorithm on the QTDB, but used our previously described implementation [3]. However, as mentioned our algorithm uses a-priori information by incorporating three reference cycles to construct the waveform boundaries of our template. Aiming at beat-to-beat QT variability extraction this step does not imply a fundamental restriction, but it favors 2DSW compared to delineation methods that aim at a fully automated measurement. When evaluating the results in terms of absolute values one should consider the limitations of the reference annotations. Although those annotations are regarded as gold standard, the comparison of reference annotations by two human annotators for selected records of the QTDB revealed deviations ($mean \pm std$) of

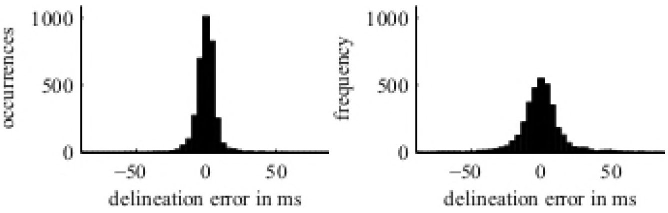

Fig. 2. Distribution of the delineation error corrected for the mean error per record for Q (left) and T end (right). Both distributions show a symmetric character.

5.3 ± 11.1 ms and 2.1 ± 22.4 ms for QRS-onset and T-end, respectively. A further improvement of the results that have been obtained by some of the algorithms, including 2DSW, seems to be hardly possible. A general limitation of our study is the structure of the QTDB. The QTDB was not intended to be used for the evaluation of methods that focus specifically on the beat-to-beat QT variability as 2DSW does. Particularly, the recording duration and the very limited number of annotated beats per record, respectively, limit the suitability of the QTDB for our purposes. However, various researchers have evaluated their methods using the QTDB and the comparison to their results demonstrates the efficiency of 2DSW for tracking QT changes. Future studies should now employ 2DSW for the analysis of QT variability from long-term recordings to verify its clinical value.

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