Quality Evaluation and Effect of Time Synchronization on the Digital Recovery of Intracardiac Electrograms

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Abstract

Digital recovery of cardiac signals from paper printed recordings in implantable cardioverter defibrillators (ICD) is needed whenever signals in digital format can not be retrieved from stored electrograms (EGM). Though many methods have been proposed for digital recovery of paper printed ECG, none has specifically addressed the intracardiac EGM, which are only available in black and white. Our aims were: (1) to propose an image processing algorithm suitable for recovering ICD stored EGM; (2) to evaluate its performance in different cardiac rhythms by using an adequate time synchronization processing for this application. An image processing algorithm was designed for recovering the signals from ICD paper printed EGM. EGM from simultaneously acquired tip-ring and can-coil ICD lead configurations were scanned. Tip-ring and can-coil recordings were automatically separated into two streams, and signal tracking was made for each stream. Recovered EGM were compared to their gold standard (ICD sampled and stored recordings). Time alignment of recovered and gold standard EGM was observed to be fundamental on the performance measurements, so that three different techniques (LS, spline, and matched filter) were benchmarked. Consistent lower performance was observed in tip-ring than in can-coil recovered EGM and performance was improved by LS alignment with respect to spline and matched filter. In conclusion, our algorithm allows to automatically recovering ICD EGM from paper printed recordings.

1. Introduction

Digital recovery of cardiac signals from paper printed recordings is required when analyzing historical ECG signals which are not available in digital format. Also, in implantable cardioverter defibrillators (ICD), it is not always possible to program the adequate setting thresholds for sampling and storing device-recorded intracardiac electrograms (EGM), due to the tachycardia cycle programming thresholds or to the patient condition. Recovering of cardiac signals in digital format from paper stored recordings can be necessary in some applications in which further analysis of the ECG or EGM is required by means of signal processing techniques, for the purpose of research and improving of the current patient diagnosis capabilities.

From a clinical point of view, the analysis of the information in the EGM or ECG when printing either in color or in black and white is the same. From a technical point of view, the digital recovery of the signal printed on grid paper gets more complicated as the number of different colours decreases. Though many methods have been proposed for digital recovery of ECG [1–7], none has specifically addressed the EGM cases, which in addition, are only available in black and white. In [1, 2], mathematical morphology was used to remove the grid lines in high quality black and white images, which is often far from the real case of recovering paper stored EGM. Additionally, previous methods in the literature need to work with signals of an uniform tracing, which is not fulfilled by ICD printed EGM.

Therefore, the aim of our work was to propose an image processing algorithm suitable for recovering black and white paper printed cardiac signals. We focused on ICD stored EGM, as this is a hard recovery problem which, to our best knowledge, has not been analyzed in the literature. We wanted to evaluate its performance in general terms, but also for different cardiac rhythms. We also pointed out and addressed the specific problem of using an adequate time synchronization processing for this application.

The scheme of the paper is as follows. In the next section, the image processing algorithm is explained, paying attention to the preprocessing, spatial-temporal conversion, and time synchronization. Then, the recovery capabilities of the proposed method are benchmarked in an ICD stored EGM database, with different cardiac rhythms, namely, sinus rhythm (SR), tachycardia (T), and ventricular fibrillation (VF). Finally, conclusions of the work are given.

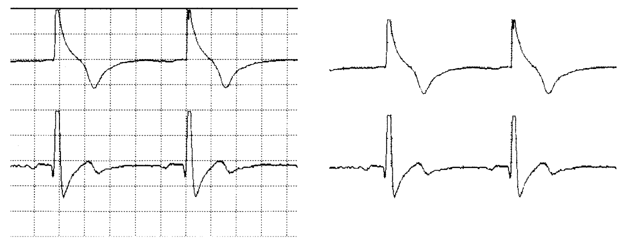
2. Image processing recovery algorithm

An algorithm is next proposed for recovering the signals from ICD paper printed EGM using image processing techniques. In brief, EGM from simultaneously acquired tip-ring and can-coil ICD lead configurations are first scanned. The grid is filtered out at this stage and tip-ring and can-coil recordings are automatically separated into two streams. For every stream, independent signal tracking is made by using an algorithm consisting of: (1) detection of the midpoint of the signal trace; (2) detection of the most likely tracking angle according to a Least Squares (LS) fit of the precedent slope; and (3) filling of the image gaps with a LS very-short-term signal adjustment. These stages are next detailed.

2.1. Preprocesing

The first step for recovering cardiac signal is to remove the grid from the scanned image (see Fig. 1). For this purpose, we started by correcting the possibly existing rotation in the EGM image by using the Hough Transform [8]. Then, we made an artificial grid to be used as a mask, which allowed us to separate the actual grid from the rest of signal tracings. The procedure consisted of using morphological operators for obtaining only the vertical and horizontal lines in the image, using its Fourier transform to determine the position of these lines, and keeping the lines whose frequency corresponds to that line periodicity. After this result, the artificial grid is available, and the grid from the original image can be readily obtained by using the pixel product between the original image and the artificial grid. We call the image at this stage *image A*.

In order to retain those pixels in the grid which also belong to the the cardiac signal, discontinuity of *image A* is increased by randomly removing 50% of the pixels in the grid (*image B*), and then an OR operator is made on the original image and on *image B*. Finally, connected groups of few pixels are removed, as these are likely to belong to the grid. This procedure can eliminate pixels from the cardiac signal which are on the grid, which can be due to fast variations of the voltage levels in the signal, and hence highly relevant to be recovered. Assuming that, in general, the signal trace width is thicker than that of the grid, this drawback is avoided by using a morphological closing with a structuring element to preserve the signal tracing and to remove the grid. Both procedures are combined with a complementary mixing, yielding *image C*. In order to recover each signal in the printed paper (can-coil and tip-ring), *image C* is segmented by means of a horizontal projection.



(a) (b)

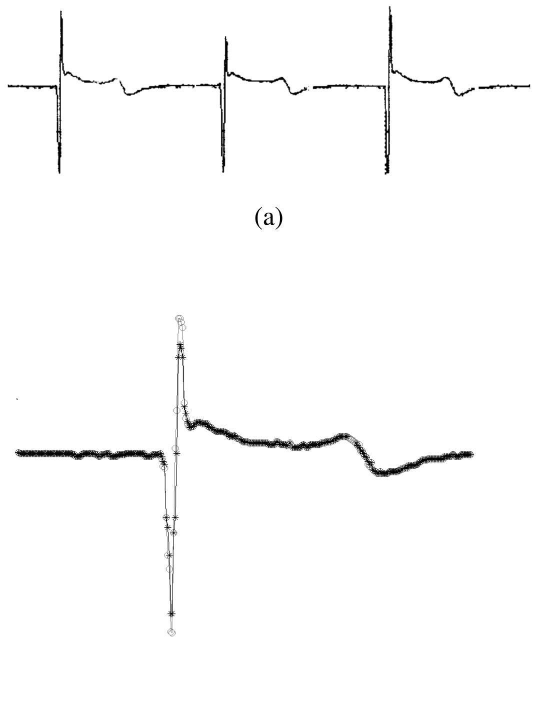
Figure 1. Paper printed EGM from a scanned image (a) and image after grid removal (b).

2.2. Space to time conversion

For the space to time units conversion, we need to know the time and voltage resolution in each printed EGM. Time resolution can be obtained from the printing velocity of the paper and the scanning resolution, whereas the voltage resolution can be obtained from scanning resolution and the voltage per square relationship. In the beginning of some EGM, a calibration squared pulse is present, and then we have to determine the number of pixels corresponding to the pulse height.

Given that the time evolution of the signal is in the horizontal direction, the image is analyzed column by column (consecutive time instants) and from left to right. For each column, we choose the pixel in the center of the trace as the representant of that time instant. Hence, a smooth (low-pass) estimation of the cardiac signal is obtained. Fig. 2 (a) shows an image with the EGM tracing, and Fig. 2 (b) the electric signal with this procedure (dark line with stars). Note that this estimation does not properly follow the fast variations of the voltage level.

For improving the tracking of fast changes, we used a time window of 5 time instants on the signal estimated in the preceding stage, and we obtain (using LS) the slope of the best fitting line to the 5 points. If this slope exceeds a threshold (which is a function of the signal tracing width), then, for a positive slope, previously estimated value is substituted by the average value of the maximum value and the low-pass signal value, whereas for a negative slope we use the same calculation in terms of the minimum instead of the maximum. Finally, in order to determine the value of the signal in the time instants were we have no signal tracing, a linear interpolation is made between the



(a)

(b)

Figure 2. Image of an EGM (a) and its recovered signal for the first beat (b).

two nearest neighbor points. Fig. 2 (b) shows (gray line with circles) an example of the final result of this stage.

2.3. Time synchronization

After recovering the waveform, the quality of the signal can be measured by making a sample-by-sample comparison with an available *gold-standard* signal, in our case given by the ICD stored EGM when it is also available. For their comparison, they need to be synchronized in time, and for this purpose we will benchmark three different methods: LS, splines, and matched filter (MF).

The LS and the spline methods automatically yield a set of characteristic points, namely, local maxima (and minima) which are the highest (lowest) in the signals to be synchronized, and they build a graph in Cartesian coordinates that represents the time instants for the characteristic points. These methods estimate the regression curve better fitting these points, in terms of a straight line for LS, or third order polinomials for splines. The new time instants for the recovered signal are estimated with the regression curve.

The time positions of the new characteristic points in the recovered signal are not necessarily associated to a constant time delay during all the signal duration. In fact, we have checked that it is usual to have a disadjustment between the characteristic points in the gold-standard and in the recovered signal throughout the recording. Accordingly, for the matched filter method, both the recovered signal and the gold-standard are divided into segments, and the cross correlation between both is obtained. The maximum of the correlation gives the time difference of a segment compared to the other, and its relative position indicates whether the recovered signal has to be delayed or advanced in that value.

3. Results

Recovered EGM from the same ICD manufacturer (Medtronic®) were compared to their gold standard in 6 SR, 8 sustained T, and 10 VF, from 17 patients. Performance was characterized according to several merit figures [9, 10], namely, the Root Mean Square (RMS), the Normalized RMS (NRMS), the Percentage Root mean square Difference (PRD), the normalized PRD to be independent of the dc level (PRD'), the maximum amplitude error (MAE), and the correlation coefficient (ρ). Printed EGM were obtained using programmer Medtronic Carelink®-2090, and subsequently scanned using a HP Scanjet 7650, with 390 ppp resolution. In all recordings, printing velocity was 25 mm/s, which was sufficient as it was near to three times the sampling frequency in ICD stored EGM (128 Hz). After scanning, a binary image was stored in a lossless format (bmp).

Time alignment of recovered and gold standard EGM was observed to be fundamental on the performance measurements, so that three different techniques (LS, spline, and MF) were benchmarked. Statistical significance was given by paired t-test yielding $\alpha < 0.05$ (denoted by $*$). Consistent lower performance was observed in tip-ring than in can-coil recovered EGM (for LS alignment, PRD 16.8 ± 9.8 vs $9.5 \pm 3.1^*$, NRMS 9.2 ± 3.3 vs $5.3 \pm 2.0^*$, MAE 1.0 ± 0.5 vs $0.3 \pm 0.2^*$). Performance was improved by LS alignment with respect to spline and matched filter (for instance, PRD 9.5 ± 3.1, $10.3 \pm 3.0^*$, $14.3 \pm 5.2^*$, respectively) in discharge EGM, but not in tip-ring EGM. All recordings were better recovered from SR than from VF and from T. As an example, for the tip-ring case: PRD $12.2 \pm 7.6^*$, 14.0 ± 4.3, 21.8 ± 12.4, respectively.

In Table 1, which shows the detailed results for can-coil and tip-ring electrode configurations in terms of the alignment methods, $^+$, *, and $^\#$, indicate significant differences between LS vs MF, LS vs splines, and MF vs splines, respectively. The best results are obtained with LS and the worst with MF, since MF synchronizes the recovered signal on a segment by segment basis and estimates new voltage levels whenever a segment has to be delayed and the next has to be advanced. For the three methods, performance is better in can-coil EGM than in tip-ring EGM, due

Can-coil	RMS	NRMS (%)	PRD (%)	PRD' (%)	MAE (mV)	ρ
LS	$0.11(0.06)^{+}$	$5.38(2.01)^{+}$	$9.56(3.18)^{+}$	$10.20(3.28)^{+}$	$0.38(0.22)^{+}$	$0.99(0.00)^{+}$
Splines	$0.12(0.07)^{*}$	$5.87(2.27)^{*}$	$10.31(3.01)^{*}$	$11.02(3.17)^{*}$	$0.39(0.22)$	$0.99(0.00)^{*}$
Matched Filter	$0.16(0.09)^{\#}$	$8.00(3.00)^{\#}$	$14.39(5.28)^{\#}$	$15.45(5.88)^{\#}$	$0.60(0.36)^{\#}$	$0.99(0.01)^{\#}$

(a)

Tip-ring	RMS	NRMS (%)	PRD (%)	PRD' (%)	MAE (mV)	ρ
LS	$0.22(0.12)^{+}$	$9.23(3.36)$	$16.81(9.89)$	$19.70(11.01)$	$1.04(0.52)$	$0.98(0.03)$
Splines	$0.23(0.13)^{*}$	$9.91(3.69)^{*}$	$17.53(8.99)$	$21.38(11.47)^{*}$	$1.04(0.52)$	$0.97(0.03)$
Matched Filter	$0.26(0.17)$	$10.62(5.42)$	$19.08(11.71)$	$22.16(12.81)$	$1.22(0.83)$	$0.97(0.04)$

(b)

Table 1. Average and (standard deviation) for merit figures when using the proposed time synchronization methods in can-coil (a) and tip-ring (b) ICD stored EGM in the database.

to the last ones consisting of faster voltage changes making consecutive fast deflection in the paper difficult to distinguish and to recover. Note that this decrease in performance is more present for LS and splines methods, as their synchronization procedure uses a regression curve, which is sensitive to the selection of the characteristic points.

When comparing the recovering performance for different rhythms in terms of the best method (LS), the quality for the recovered signal is significantly better in SR, then in VF, and last in T. These differences can be partly explained by the higher velocity of the changes in the paper tracing for T signals.

4. Conclusions

Our algorithm allows to automatically recovering ICD EGM from black and white paper printed recordings. Quality evaluation shows that the performance depends on the lead type (can-coil or tip-ring), on the use of an adequate time synchronization, and the underlying arrhythmia.

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