

Abnormal Repolarization in the Acute Myocardial Infarction Patients: A Frequency-Based Characterization

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Abstract: Despite ST elevation having poor sensitivity for acute myocardial infarction (AMI), it remains the main electrocardiographic (ECG) repolarization index for AMI diagnosis. Aim of the present study was to propose a new $f99$ index, defined as the frequency at which the repolarization normalized cumulative energy reaches 99%, for ECG AMI discrimination from health with good sensitivity and good specificity. Evaluation of such $f99$ index was performed on 12-standard-lead (I, II, III, aV1, aVr, aVf, V1 to V6) ECG recordings of 47 healthy controls and 108 acute myocardial infarction (AMI) patients. Repolarization dispersion caused $f99$ distributions to be significantly lead dependent. In most leads (leads I, II, aV1, aVr, V2-V6), $f99$ median value was lower in the healthy controls (10-17 Hz) than in the AMI patients (12-38 Hz) indicating higher frequency components (i.e. a more fragmented repolarization) in the latter population. AMI patients from healthy controls discrimination by $f99$, evaluated in terms of sensitivity (Se) and specificity (Sp), was also lead dependent. Single-lead analysis indicated leads I (Se=80%, Sp=77%) and aV1 (Se=84%, Sp=74%) as optimal. Instead, lead-system analysis, performed to overcome dispersion issues, provided the best results when averaging over the 6 precordial leads (Se= 81% and Sp=74%). In conclusion, our new $f99$ index appears as a promising tool for non-invasively and reliably discriminate AMI patients from healthy subjects.

Keywords: Digital electrocardiography, ECG repolarization index, myocardial infarction, repolarization variability, T-wave frequency content.

1. INTRODUCTION

Defects in the cardiac repolarization are known to be associated to several life-threatening diseases [1-4]. In the electrocardiogram (ECG) such defects appear as abnormalities of the ST segment and T-wave, which can be non-invasively characterized by means of indexes. The most popular ECG repolarization indexes are the QT interval [2,3], the ST elevation [5,6] and the T-wave alternans [4,7]. Additional morphological indexes present in the literature include the T-wave duration parameters [8,9], the T-wave amplitude parameters [10,11] and others [12-16]. Abnormalities in the ECG repolarization morphology are reflected, in the frequency domain, in a variation of the T-wave frequency content. Though, repolarization indexes based on this feature have only occasionally been proposed [17-19].

The acute myocardial infarction (AMI: a disease in which the blood stops flowing properly to part of the heart and the heart is injured because not receiving enough oxygen) is one of the leading causes of death and disability in the world [20]. Even though in most cases ST elevation is a result of non-AMI causes [5] and several other ECG repolarization abnormalities have been observed in the AMI patients [2,18, 19,21,22], the ST elevation remains the ECG repolarization

index mainly used to diagnose the presence of an AMI [23,24] since initial ST elevation is part of the classic evolutionary pattern of the AMI [25]. Still, ST elevation has poor sensitivity for AMI given that up to 50% of patients exhibit atypical repolarization changes which may include isolated ST depression, T inversion or even normal ECG [24]. In order to significantly improve the rate of correct AMI diagnosis from ECG tracings, new repolarization parameters are needed. Thus, aim of the present study was to propose a new repolarization index based on the T-wave frequency content, termed $f99$, able to discriminate AMI patients from healthy subjects with both a good sensitivity and a good specificity. Being defined in the frequency domain, $f99$ computation requires automatic analysis of the ECG signals. Often, many of the above-mentioned time-domain repolarization parameters are still manually evaluated. Compared to human evaluation, automatic ECG analysis allows a more objective characterization of the ECG features by eliminating the subject-related variations of the measures, even though some inter-method variations may persist [26,27].

2. METHODS

2.1. Clinical Data

Our clinical data consisted of short (30 s to 2 min) 12-standard-lead (I, II, III, aV1, aVr, aVf, V1 to V6) digital ECG recordings (1 KHz sampling frequency) from 47 healthy controls and 108 myocardial infarction patients (AMI), all belonging to the PTB Diagnostic Physionet

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database (www.physionet.org). Among the AMI patients, 49 were affected by anterior acute myocardial infarction (ANAMI) and 59 by inferior acute myocardial infarction (INAMI). Additional clinical information relative to the two populations is reported in Table 1.

2.2. Repolarization Characterization

Preprocessing. Before T-wave frequency-content evaluation, ECG tracings underwent a preprocessing stage consisting of $F_s=200$ Hz resampling, low-frequency (≤ 0.5 Hz) noise removal and 50 Hz line noise removal. Eventually, after R-peak detection, a 20-beat 12-lead ECG window characterized by stable HR (RR-interval standard deviation $<10\%$ of mean RR) and no ectopic beats and artifacts was randomly extracted from each ECG tracing.

Repolarization frequency-content characterization. Repolarization frequency-content evaluation was performed in each ECG lead independently. From the median beat, computed using the 20 available beats, the repolarization onset (*RepOn*) and offset (*RepOff*) were identified as:

$$RepOn = 70 \text{ ms from the R - peak} \tag{1}$$

$$RepOff = 0.3\sqrt{medianRR} \cdot 1000 \text{ ms from the RepOn point.} \tag{2}$$

Eq. (2) is an adjustment of an empirical formula [28] finalized to avoid cases of P-wave inclusion in the T-wave window, and median RR (s) is the median RR interval. The median repolarization waveform was then forced to be 260 ms long by opportune resampling. Eventually, the repolarization signal (*RPS*) was constructed by zero padding everything outside the resampled median repolarization waveform till 1 second.

RPS frequency-content evaluation was performed by computing the Fourier power spectrum ($PS_{RPS}(k)$; Eq. 3) and energy signal ($E_{RPS}(k)$; Eq. 4):

$$PS_{RPS}(k) = \sum_{n=0}^{N_s-1} RPS(n) \cdot \exp(-j2\pi \frac{k}{N_s} n) \tag{3}$$

$$E_{RPS}(k) = \sum_{m=0}^k PS_{RPS}(m) \tag{4}$$

where N_s is the number of samples ($N_s=200$), and n and k are adimensional indexes to get time and frequency as $t_n=n \cdot (1/F_s)=n \cdot 0.005$ s, with $n=1, 2, \dots, N_s$, and $f_k=k$ Hz, with $k=1, 2, \dots, N_s/2$, respectively. After having computed the total energy (E_{RPS_Total} ; Eq. 5), the $PS_{RPS}(k)$ and the $E_{RPS}(k)$ were normalized and expressed as percentages ($PS_{RPS}\%(k)$ and $E_{RPS}\%(k)$, respectively; Eq. 6 and Eq. 7):

$$E_{RPS_Total} = \sum_{k=0}^{\frac{N_s}{2}-1} PS_{RPS}(k) \tag{5}$$

$$PS_{RPS}\%(k) = \frac{PS_{RPS}(k)}{E_{RPS_Total}} \cdot 100 \tag{6}$$

$$E_{RPS}\%(k) = \frac{E_{RPS}(k)}{E_{RPS_Total}} \cdot 100 \tag{7}$$

By definition, $E_{RPS}\%(k)$ is a monotonically increasing function which saturates at 100%. The frequency at which $E_{RPS}\%$ first reaches or overcomes 99%, called f_{99} , represents an index to characterize repolarization.

Abnormal repolarization identification. Abnormal repolarization was identified when f_{99} exceeded a threshold defined as the 75th percentile of the f_{99} distribution over the healthy controls.

2.3. Repolarization Analysis Types

Two types of repolarization analysis were performed:

- *Single-lead analysis.* The f_{99} values were computed in each ECG lead, and the abnormal repolarization identification criterion was then applied to their single-lead distributions.
- *Lead-system analysis.* The single-lead f_{99} values were averaged over the 6 precordial and 12-standard-leads, and the abnormal repolarization identification criterion was then applied to the distributions of the averaged f_{99} values.

Table 1. Clinical parameters. Mean±standard deviation values or number of occurrences are reported.

	Healthy Controls (47)	ANAMI (49)	INAMI (59)	AMI (108)
Age (year)	45±15	60±11°	58±11°	59±11°
Gender (male)	37 (82%)	39 (80%)	49 (83%)	88 (82%)
Hypertension	0 (0%)	12 (25%) [§]	20 (34%)°	32 (30%)°
Obesity	0 (0%)	4 (8%)	5 (8%)*	9 (8%)
Diabetes	0 (0%)	4 (8%)	12 (20%) [§]	16 (15%) [§]
Other pathologies	0 (0%)	28 (57%)°	29 (49%)°	57 (53%)°
Heart rate (bpm)	69±12	82±15°	81±17 [§]	81±16°

*P<0.05 when comparing against the healthy controls

§P<10⁻³ when comparing against the healthy controls

°P<10⁻⁵ when comparing against the healthy controls

2.4. Algorithm Implementation and Simulation Test

The $f99$ algorithm was implemented in MATLAB and validated using simulated data with known input data. Specifically, a signal $y(t)$, constituted by the summation of two sinusoids $y_1(t)$ and $y_2(t)$, was considered:

$$y(t) = y_1(t) + y_2(t) = A_1 \cos(2\pi f_1 t) + A_2 \cos(2\pi f_2 t). \quad (8)$$

Validation was performed by keeping constant the values of f_1 , f_2 , and A_1 ($f_1=1$ Hz; $f_2=15$ Hz; $A_1=1$ a.u.), while the A_2 was varying from 0 to 1 a.u. (0.01 steps). Being $f99$ the frequency at which the signal total energy ($E=E_1+E_2=A_1^2+A_2^2$) reaches or overcomes 99%, $f99$ is correctly estimated if it equals 1 Hz till $A_2=A_2^*$ and then becomes equal to 15 Hz. A_2^* is obtained by putting $E_1=0.99 \cdot (E_1+E_2)$, which implies $0.99 \cdot (A_2^*)^2 = (1-0.99) A_1^2$, that is:

$$A_2^* = \sqrt{0.01/0.99} = 0.1 \quad (9)$$

2.5. Robustness Tests

To evaluate $f99$ robustness, three kinds of tests were considered:

- **Robustness to dispersion.** Single-lead $f99$ distributions were compared to evaluate the presence of $f99$ inter-lead dispersion.
- **Robustness to repolarization window offset.** The $f99$ values were computed using the nominal *RepOn* and *RepOff* points (Eq. 1 and Eq. 2) and after a random ± 20 ms shift of *RepOff* from its nominal location. Results obtained in the two experiments were compared to investigate $f99$ dependency on *RepOff* identification.
- **Robustness to heart rate.** The association between $f99$ and corresponding HR was evaluated to investigate the dependency of the former parameter on the latter.

2.6. Statistics

Normality of parameters distributions was tested using the Lilliefors test. Parameters characterized by normal and not-normal distributions were compared using the T-test and the Wilcoxon rank-sum test, respectively. Binary parameters distributions were compared using the chi-square test or, when not possible (expected cell frequency <5), the Fisher exact one-tailed probability test. The Kruskal-Wallis test was used to perform the one-way ANOVA test to compare distributions over the leads. Lead-pairs comparison was performed using the multiple comparison procedure. Associations between two parameters distributions were evaluated using the correlation coefficient (ρ). Eventually, $f99$ ability to discriminate abnormal repolarization was evaluated using sensitivity (Se), and specificity (Sp , fixed at 75% by the abnormal repolarization criterion defined above). Statistical significance level was 0.05.

3. RESULTS

Simulation study. In our simulation study, $f99$ resulted equal to 1 Hz for A_2 ranging from 0 to $A_2^*=0.1$, and to 15 Hz for higher values of A_2 (Fig. 1), confirming the goodness of our $f99$ -algorithm MATLAB implementation.

Single-lead analysis. In most leads, the AMI patients' spectra were characterized by larger high-frequency components than the healthy controls' spectra (Fig. 2). Consequently, compared to the AMI patients, the healthy controls were usually characterized by $E_{RPS}\%$ curves saturating at lower frequencies (Fig. 3) and by significantly lower $f99$ values (Table 2). Lead III was the only one showing an opposite trend, whereas aVf and V1 $f99$ distributions did not differ significantly between the two populations (Table 2). Analogous findings were obtained when comparing ANAMI and INAMI subgroups against the healthy controls (Table 2). Ability of $f99$ in discriminating

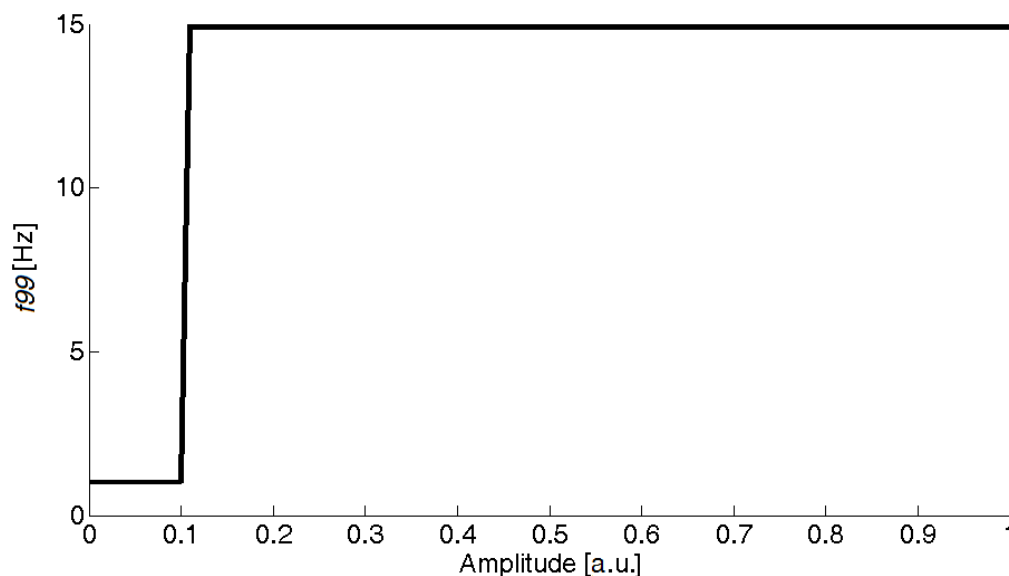


Fig. (1). Trend of $f99$ computed from a simulated signal $y(t)$ constituted by the summation of two sinusoids $y_1(t)$ and $y_2(t)$ characterized by constant frequency values ($f_1=1$ Hz, $f_2=15$ Hz, respectively), constant $y_1(t)$ amplitude ($A_1=1$ a.u.) and varying $y_2(t)$ amplitude ($A_2=0-1$ a.u.).

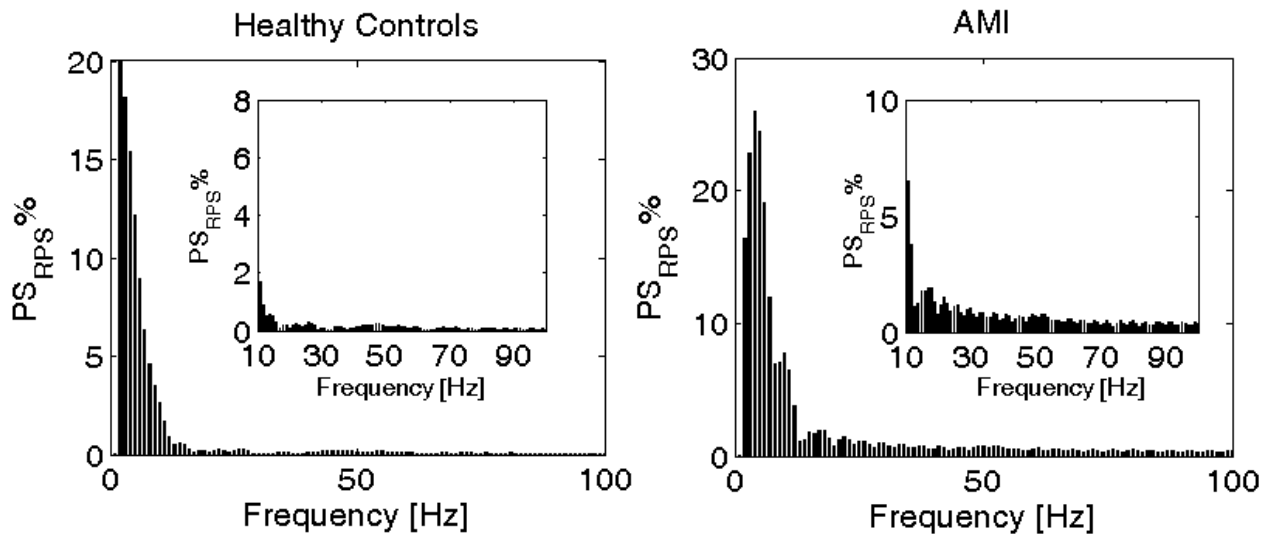


Fig. (2). Typical normalized spectra of a healthy control (panel a) and an AMI patient (panel b). Plots refer to lead V2. The inset represents a zoomed portion (from 10 to 100 Hz) of the larger graph finalized to highlight high-frequency components that otherwise would remain hidden because of the presence of much higher-amplitude low-frequency (below 10 Hz) components.

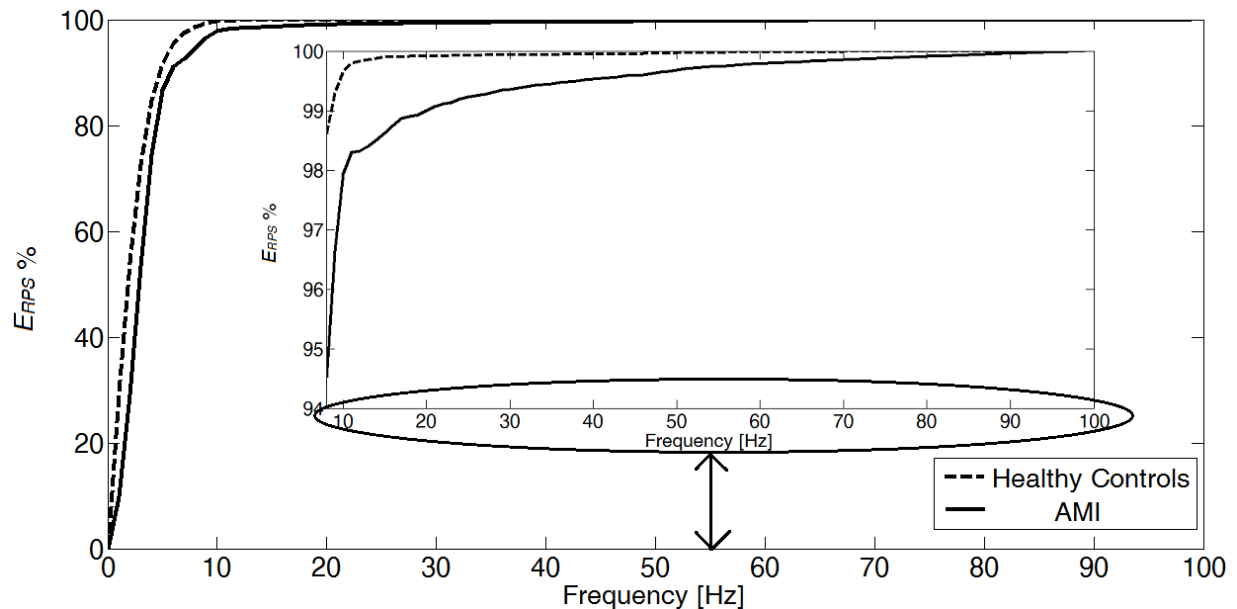


Fig. (3). Typical normalized energy curves of a healthy control (dotted line) and an AMI patient (solid line). Plots refer to lead V2 (same subjects of Fig. 2). The inset represents a zoomed portion (from 10 to 100 Hz) of the larger graph finalized to highlight the distance between the energy graphs of the healthy controls and AMI patients.

pathological from healthy conditions, evaluated in terms of Se and Sp , was lead dependent (Table 3). Optimal leads could also vary with AMI subgroup. Leads I and aVI discriminated both the ANAMI and INAMI patients from the healthy controls. Instead, lead V2 discriminated the ANAMI group better than the INAMI group, while lead V5 vice versa (Table 3).

Lead-system analysis. Mean $f99$ values, averaged over the 6 precordial and 12-standard-leads, were significantly lower in the healthy controls than the AMI patients (Table 2). However, discrimination between the two populations was superior when averaging over the 6 precordial leads than over the 12-standard-leads (Table 3). Analogous results were

obtained when analyzing the two AMI subgroups independently (Tables 2 and 3).

Robustness to dispersion. No specific lead showed significantly higher or lower $f99$ values compared to all other leads (Table 2). However, statistically significant differences were identified among couples of leads, so that final values of Se and Sp were indeed significantly lead dependent (Table 3).

Robustness to repolarization window offset. Distributions of $f99$ parameter were very robust to changes in the $RepOff$ identification in all populations (Table 4). Consequently, values of Se and Sp were very close to those obtained using the $RepOff$ nominal value (Table 5).

Table 2. Values of 50th [25th, 75th] percentiles of the *f99* distributions.

	Healthy Controls (47)	ANAMI (49)		INAMI (59)		AMI (108)	
	<i>f99</i> (Hz)	<i>f99</i> (Hz)	P	<i>f99</i> (Hz)	P	<i>f99</i> (Hz)	P
Single-lead analysis							
I	13 [12,15]	40 [23,54]	<10 ⁻⁷	34 [18,46]	<10 ⁻⁷	37 [20,52]	<10 ⁻⁹
II	17 [13,24]	34 [15,53]	<10 ⁻³	38 [17,53]	<10 ⁻³	37 [15,53]	<10 ⁻⁴
III	50 [22,60]	23 [11,44]	<10 ⁻⁴	25 [14,43]	<10 ⁻³	24 [13,43]	<10 ⁻⁴
aVI	13 [12,18]	42 [22,54]	<10 ⁻⁹	35 [21,53]	<10 ⁻⁸	38 [22,53]	<10 ⁻¹¹
aVr	15 [11,46]	26 [12,50]	NS	27 [15,46]	<0.05	27 [15,50]	<0.05
aVf	24 [14,50]	24 [14,39]	NS	22 [12,40]	NS	22 [13,40]	NS
V1	18 [13,25]	23 [15,31]	NS	12 [10,41]	NS	19 [11,35]	NS
V2	10 [9,10]	15 [12,22]	<10 ⁻⁷	10 [9,12]	NS	12 [10,20]	<10 ⁻⁴
V3	10 [9,11]	14 [11,20]	<10 ⁻⁸	11 [10,21]	<10 ⁻³	13 [10,21]	<10 ⁻⁶
V4	11 [10,12]	14 [11,22]	<0.01	19 [11,38]	<10 ⁻⁴	15 [11,29]	<10 ⁻⁴
V5	13 [11,15]	25 [12,43]	<0.01	40 [18,53]	<10 ⁻⁷	31 [14,47]	<10 ⁻⁶
V6	14 [13,22]	37 [18,53]	<10 ⁻⁵	36 [17,53]	<10 ⁻⁴	37 [18,53]	<10 ⁻⁶
Lead-system analysis							
Mean V1-V6	14 [13,16]	24 [16,31]	<10 ⁻⁷	25 [17,31]	<10 ⁻⁶	24 [17,31]	<10 ⁻⁸
Mean 12 std	19 [16,23]	28 [22,34]	<10 ⁻⁵	30 [21,35]	<10 ⁻⁵	29 [21,35]	<10 ⁻⁶

P: P-value when comparing *f99* values against the healthy controlsNS: not statistically significant ($P \geq 0.05$)**Table 3.** Values of *f99* threshold over which abnormal repolarization is recognized together with corresponding values of sensitivity (Se) and specificity (Sp).

	<i>f99</i> threshold (Hz)	Healthy Controls	ANAMI	INAMI	AMI
		Sp	Se	Se	Se
Single-lead analysis					
I	15.0	77%	82%	78%	80%
II	24.3	74%	61%	61%	61%
III	60.0	77%	6%	7%	6%

Table 3. Contd.....

		Healthy Controls	ANAMI	INAMI	AMI
	<i>f99</i> threshold (Hz)	Sp	Se	Se	Se
aV1	17.8	74%	84%	85%	84%
aVr	45.5	74%	33%	25%	29%
aVf	50.3	74%	16%	17%	17%
V1	25.0	77%	43%	32%	37%
V2	10.0	79%	82%	49%	64%
V3	11.0	87%	71%	44%	56%
V4	12.0	83%	57%	63%	60%
V5	15.0	79%	57%	78%	69%
V6	22.0	79%	65%	69%	68%
Lead-system analysis					
Mean V1-V6	15.9	74%	80%	81%	81%
Mean 12 Std	23.1	74%	69%	69%	69%

Table 4. Values of the correlation coefficient (ρ) between *f99* distributions obtained using nominal and randomly shifted (within ± 20 ms) *RepOff* points.

	Healthy Controls	ANAMI	INAMI	AMI
Single-lead analysis				
I	0.98	0.97	0.99	0.98
II	0.99	0.98	0.99	0.99
III	0.98	0.99	0.99	0.99
aV1	0.98	0.98	0.99	0.99
aVr	1.00	0.99	0.99	0.99
aVf	0.99	0.99	0.99	0.99
V1	0.99	0.99	1.00	1.00
V2	0.99	0.95	0.98	0.97
V3	0.96	0.94	0.100	0.98
V4	0.99	0.94	0.99	0.98
V5	0.99	0.97	0.99	0.98
V6	0.99	0.97	0.99	0.98
Lead-system analysis				
Mean V1-V6	0.98	0.97	0.99	0.98
Mean 12 Std	0.99	0.98	0.99	0.99

Robustness to heart rate. In all populations, *f99* values were substantially independent from HR (Table 6).

4. DISCUSSION

This study proposes *f99* as an innovative frequency-based index for repolarization characterization and AMI patients

Table 5. Values of f_{99} threshold over which abnormal repolarization is recognized together with corresponding values of sensitivity (Se) and specificity (Sp) when *RepOff* was randomly shifted within ± 20 ms from its nominal value.

		Healthy Controls	ANAMI	INAMI	AMI
	f_{99} threshold (Hz)	Sp	Se	Se	Se
Single-lead analysis					
I	16.0	77%	84%	80%	81%
II	23.5	74%	63%	59%	61%
III	59.0	77%	6%	10%	8%
aVl	18.8	74%	84%	83%	83%
aVr	42.8	74%	33%	27%	30%
aVf	51.3	74%	16%	17%	17%
V1	25.5	74%	45%	34%	39%
V2	10.0	77%	82%	49%	64%
V3	11.0	81%	65%	47%	56%
V4	12.0	79%	61%	61%	61%
V5	15.8	74%	59%	80%	70%
V6	21.0	77%	67%	71%	69%
Lead-system analysis					
Mean V1-V6	16.0	77%	78%	81%	80%
Mean 12 Std	23.4	74%	71%	73%	72%

discrimination from healthy subjects. The algorithm for f_{99} computation was tested on simulated data to confirm its proper functioning. Instead, f_{99} clinical usefulness was evaluated on ECG tracings from 47 healthy controls and 108 AMI patients (49 ANAMI e 59 INAMI), who are known to show abnormal repolarization [17, 21, 22].

The f_{99} index, defined as the frequency at which the repolarization normalized cumulative energy reaches 99%, was computed in each one of the 12-standard-leads independently, and averaged over the 6 precordial and 12-standard-leads. In most leads (9 out of 12, Table 2), f_{99} median values was significantly lower for the healthy controls than for the AMI patients. This finding implies that AMI T-waves have a normalized power spectrum characterized by higher frequency components which indicate a more fragmented repolarization. On this basis, f_{99} was used to discriminate abnormal from normal repolarization. More specifically, abnormal repolarization was identified when f_{99} exceeded a threshold defined as the 75th percentile of the f_{99} distribution over the healthy controls. Such threshold definition implies a nominal Sp of 75%. However, actual values of Sp were either slightly lower (74%, Table 3) or higher (77%-87%, Table 3). Lower values of Sp are due to the fact that the healthy-control population

counts less than 100 subjects. Instead, higher values of Sp are due to the fact that there can be more than one healthy control characterized by the same f_{99} value immediately under threshold. Se values were strongly lead dependent ($Se=6\%-85\%$, Table 3), indicating a significant repolarization dispersion identified by f_{99} . Leads I and aVl were able to significantly discriminate abnormal from normal repolarization, independently of the infarct location (lead I: $Se=78\%-82\%$, $Sp=77\%$; lead aVl: $Se=84\%-85\%$, $Sp=74\%$, Table 3). Instead, lead V2 allowed identification of abnormal repolarization only in the ANAMI patients ($Se=82\%$, $Sp=79\%$, Table 3) while lead V5 only in the INAMI patients ($Se=78\%$, $Sp=79\%$, Table 3). These findings indicate that f_{99} is characterized by a certain amount of dispersion, similarly to what happens for other repolarization indexes [29,30]. Since the leads provide spatial information about the heart's electrical activity in different directions, the optimal lead for discriminating abnormal repolarization by f_{99} may depend on the infarct location. More specifically, leads closer to the AMI location will identify the disease better than the others.

Since it is not possible to know a priori which will be the optimum lead to identify an AMI, to overcome issues related to repolarization dispersion, values of f_{99} averaged over the

Table 6. Values of the correlation coefficient (ρ) between $f99$ distributions and heart rate.

	Healthy Controls	ANAMI	INAMI	AMI
Single-lead analysis				
I	0.28	0.44*	0.07	0.23*
II	0.42*	0.41*	0.11	0.22*
III	0.08	0.41*	0.12	0.24*
aV1	0.46*	0.37*	0.16	0.24*
aVr	0.14	0.36*	0.04	0.18
aVf	0.31*	0.52*	0.09	0.26*
V1	0.03	0.14	-0.05	0.01
V2	-0.02	0.20	-0.12	-0.02
V3	0.18	0.20	0.10	0.13
V4	0.11	0.19	0.25	0.21*
V5	0.20	0.35*	0.07	0.16
V6	0.34*	0.18	-0.06	0.04
Lead-system analysis				
Mean V1-V6	0.20	0.33*	0.05	0.14
Mean 12 Std	0.36*	0.56*	0.12	0.29*

*Statistically significant ($P < 0.05$)

6 precordial and 12-standard-leads were provided. Between these two averaged indexes, the former discriminated abnormal repolarization ($Se = 80\% - 81\%$, $Sp = 74\%$, Table 3) better than the latter ($Se = 69\%$, $Sp = 74\%$, Table 3) since the $f99$ distributions were showing a more homogeneous trend among the precordial leads than the limb and augmented-limb leads (Table 2). Thus, lead-system analysis showed that the 6 precordial leads were superior to the 12-standard-leads in discriminating abnormal repolarization, even though the single-lead analysis showed that the optimal lead could not be precordial.

The $f99$ index, either measured on a single lead or averaged over a lead system, is statistically independent from the exact determination of the repolarization window (Tables 4 and 5), and does not require the exact identification of the T-wave offset, usually very difficult in clinical cases [9]. T-wave offset estimation can indeed occur with a few tens of ms of tolerance (Table 5). In addition, $f99$ was independent from HR (Table 6). In general, repolarization significantly depends on HR [10] so that some indexes, like the popular QT, may require a correction to adjust to it. The $f99$ independency of HR is due to the fact that such adjustment is performed during the construction of the RPS (see Methods), which requires a stretch or a compression of the repolarization segment to match a length of 260 ms (assumed as standard), and a subsequent zero padding to

reach a 1 s length for each heart cycles. Thus, the normalized power spectrum does not provide the frequency content of the real T-wave, but rather the amplitude of the harmonics after forcing the fundamental frequency to be at 1 Hz. In other words, $f99$ although expressed in Hz for simplicity and clarity, represents the number of harmonics the normalized cumulative energy needs to reach 99%.

CONCLUSION

The present study proposed a new $f99$ index, defined as the frequency at which the repolarization normalized cumulative energy reaches 99%, for ECG AMI discrimination from health. Evaluation of such $f99$ index was performed on 12-standard-lead ECG recordings of 47 healthy controls and 108 AMI patients. Repolarization dispersion caused $f99$ distributions to be significantly lead dependent indicating that optimal lead for discriminating abnormal repolarization may depend on the infarct location. To overcome dispersion issues, lead-system analysis was performed by averaging $f99$ over the 6 precordial leads and proved to be able to identify the presence of AMI with good sensitivity and specificity. Thus, our new $f99$ index appears as a promising tool for non-invasively and reliably discriminate AMI patients from healthy subjects.

LIST OF ABBREVIATIONS

AMI	=	acute myocardial infarction
ANAMI	=	anterior acute myocardial infarction
$E_{RPS}(k)$	=	RPS energy
E_{RPS_Total}	=	RPS total energy
$E_{RPS\%}(k)$	=	RPS normalized and expressed as percentage energy
f_{99}	=	frequency at which $E_{RPS\%}$ reaches or overcomes 99%
HR	=	heart rate
INAMI	=	inferior acute myocardial infarction
mean V1-V6	=	mean f_{99} values averaged over the 6 precordial leads
mean 12 std	=	mean f_{99} values averaged over the 12 standard leads
$PS_{RPS}(k)$	=	RPS power spectrum
$PS_{RPS\%}(k)$	=	RPS normalized and expressed as percentage power spectrum
RepOn	=	repolarization onset
RepOff	=	repolarization offset
RPS	=	repolarization signal
SCD	=	sudden cardiac death

ETHICAL APPROVAL

All Physionet databases have been fully deidentified (anonymized) and may be used without further institutional review board approval.

CONFLICT OF INTEREST

C. Giuliani, A. Agostinelli and F. Di Nardo have no financial and/or personal relationships with people or organizations that could inappropriately influence (bias) this work.

L. Burattini and S. Fioretti declare their partnership to the academic spin-off B.M.E.D. SRL (Bio-Medical Engineering Development, Department of Information Engineering, Polytechnic University of Marche, Ancona, Italy, www.bmed-bioengineering.com).

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