Hindawi Publishing Corporation
EURASIP Journal on Advances in Signal Processing
Volume 2008, Article ID 670529, 10 pages
doi:10.1155/2008/670529

Research Article

Computational Issues Associated with Automatic Calculation of Acute Myocardial Infarction Scores

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Received 2 December 2007; Revised 2 June 2008; Accepted 16 July 2008

Recommended by Qi Tian

This paper presents a comparison among the three principal acute myocardial infarction (AMI) scores (Selvester, Aldrich, Anderson-Wilkins) as they are automatically estimated from digital electrocardiographic (ECG) files, in terms of memory occupation and processing time. Theoretical algorithm complexity is also provided. Our simulation study supposes that the ECG signal is already digitized and available within a computer platform. We perform 1000 000 Monte Carlo experiments using the same input files, leading to average results that point out drawbacks and advantages of each score. Since all these calculations do not require either large memory occupation or long processing, automatic estimation is compatible with real-time requirements associated with AMI urgency and with telemedicine systems, being faster than manual calculation, even in the case of simple costless personal microcomputers.

1. INTRODUCTION

In 2004, AMI was responsible for 22.93% of deaths associated with cardiovascular diseases, which represents 6.39% of the total number of deaths in Brazil [1]. In the United States [2], coronary heart disease accounted for 489,171 deaths in 1990. In consequence, AMI may be considered a public health affair.

Current medical protocols require that, for AMI diagnosis, the patient should present at least two of the following symptoms [3, 4].

(S1) chest pain;

(S2) specific ECG-waveform changements, particularly ST elevation and/or ST depression;

(S3) high concentration of biochemical markers associated with the cardiac muscle necrosis, for example, the concentration of enzymes Troponin and CK-MB, which may be evaluated by means of blood examinations.

Notice that, from (S1)–(S3), the last symptom is the most important condition for assuring AMI diagnosis, and may also be used as a relevant indicator of the injured myocardial area, pointing out possible therapeutic procedures. However, unconventional symptoms may be present in the patient [5]. In addition, detection of elevations on the concentration of biochemical markers in the human plasma is not instantaneous, taking some time after the necrosis [3]. Such detection also requires several hours to be completed [6] due to the biochemical processes associated with this examination. In consequence, based on (S2), ECG still remains the major tool for speeding up AMI diagnosis, leading to the choice of the treatment to be applied [6]. The costs of ECG are lower than those associated with biochemical markers examination. One should also point out that ECG is noninvasive and simple, which explains its regular use, especially during the first hours after the patient arrival to the hospital, as well as during the monitoring of the AMI clinical evolution.

ECG-based diagnosis of AMI is successful for about 80% of the cases [7, 8]. A recent consensus conference [3, 4, 6], organized by the Joint Committee of the European Society of Cardiology and the American College of Cardiology, has reinforced the usefulness of the ST segment for this purpose. For such diagnosis, ST elevation must appear in two or more adjacent leads, presenting amplitudes higher than two

millimeters for leads V1–V3; or higher than one millimeter for the other leads. These values suppose measurements taken at the *J* point. In addition, the sum of ST elevations considering all leads may be associated with the ischemic acuteness of the cardiac tissue lesion, whereas other studies point out that the number of leads presenting ST elevation may be related to the extent of the injured area [9, 10]. ST-segment changements may be also used as a parameter for assessing the effects of AMI treatments. In fact, the literature [3, 8, 9, 11] reports decrease of ST-elevation after the treatment.

Nevertheless, there are several other clinical issues and pathologies leading to ECG-waveform changements, particularly regarding the ST segment, such as bundle branch block, pacemakers [9], instrumentation, and heart rate variability [8]. Despite these limitations, ECG analysis may be considered until now the most simple, low cost, and widespread means to evaluate and provide diagnosis on cardiac ischemias [12]. It may also be useful to assess the effects of therapies and to locate occlusions [7]. Based on the ideas presented in [9, 10], several different indices have been developed and tested by the literature, in order to further extract useful information from the ECG, so that to speed up diagnosis. These indices are based on specific morphologies of the ECG during AMI, as disscussed below [12].

The Selvester score was created in 1972 by Selvester et al. [13], which focuses the analysis on the QRS complex. It is based on 57 criteria, considering all the leads (see the Selvester table in Table 6), summing up to 32 points. Each point is physiologically equivalent to the necrosis of 3% of the left ventricle, thus providing the estimation of the total injured area by the AMI [13]. A simplified version of this score was developed in 1982 by [14], including 37 criteria and 29 total number of points, which was experimentally validated. This score was thoroughly tested, providing a tool with high specificity. During the chronic phase of the AMI, this score is inversely proportional to the ejection fraction (EF) of the left ventricle and directly proportional to the dimension of the injured area [14].

The Aldrich score was developed in 1988 [15], aiming at the estimation of the myocardial area under potential risk of necrosis in the future, based on ECGs taken no later than eight hours after the beginning of the infarction. The calculation considers just ST-segment elevation/depression in all leads, particularly the sum of all elevations (considering all leads) and the number of leads associated with ST elevation/depression. The reference for such measurements is taken with respect to the *J* point, and equations depend on the location of the AMI. Subsequent works in the literature [16, 17] modified the original proposition by including other parameters. It must be pointed out that the Aldrich score performance decreases for patients undergoing thrombolytic therapy [8, 11, 12, 16–18].

The Anderson-Wilkins score evaluates the time delay between coronary occlusion and the patient first aid by medical services [12, 19]. Such time delay is generally known as "ischemic time," which may be considered as a benchmark for assessing the AMI acuteness, as well as the percentage of the myocardial tissue which may be recovered by the subsequent application of reperfusion therapy. It should be pointed out, however, that the beginning of AMI symptoms reported by the patient may be unaccurate, since atypical AMIs may not lead to pain [5, 19]. The Anderson-Wilkins score classify the ECG waves in four types, based on an analysis of the QRS complex and the *T* wave [12, 18–21]. These types indicate the degree of time evolution of the ischemia. Although the original version of the Anderson-Wilkins score presented different performances for anterior and inferior AMI, a recent work in the literature [18] has modified the equations, so that to overcome this drawback.

It is necessary to summarize information and compare these scores. In fact, since QRS waveform changements take place just in more advanced steps of the AMI process, and since these changements are related to myocardial necrosis, the Selvester score aims at estimating the percentage of the myocardial area which has already been injured by the AMI. On the other hand, since the ST elevation/depression is related to the ischemic process without necrosis, the Aldrich score may be considered as an estimator of the myocardial area under the risk of future necrosis, as the AMI evolves without treatment. Finally, Anderson-Wilkins score analyzes two different classes of ECG elements: earlier waveform changements (such as ample *T* waves and ST depression/elevation), and delayed changements (such as the pathological *Q* wave). In consequence, this score points out the degree of time evolution of the AMI, putting forward the time limit for the medicine to start reperfusion therapy.

In the literature, the classical procedure for score calculation is based on the visual inspection of the ECG, followed by manual measurements with a ruler, which provides the final quantities in millimeters to be applied in mathematical expressions. This process is of course cumbersome, lengthy, and subject to errors, which may introduce delays and unaccuracy in the medical decision.

The clinical performance of these scores has been assessed since the 1980s by several works of the literature. Although they are not already used daily by cardiologists, Aldrich and Anderson-Wilkins scores may be considered those with the highest applicability. The first score is able to put forward the acuteness of the AMI, which in turn helps the decision on the therapy to be used and to establish prognosis on the evolution of the patient clinical situation. On the other hand, the second score points out the degree of time evolution of the AMI, which is quite important to identify patients to whom reperfusion procedure is still feasible and efficient. Selvester score, though being studied since the 1980s and considered as a benchmark, may not be used at the early stages of the patient care. This score supposes that the AMI has already injured the heart. Consequently, if the medicine evaluates the difference between the myocardial area under the risk of injury, which is pointed out by the Aldrich score; and that one which was already damaged, as indicated by the Selvester score; it is possible to estimate the quantity of myocardial area under safe conditions. This last one, of course, reveals the efficiency of the medical treatment.

It should be pointed out that particular conditions of the ischemia may prevent the application of scores. In fact, for all of them [12, 13, 15, 19], it is supposed that the patient

does not use pacemakers and that the admission heart rate is lower than 110 beats/minute. In addition, excluding criteria also involve patients presenting complete left or right bundle brunch block, anterior or posterior fascicular block, and right or left ventricular hyperthrophy.

As microeletronic technology evolved, ECG signal processing was established, so that digital ECG files are currently in use, making possible the application of informatics to assist medicines [22]. Application of computers for AMI scores estimation is a very young research field. In [23, 24], authors study the digital automatic estimation of ST elevation for a 12-lead ECG, which is compared to the classical manual procedure. Moderate and good levels of clinical agreement between cardiologist's analysis and automatic estimation were obtained, though there are important issues regarding the lowest level of accuracy that can be obtained from digital ECGs. In [23], the bound is established as 45 microvolts for detecting ST elevation greater than 0.1 mV, so that computer measurements always lead to smaller values of ST elevation with respect to the cardiologist's analysis. In [24], however, the bound is set as 50 microvolts, and computer estimation presents more accurate results than human observation. Both articles evaluated the ST elevation/depression at different J points ($J+20$, $J+40$, $J+60$, and $J+80$ milliseconds). Articles [20, 25] deal with the digital automatic estimation of the Selvester and of the Anderson-Wilkins scores, respectively, which were also compared to the scores manually calculated by cardiologists. Very high agreement rates were achieved, leading to a procedure that takes very few time in comparison with visual analysis, thus pointing out the high accuracy and real-time capabilities of ECG signal processing. Finally, in [26], authors present an image-processing method for scanning analogic ECGs, so that to transform the printed ribbons in digital files, which are well suited for telemedicine applications and ECG signal processing.

As discussed above, although several efforts have already been deployed, to the best of our knowledge few works addressed the computational issues associated to automatic score estimation, in terms of processing time and required memory. This is a basic topic for any signal processing algorithm design [22], especially in the context of telemedicine, wherein transmission rates and data exchange are subject to several constraints; as well as in the context of AMI urgencies, which requires diagnosis and therapeutical decisions in real time. In addition, taking into account trends on reducing the number of the leads for ECG recording [12, 27], it is necessary to establish bounds on the computational requirements for calculating original scores, so that to assess to which extent such reduction will impact on the automatic estimation complexity.

The article is organized as follows. Section 2 provides a brief review on the calculation of each score, including important details from a computational viewpoint, which enables the estimation of theoretical computational complexity and memory occupation. Section 3 introduces the simulation methodology, which is followed by results in Section 4. The major conclusions and future work are summarized in Section 5.

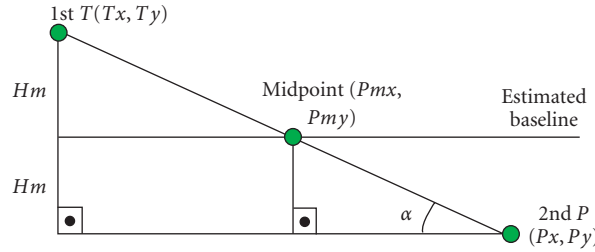

Figure 1: Baseline estimation based on the TP segment.

2. SCORE CALCULATION AND THEORETICAL COMPUTATIONAL COMPLEXITY/MEMORY OCCUPATION

The following results regarding computational complexity are based on the estimation of the total number of operations. According to [28], *operation* involves any basic mathematical task performed by simple computational devices (e.g., microprocessors), such as divison, sum, subtraction, multiplication, and comparison ($<, >, <=, >=, ==, !=$). In this context, the computational complexity is abbreviated as CC, and it is expressed in terms of n, the number of leads used to perform ECG measurements.

The theoretical memory occupation (TMO) is defined as the total number of variables that must be in memory in order to perform all calculations leading to the score. This total number is then multiplied by one byte, thus providing the measurement of TMO in bytes.

2.1. Aldrich score [15]

In order to calculate the Aldrich score, the AMI must lead to ST elevations higher than 0.1 mV, in at least two adjacent leads, except for aVR. The isoelectric line is determined by the TP segment (Figure 1), which is obtained by connecting the first T point to the subsequent P point. Then the baseline is traced as the horizontal line that passes through the midpoint connecting the two preview ones, according to

$$Pmy = \frac{Ty - Py}{2}, \tag{1}$$

where Ty is the amplitude for the first T point [mV]; Py is the amplitude for the subsequent P point [mV].

In the following, the AMI must be classified into anterior or inferior. An anterior AMI leads to ST elevations in leads DII, DIII, and aVF; whereas the inferior involves ST elevations in V1–V4. If there are ST elevations in DI, aVL, or V5-V6, the classification is also based on the leads cited previously, but considering those with higher amplitude of ST elevation.

If the AMI is anterior, the Aldrich score is calculated by (2) as follows:

$$\mathrm{AS}_{\mathrm{ant}} = 3 \cdot (1,5 \cdot N_{\mathrm{ST}} - 0,4), \tag{2}$$

where $\mathrm{AS}_{\mathrm{ant}}$ is the resulting Aldrich score and N_{ST} is the number of leads with ST elevation.

Table 1: T-wave morphology.

Type of T-wave	Acronym	Necessary characteristics for the classification T is the maximum peak of T-wave [mV]
High T-wave	TT	{$T \geq 1.0$ mV in V2–V4} OR {$T \geq 0.75$ mV (7.5 mm) in V5} OR {$T \geq 0.5$ mV (5 mm) in DI or DII or aVF or V1 or V6} OR {$T \geq 0.25$ mV (2.5 mm) in aVL or DIII}
Positive T-wave	PT	{$T \geq 0.05$ mV (0.5 mm)} and do not fulfill TT criteria
Flatten T-wave	FT	T-wave with modulus ≤ 0.05 mV (0.5 mm)
T negative-terminating wave	EN	{50% of initial positive T-wave ≥ 0.05 mV (0.5 mm)} and {the other part with modulus ≥ 0.05 mV (0.5 mm)}.
Half-negative T-wave	MN	{More than 50% of T-wave with negative modulus ≥ 0.05 mV (0.5 mm)}

If the AMI is inferior, the ST elevation is measured in millimeters at the J point, which may be considered the final point of QRS complex, just before the ST, according to (3). This measurement must be rounded to the next integer value:

$$\text{Supra}_{\text{ST}}(d) = \left| Jy(d) - Pmy(d) \right| \text{ [mm]}, \tag{3}$$

where d is the lead in which the ST elevation is estimated; $Jy(d)$ is the amplitude of the J point in lead d [mm]; Pmy is the amplitude for the baseline, estimated by (1), which must be converted into [mm].

Then the Aldrich score is calculated as follows:

$$\begin{aligned} \text{AS}_{\text{inf}} = 3 \cdot [0.6 \cdot (&\text{Supra}_{\text{ST}}(\text{II}) + \text{Supra}_{\text{ST}}(\text{III}) \\ &+ \text{Supra}_{\text{ST}}(aVF)) + 2], \end{aligned} \tag{4}$$

where AS_{inf} is the Aldrich score and $\text{Supra}_{\text{ST}}(d)$ is estimated by (3) at lead (d).

The result of the calculation, in any of the formulas (2) or (4), is the percentage of myocardium under the risk of necrosis as the AMI progresses.

The computational complexity (CC) and theoretical memory occupation (TMO, $n = 12$ leads) evaluations are presented below.

(A) Baseline calculation for each lead, using (1):

CC = $3n$ operations; TMO = 12 leads × 3 variables = 36 variables.

(B) ST elevation estimation in 12 leads, using (3): TMO = 12 leads × 2 variables = 24 variables.

(C) Decision on AMI type (anterior or inferior)

(D) Estimation of Aldrich score, using (3)-(4) if it is inferior; or (2), if anterior.

(i) Inferior AMI: CC = $3n + 6$ operations; TMO = 1 variable.

(ii) Anterior AMI: $3n + 3$ operations; TMO = 2 variables.

Summing up all the operations described above, one gets the final computational complexity (CC) and theoretical memory occupation (TMO).

(i) Inferior AMI:

$$\text{CC}_{\text{Aldrich}} = 6n + 6 \text{ operations}; \qquad \text{TMO}_{\text{Aldrich}} = 61 \text{ bytes}. \tag{5a}$$

(ii) Anterior AMI:

$$\text{CC}_{\text{Aldrich}} = 6n + 3 \text{ operations}; \qquad \text{TMO}_{\text{Aldrich}} = 62 \text{ bytes}. \tag{5b}$$

For the most common case in clinical practice, $n = 12$, leading to $\text{CC}_{\text{Aldrich}} = 6 \times 12 + 6 = 78$ operations.

2.2. Selvester score [13, 25]

Three steps are necessary in order to estimate the Selvester score, according to the table presented in Table 6 which describes the rules of this procedure.

Step (i): the score is intialized with zero.

Step (ii); the leads are analyzed, observing the group of rules in Selvester table (see Table 6).

This step involves the knowledge of the maximum peaks associated with Q, R, and S, as well as the duration of Q-wave and R-wave. From Selvester table, within one single lead, there are one or more rules, which are divided into groups (a) and (b). For each group, the rules must be checked upside down (from the top to the bottom), until one rule is evaluated as "true." Once the "true rule" is identified for the group, its points are summed to compose the overall score.

For instance, considering lead I, if the first rule of group (b) (Ramp <= Qamp) is satisfied, one must add 1 point to the score.

Step (iii): after all rules are evaluated, following the order of leads established by the Selvester table, the points must be summed up, leading to the final Selvester score.

In terms of computational complexity, the Selvester score uses basically sums and comparisons. Based on Table 6, for the worst case, there are 53 comparisons and 21 sums,

Table 2: Pathological Q-wave classification conditions.

LEAD	CONDITION (Qdur is the duration of Q wave [millisecond])
DI	Qdur ≥ 30 ms (0.75 mm)
DII	Qdur ≥ 30 ms (0.75 mm)
DIII	Qdur ≥ 30 ms (0.75 mm) in aVF
aVL	Qdur ≥ 30 ms (0.75 mm)
aVF	Qdur ≥ 30 ms (0.75 mm)
V1	Any Qdur
V2	Any Qdur
V3	Any Qdur
V4	Qdur ≥ 20 ms (0.5 mm)
V5	Qdur ≥ 30 ms (0.75 mm)
V6	Qdur ≥ 30 ms (0.75 mm)

leading to 74 operations for the 12-lead ECG. In terms of TMO, for each lead, one should estimate amplitude and duration for Q, R, and S waves, thus leading to 12 leads × 6 variables = 72 variables. One should also consider 11 composite quantities such as Q/R, from the Selvester table. In consequence, one should write the CC and the TMO as follows:

$$\begin{aligned} \mathrm{CC}_{\mathrm{Selvester}} &= 74 \text{ operations;} \\ \mathrm{TMO}_{\mathrm{Selvester}} &= 83 \text{ bytes;} \quad (n = 12 \text{ leads}). \end{aligned} \tag{6}$$

2.3. Anderson-Wilkins score [19]

The Anderson-Wilkins acuteness score is based on the simultaneous analysis and classification of ST elevation, the T-wave variations, and the presence/absence of pathological Q waves. Table 1 shows T-wave classification, whereas Table 2 explains the conditions, established particularly at each ECG lead, for Q-wave being considered pathological.

The calculation of Anderson-Wilkins score employs the following steps.

Step 1. Diagnose AMI with ST elevation, which must be greater than 0.1 mV and must take place at least in two adjacent leads, except in aVR, considering TP segment as baseline and measurements with respect to J point.

Step 2. For each lead, classify the T-waves according to Table 1 as {TT, PT, FT, EN, MN}.

Step 3. For each lead, considering Table 2, establish whether pathological Q-waves take place.

Step 4. Classify the leads into classes according to Table 3. For one lead being considered of one specific class, it must satisfy the three conditions (ST elevation, T-wave classification, and pathological Q presence) at the same time.

Step 5. Calculate the Anderson-Wilkins score using (7):

$$\mathrm{EAW} = \frac{4 \cdot nD_{1\mathrm{A}} + 3 \cdot nD_{1\mathrm{B}} + 2 \cdot nD_{2\mathrm{A}} + nD_{2\mathrm{B}}}{nD_{1\mathrm{A}} + nD_{1\mathrm{B}} + nD_{2\mathrm{A}} + nD_{2\mathrm{B}}}, \tag{7}$$

where $nD_{1\mathrm{A}}$ is the number of leads pertaining to class 1A; $nD_{1\mathrm{B}}$ is the number of leads classified as 1B; $nD_{2\mathrm{A}}$ is the number of 2A leads, and $nD_{2\mathrm{B}}$ is the number of 2B leads.

In consequence, the Anderson-Wilkins score is estimated with amplitude between 0–4, for which the high values are associated with more acute ischemia.

Based on Steps 1–5 described above, there are $18n + 37$ operations required to estimate the Anderson-Wilikins score, and considering the 12-lead ECG, there are 253 operations in the worst case scenario. Thus CC is expressed as below:

$$\mathrm{CC}_{\text{A-Wilkins}} = 18n + 37 \text{ operations.} \tag{8a}$$

In terms of TMO, one should analyze the algorithm step by step, considering the worst case scenario presented below.

Step 1. Estimate baseline by (1) and the ST elevation based on (3) for all $n = 12$ leads.

$3 \times 12 + 1 \times 12 = 48$ variables.

Step 2. Classification of T-waves according to Table 1.

13 variables (including all T amplitudes of all leads) + all 12 classifications = 25 variables.

Step 3. Classification of Q-waves according to Table 2.

11 variables (including all Q durations of all leads) + all 12 classifications = 23 variables.

Step 4. Finding a class for all leads according to Table 3.

For T-wave classification column, there are $2 \times 12 = 24$ variables for comparisons.

For Pathological Q waves, there are 12 variables for comparisons.

Step 5. Final calculation of the score based on (7).

There are 9 variables, including the score itself.

Summing up all the TMO results presented in the last paragraph:

$$\mathrm{TMO}_{\text{A-Wilkins}} = 141 \text{ bytes} \quad (n = 12 \text{ leads}). \tag{8b}$$

3. METHODS

Based on the procedures described in Section 2, the three scores were implemented as algorithms on a C++ platform. The Microsoft Foundation Classes (MFCs) library was employed for the graphical user interface, as well as for the use of a library, devoted to the assessment of processing time. All simulations were carried out using an *IBM-PC* microcomputer with the following characteristics. Processor: *AMD Semprom* 2400 + 1.668 GHz; Motherboard: *ASUS A7V8X-X*; RAM memory: 768 MB DDR, 333 MHz; HD memory: 120 GB.

The input to these computer programs is a matrix containing ECG data necessary for all calculations, which involves measurements taken at P-wave, the QRS complex, J point, and T-wave. There are twelve lines in the matrix, each one associated with one specific lead. The vector $\mathbf{C}$, defining each line of this matrix, is described below:

$$\mathbf{C} = \begin{bmatrix} \mathbf{C1} & \mathbf{C2} \end{bmatrix}, \tag{9a}$$

where **C1** and **C2** are subvectors, respectively, associated with the first complete ECG cycle and the subsequent complete

Table 3: Grouping leads into classes for Anderson-Wilkins score calculation.

Class of lead (acronym)	ST elevation + indicates presence, − indicates absence	T-wave classification (see acronyms in Table 1)	Pathological Q-waves (Table 2) + indicates presence, − indicates absence
1A	+ or −	TT	−
1B	+	PT	−
2A	+ or −	TT	+
2B	+	PT	+
3	+	EM or FT	+
4	+	MN	+
U	+	EM, FT, or MN	−

ECG cycle, as defined below:

$$\begin{aligned}\mathbf{C1} = [&Pix, Piy, Pmx, Pmy, Pfx, Pfy, Qix, Qiy, Qmx,\\ &Qmy, Qfx, Qfy, Rix, Riy, Rmx, Rmy, Rfx, Rfy,\\ &Jmx, Jmy, Six, Siy, Smx, Smy, Sfx, Smy,\\ &\{Tix, Tiy, \ldots, Tmx, Tmy, \ldots, Tfx, Tfy\}],\end{aligned} \tag{9b}$$

where i stands for initial, m for maximum, f for final, x for time [millisecond], and y for amplitude [mV]. Notice that the subset $\{Ti, \ldots, Tm, \ldots, Tf\}$ is composed of all the samples of T-wave. Considering that the ECG signal is sampled at one millisecond, that the normal T-wave lasts about 120 milliseconds [29], and also considering all the elements of the vector in (9b), the length of vector **C** in (9a) is $2 \times (26 + 2 \times 120) = 532$ elements. Subvector **C2** is defined in a similar way as in (9b), including the same data described in this paragraph, however, the P, Q, R, J, S and T quantities are associated to the subsequent ECG cycle, with respect to that one leading to the definition of subvector **C1**.

For Aldrich score calculation, just the data from points $\{P, Q, R, J, S, T, P2$ (second $P)\}$ are necessary. The Selvester score uses waves and not only specific peak points of the ECG waves, thus requiring amplitude and time for initial, maximum, and ending points of the P, Q, R, S, T waves. For Anderson-Wilkins score, the input must include initial and final Q-wave point data, as well as all the samples associated with the T-wave.

It is supposed that automatic recognition of the elements in each vector (9a)-(9b) is perfect, so that the computer has already analyzed the raw digital ECG data and generated the input data matrix, the lines of which are given by (9a)-(9b), for all leads. In consequence, our computational evaluation does not take into consideration time processing and memory occupation associated with the identification of any sample in (9a)-(9b).

Processing time is estimated based on the *m_Timer. Start*(1,0) routine, which starts the *winmm.dll* timer. Multimedia timers allow the best resolution for event firing, which is a necessary feature to accomplish the task of processing-time evaluation.

In order to measure memory occupation of the algorithms, the *Windows XP Task Manager* was used. This operational system routine enables the assessment of memory occupation of any process, by monitoring the *Task Manager* application. For instance, suppose that one needs to measure the memory occupation for the *Notepad* process. The graphical user interface of *Task Manager* displays status and memory occupation of the process list, thus the *Notepad* process data can be monitored during runtime.

In order to avoid interference of other softwares or processes on the measurements, just the windows associated with the C++ *compiler*, *Multimedia Timer*, and the *Task Manager* remained open during simulations.

For each score algorithm, we have carried out a Monte Carlo simulation study of both memory occupation (MO) and time processing (TP), by estimating the average MO in Kilobytes and the average TP in milliseconds. Results to be presented in Section 4 suppose averages based on one million (1000000) different experiments. The input matrices for all these evaluations, containing digitized ECG data, were the same for all the three algorithms. The one million different input matrices were randomly generated based on average values reported in the literature [13, 15, 19, 26, 29], to which slow-amplitude random numbers were added by software processing. The "slow-amplitude" adjectif means that, for voltages, amplitudes do not exceed 1 millivot; whereas for times, amplitudes do not exceed 10 milliseconds.

4. RESULTS

Figure 2 depicts the graphic representation of (5a)-(5b), (8a)-(8b), and (6). In order to generate this figure, we have considered clinical practical values [29] for the number of leads n, so that $n = \{2, 3, 6, 12, 14, 16, 20, 50\}$. Notice that $n = 2, 3$ refers to simple cardiac monitoring; $n = 12$ is the standard ECG configuration; $n = 14, 16$ may be carried out in order to get specific information from any cardiac region; whereas $n = 50$ is associated with mapping the epicardial surface.

Table 4 presents CC and TMO for the daily situation $n = 12$ leads, as well as its product CC $\times$ TMO, which characterizes the global algorithm complexity considering, at the same time, memory occupation and the number of operations. These values were obtained at (5a)-(5b), (8a)-(8b), and (6).

In Figure 2, notice that computational complexity is evaluated in terms of the global number of operations necessary for performing one calculation of the scores. Results are very close to each other, but Aldrich score presents

Table 4: Theoretical computational complexity (CC) and memory occupation (TMO); $n = 12$.

Score	Theoretical CC [operations]	Theoretical memory occupation [bytes]	CC × TMO [operations · bytes]
Aldrich	78	62	4836
Selvester	74	83	6142
Anderson-Wilkins	253	141	35673

Table 5: Average experimental results for each score, considering Figure 3 ($n = 12$).

Score	Processing time (PT) [millisecond]		Memory occupation (MO) [Kbytes]		Product of average PT × average MO [millisecond × Kbytes]
	Average	Standard deviation	Average	Standard deviation	
Anderson-Wilkins	0.8845	0.0209	154.22	7.7323	136.41
Selvester	0.7152	0.0038	149.30	11.3534	106.80
Aldrich	0.4485	0.2864	111.70	20.1108	50.10

the lowest complexity as the number of leads n grows. Table 4 points out clearly that Aldrich score is the less complex one for $n = 12$, whereas Anderson-Wilkins is the most complex. This last score, from the theoretical viewpoint, requires too much operations and bytes per iteration, with respect to the other two scores.

Figure 3 presents experimental results relating memory occupation and execution time for $n = 12$, which is the most common clinical situation.

From Figure 3, one may state that the memory occupations of the three algorithms are very similar to each other. Notice also that, holding a value of memory occupation fixed, Selvester score PT is lower than Anderson-Wilkins PT. In addition, whereas for Selvester score and for Anderson-Wilkins score the MO does not change too much for all the ranges of PT, the memory occupation for Aldrich score does vary as a function of PT. In consequence, the Selvester score is the most stable implementation, since its plot (see Figure 3) is a straight line, which may be associated to little variance in terms of the quantity MO. On the other hand, Aldrich score is quite unstable.

Table 5 depicts average results that can be estimated based on Figure 3, also supposing $n = 12$.

Table 5 confirms previous conclusions discussed in the last paragraphs. The unstability of Aldrich score is clearly depicted by the highest values attained by its variance, both in terms of PT and of MO. Selvester score, on the other hand, is the most stable algorithm. Aldrich score, however, presents the lowest average PT and the lowest average MO. In addition, if one compares the last column of Table 5 (experimental product PT × MO) to the last column of Table 4 (theoretical product CC × TMO), simulation and theory agree quite well with each other, and both put forward that Aldrich score is the least complex algorithm.

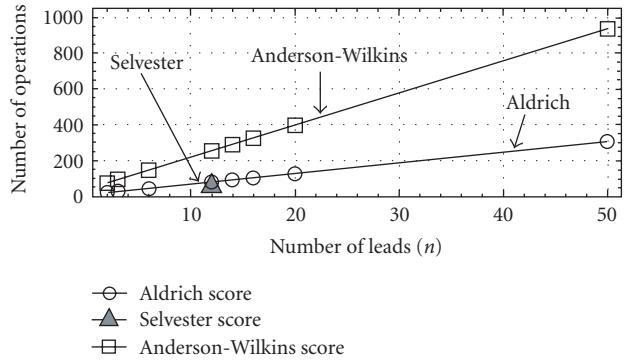

Figure 2: Theoretical computational complexity of (5a)-(5b), (8a)-(8b), and (6); depicted as a function of $n = \{2, 3, 6, 12, 14, 16, 20, 50\}$.

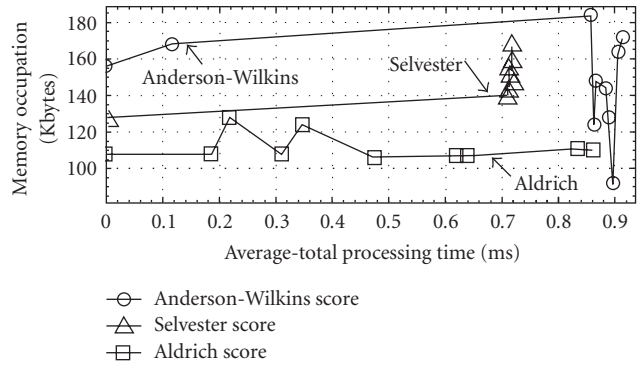

Figure 3: Experimental processing time (PT) versus memory occupation (MO) for $n = 12$ leads.

5. CONCLUSIONS AND FUTURE WORK

Results point out that performances of algorithms are very close to each other, either as the number of leads n grows (Figure 2), or in the daily situation of $n = 12$ (Figure 3, Tables 4 and 5). However, as n varies, Aldrich score presents the lowest theoretical computational complexity. For $n = 12$, Aldrich score seems to be the most efficient one, since it presents the lowest average memory occupation and the lowest average processing time. This conclusion was achieved from both theory and experiments. However, as one also considers the case $n = 12$, the standard deviations of both Selvester and Anderson-Wilkins scores are very little in comparison with those associated with Aldrich score, thus pointing out that the last algorithm is quite unstable.

Table 6: Rules for Selvester score estimation [13].

Rule	ECG lead	Criteria				Points	Maximum points/lead
1	I	(a)	*Q*dur	>=	30 ms	1	2
2		(b)	*R*amp	<=	*Q*amp	1	
3			*R*amp	<=	0.2 mV	1	
4	II	(a)	*Q*dur	>=	40 ms	2	2
5			*Q*dur	>=	30 ms	1	
6	aVL	(a)	*Q*dur	>=	30 ms	1	2
7		(b)	*R*amp	<=	*Q*amp	1	
8	aVF	(a)	*Q*dur	>=	50 ms	3	5
9			*Q*dur	>=	40 ms	2	
10			*Q*dur	>=	30 ms	1	
11		(b)	*R*amp	<=	*Q*amp	2	
12			*R*amp	<=	2∗*Q*amp	1	
13	V1 anterior	(a)	Any *Q*			1	1
14	V1 posterior	(a)	*R*amp	>=	*S*amp	1	4
15		(b)	*R*dur	>=	50 ms	2	
16			*R*amp	>=	1 mV	2	
17			*R*dur	>=	40 ms	1	
18			*R*amp	>=	0.6 mV	1	
19		(c)	*Q*amp AND *S*amp	<=	0.3 mV	1	
20	V2 anterior	(a)	Any *Q*			1	1
21			*R*dur	<=	10 ms	1	
22			*R*amp	<=	0.1 mV	1	
23			*R*amp	<=	*R*amp(V1)	1	
24	V2 posterior	(a)	*R*amp	>=	1.5∗*S*amp	1	4
25		(b)	*R*dur	>=	60 ms	2	
26			*R*amp	>=	2 mV	2	
27			*R*dur	>=	50 ms	1	
28			*R*amp	>=	1.5 mV	1	
29			*Q*amp AND *S*amp	<=	0.4 mV	1	
30	V3	(a)	Any *Q*			1	1
31			*R*dur	<=	20 ms	1	
32			*R*amp	<=	0.2 mV	1	
33	V4	(a)	*Q*dur	>=	20 ms	1	3
34		(b)	*R*amp	<=	0.5∗*S*amp	2	
35			*R*amp	<=	0.5∗*Q*amp	2	
36			*R*amp	<=	*S*amp	1	
37			*R*amp	<=	*Q*amp	1	
38			*R*amp	<=	0.7 mV	1	
39	V5	(a)	*Q*dur	>=	30 ms	1	3
40		(b)	*R*amp	<=	*S*amp	2	
41			*R*amp	<=	*Q*amp	2	
42			*R*amp	<=	2∗*S*amp	1	
43			*R*amp	<=	2∗*Q*amp	1	
44			*R*amp	<=	0.7 mV	1	

Table 6: Continued.

Rule	ECG lead		Criteria			Points	Maximum points/lead
45		(a)	*Q*dur	>=	30 ms	1	
46			*R*amp	<=	*S*amp	2	
47	V6		*R*amp	<=	*Q*amp	2	3
48		(b)	*R*amp	<=	3∗*S*amp	1	
49			*R*amp	<=	3∗*Q*amp	1	
50			*R*amp	<=	0.6 mV	1	

Where, *Q*dur, *R*dur: duration of, respectively, *Q*-wave and of *R*-wave [millisecond]. *Q*amp, *R*amp: maximum peak of, respectively, *Q*-wave and of *R*-wave [mV]. *S*amp: maximum peak of *S*-wave [mV].

Average processing times and average memory occupations of Table 5 must be carefully considered. In fact, they point out that simple computer platforms based on C++ do enable fast estimation of AMI scores without too much memory requirements. Particularly, average processing times should be compared to the times required by manual measurements commonly performed by medicines. In our research group, medical science undergraduate students with good clinical practice take about fifteen minutes in average for estimating the simple Aldrich score.

Future work involves the assessment of both memory occupation and time processing as the number of leads n varies. The computational complexity of Selvester score should also be calculated as a function of n, and the unstability of Aldrich score should be better evaluated. We are also developing a more accurate methodology for assessing MO and TP, based on well-established C++ functions that can be inserted into the algorithm implementation. Finally, the automatic estimation of P, Q, R, S, J and T quantities from digital ECG recordings is on course, so that to include this computational effort in our evaluation.

ACKNOWLEDGMENTS

The authors would like to thank undergraduate medical science students Geraldo RR Freitas and Lucila SS Rocha, as well as Professor Elmiro S Resende (Medical Sciences School, UFU), for their technical contribution regarding bibliography, as well as for details on the procedure for estimating the AMI scores. They are also indebted to Professor G. S. Wagner, from Duke University Medical Center, USA, for his regular technical disscussions and support to their research.

REFERENCES

[1] DATASUS, "Health Information and Biostatistical Index," Official website of the Brazilian National Health Ministry, November 2007, http://w3.datasus.gov.br/datasus/datasus.php.

[2] R. F. Gillum, "Trends in acute myocardial infarction and coronary heart disease death in the United States," *Journal of the American College of Cardiology*, vol. 23, no. 6, pp. 1273–1277, 1994.

[3] The Joint European Society of Cardiology/American College of Cardiology, "Myocardial infarction redefined—a consensus document," *European Heart Journal*, vol. 21, no. 18, pp. 1502–1513, 2000.

[4] S. A. Achar, S. Kundu, and W. A. Norcross, "Diagnosis of acute coronary syndrome," *American Family Physician*, vol. 72, no. 1, pp. 119–126, 2005.

[5] D. Brieger, K. A. Eagle, S. G. Goodman, et al., "Acute coronary syndromes without chest pain, an underdiagnosed and undertreated high-risk group: insights from the global registry of acute coronary events," *Chest*, vol. 126, no. 2, pp. 461–469, 2004.

[6] S. A. Hahn and C. Chandler, "Diagnosis and management of ST elevation myocardial infarction: a review of the recent literature and practice guidelines," *The Mount Sinai Journal of Medicine*, vol. 73, no. 1, pp. 469–481, 2006.

[7] H. Blanke, M. Cohen, G. U. Schlueter, K. R. Karsch, and K. P. Rentrop, "Electrocardiographic and coronary arteriographic correlations during acute myocardial infarction," *The American Journal of Cardiology*, vol. 54, no. 3, pp. 249–255, 1984.

[8] P. Schweitzer, "The electrocardiographic diagnosis of acute myocardial infarction in the thrombolytic era," *American Heart Journal*, vol. 119, no. 3, part 1, pp. 642–654, 1990.

[9] J. E. Madias, "Use of precordial ST-segment mapping," *American Heart Journal*, vol. 95, no. 1, pp. 96–101, 1978.

[10] B. L. Nielsen, "ST-segment elevation in acute myocardial infarction: prognostic importance," *Circulation*, vol. 48, no. 2, pp. 338–345, 1973.

[11] R. Schöder, K. Wegscheider, K. Schröder, R. Dissmann, and W. Meyer-Sabellek, "Extent of early ST segment elevation resolution: a strong predictor of outcome in patients with acute myocardial infarction and a sensitive measure to compare thrombolytic regimens. A substudy of the International Joint Efficacy Comparison of Thrombolytics (INJECT) trial," *Journal of the American College of Cardiology*, vol. 26, no. 7, pp. 1657–1664, 1995.

[12] Y. Birnbaum and D. L. Ware, "Electrocardiogram of acute ST-elevation myocardial infarction: the significance of the various "scores"," *Journal of Electrocardiology*, vol. 38, no. 2, pp. 113–118, 2005.

[13] R. H. Selvester, R. E. Sanmarco, J. C. Solomon, and G. S. Wagner, "The ECG: QRS change," in *Myocardial Infarction: Measurement and Intervention*, G. S. Wagner, Ed., Developments in Cardiovascular Medicine, chapter 14, pp. 23–50, Martinus Nijhoff, The Hague, The Netherlands, 1982.

[14] G. S. Wagner, C. J. Freye, S. T. Palmeri, et al., "Evaluation of a QRS scoring system for estimating myocardial infarct size. I. Specificity and observer agreement," *Circulation*, vol. 65, no. 2, pp. 342–347, 1982.

[15] H. R. Aldrich, N. B. Wagner, J. Boswick, et al., "Use of initial ST-segment deviation for prediction of final electrocardiographic size of acute myocardial infarcts," *The American Journal of Cardiology*, vol. 61, no. 10, pp. 749–753, 1988.

[16] P. Clemmensen, P. Grande, H. R. Aldrich, and G. S. Wagner, "Evaluation of formulas for estimating the final size of acute myocardial infarcts from quantitative ST-segment elevation on the initial standard 12-lead ECG," *Journal of Electrocardiology*, vol. 24, no. 1, pp. 77–80, 1991.

[17] M. L. Wilkins, C. Maynard, B. H. Annex, et al., "Admission prediction of expected final myocardial infarct size using weighted ST-segment, Q wave, and T wave measurements," *Journal of Electrocardiology*, vol. 30, no. 1, pp. 1–7, 1997.

[18] B. Hedén, R. Ripa, E. Persson, et al., "A modified Anderson-Wilkins electrocardiographic acuteness score for anterior or inferior myocardial infarction," *American Heart Journal*, vol. 146, no. 5, pp. 797–803, 2003.

[19] M. L. Wilkins, A. D. Pryor, C. Maynard, et al., "An electrocardiographic acuteness score for quantifying the timing of a myocardial infarction to guide decisions regarding reperfusion therapy," *The American Journal of Cardiology*, vol. 75, no. 8, pp. 617–620, 1995.

[20] R. S. Ripa, E. Persson, B. Hedén, et al., "Comparison between human and automated electrocardiographic waveform measurements for calculating the Anderson-Wilkins acuteness score in patients with acute myocardial infarction," *Journal of Electrocardiology*, vol. 38, no. 2, pp. 96–99, 2005.

[21] K. E. Corey, C. Maynard, O. Pahlm, et al., "Combined historical and electrocardiographic timing of acute anterior and inferior myocardial infarcts for prediction of reperfusion achievable size limitation," *The American Journal of Cardiology*, vol. 83, no. 6, pp. 826–831, 1999.

[22] L. Sörnmo and P. Laguna, *Bioelectrical Signal Processing in Cardiac and Neurological Applications*, Academic Press, Amsterdam, The Netherlands, 1st edition, 2005.

[23] M. J. Eskola, K. C. Nikus, L.-M. Voipio-Pulkki, et al., "Comparative accuracy of manual versus computerized electrocardiographic measurement of J-, ST- and T-wave deviations in patients with acute coronary syndrome," *The American Journal of Cardiology*, vol. 96, no. 11, pp. 1584–1588, 2005.

[24] M. M. Pelter, M. G. Adams, and B. J. Drew, "Computer versus manual measurement of ST-segment deviation," *Journal of Electrocardiology*, vol. 30, no. 2, pp. 151–156, 1997.

[25] B. M. Horáček, J. W. Warren, A. Albano, et al., "Development of an automated Selvester Scoring System for estimating the size of myocardial infarction from the electrocardiogram," *Journal of Electrocardiology*, vol. 39, no. 2, pp. 162–168, 2006.

[26] F. Badilini, T. Erdem, W. Zareba, and A. J. Moss, "ECGScan: a method for conversion of paper electrocardiographic printouts to digital electrocardiographic files," *Journal of Electrocardiology*, vol. 38, no. 4, pp. 310–318, 2005.

[27] C. Ho, B. Eloff, F. Lacy, L. Shoemaker, and E. Mallis, "Issues for ECG devices with preinstalled leads and reduced leads," *Journal of Electrocardiology*, vol. 39, no. 4, supplement 1, p. S33, 2006.

[28] H. S. Wilf, *Algorithms and Complexity*, AK Peters, London, UK, 2002.

[29] J. G. Webster, Ed., *Medical Instrumentation: Application and Design*, John Wiley & Sons, New York, NY, USA, 3rd edition, 1998.