PCT

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : G06F 19/00, A61B 5/042	**A1**	(11) International Publication Number: **WO 98/09241**
		(43) International Publication Date: 5 March 1998 (05.03.98)

(21) International Application Number: PCT/CA97/00615

(22) International Filing Date: 27 August 1997 (27.08.97)

(30) Priority Data:
08/705,621   29 August 1996 (29.08.96)   US
08/846,348   30 April 1997 (30.04.97)   US

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(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE, HU, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, TJ, TM, TR, TT, UA, UG, UZ, VN, ARIPO patent (GH, KE, LS, MW, SD, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).

Published
With international search report.

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(54) Title: ECG P-QRS-T ONSET, OFFSET AND PEAK DETECTION METHOD AND APPARATUS
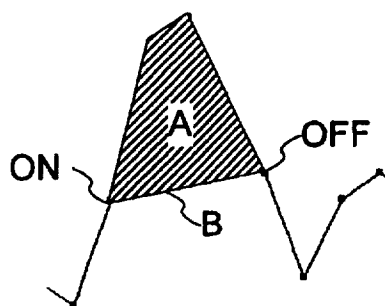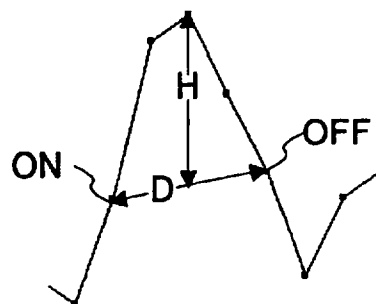
(R)   (S)

(57) **Abstract**

A method and apparatus for detecting P or T waves in an electrocardiogram signal in intervals before and after each (previously) detected QRS wave. Within each interval, a candidate pair of samples are selected. If the candidate pair are separated by a time duration which does not exceed a predefined time duration then that pair is rejected and the process repeats. Otherwise, the area "A" of a closed polygon bounded by all of the samples between and including the candidate pair is derived (the polygon's base line extends linearly a distance "d" between the candidate pair of sample intervals). The maximum vertical displacement "h" between the base line and any portion of the polygon above the base line is derived. If "h" does not exceed a predefined minimum vertical displacement, then the candidate pair is rejected and the process repeats. Otherwise, a value Gamma = A*h/d is derived for the candidate pair. If Gamma does not exceed any value of Gamma derived previously in respect of any previously selected candidate pair, then the candidate pair is rejected and the process repeats. Otherwise, a value BestGamma is set equal to the candidate pair's value Gamma. Another candidate pair is then selected and the process repeats. The P or T wave is selected as that whose value Gamma equals the value BestGamma.

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ECG P-QRS-T ONSET, OFFSET AND
PEAK DETECTION METHOD AND APPARATUS

Field of the Invention

5   This application pertains to identification of P, T
and QRS waves in electrocardiogram ("ECG") signals.

Background of the Invention

           ECG signals are obtained by applying adhesive patch or
10   metal plate electrodes to a patient's chest and connecting
the electrodes to a cardiograph machine. The cardiograph
measures voltage differences between pairs of electrodes.
The voltage difference between each pair of electrodes is
a "lead". The cardiograph sequentially measures the leads
15   at regular time intervals and stores the measurements. A
sequence of such measurements is referred to as set of "ECG
samples". The "sampling rate" is the frequency at which
the measurements are made. Sampling rates of 125, 250,
500, or 1000 samples per second are typical. Typical
20   ranges for the measurements are -5mV to +5mV, divided into
2^8, 2^{12}, or 2^{16} measurement intervals.

           Figure 1 depicts a typical ECG signal consisting of
several heart beat segments. Each beat of a patient's
heart produces a unique ECG signal segment, such as the
25   single heart beat cycle ECG signal segment shown in Figure
2. According to well known principles of cardiology, each
heart beat cycle typically includes a "P" wave 10, a "QRS"
wave 12 and a "T" wave 14. Each of these waves is repre-
sentative of a particular characteristic of the patient's
30   heart beat.

           Each P, QRS, and T wave begins at a specific "onset"
and ends at a specific "offset". Each wave also has a
"peak", which is the wave's maximum displacement relative
to a predefined "baseline". However, electrodes placed in
35   different locations on the same patient yield different ECG
signals in response to the same heart beat. Accordingly,
variations from lead to lead in the onset, offset, and peak
values for each P, QRS, and T wave are common. For some

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leads in some ECG signals, a P, QRS or T wave may not be evident at all.

The aforementioned "baseline" is the electrical signal measured by the cardiograph in the absence of cardiac
5   activity.   The baseline is not flat, but wanders up and down as the patient's body moves. Accordingly, P, QRS and T waves are not seen relative to a flat horizontal line, but relative to a wandering baseline, as shown in Figure 3. Variations in ECG signal measurements can also result from
10 noise introduced by movement of the patient's body, elec-tromagnetic interference, etc. For example, patient muscle activity can introduce high frequency noise as shown in Figure 4.   Such noise can be of the same amplitude as the P or T waves, and must be removed for accurate measurement
15 of P or T waves.

Various prior art techniques have been devised to detect P, QRS, or T waves in ECG signals. For example, Pan et al use a moving window integrator to detect QRS waves, but make no attempt to detect P or T waves (see Pan, J. and
20 Thompkins, W. J.; "A Real-Time QRS detection Algorithm", IEEE Transactions on Biomedical Engineering, vol. 32, pp. 230-236, 1985).

Reddy, et al use a derivative and threshold technique to detect P waves (see Reddy, et. al; "Detection of P Waves
25 in Resting ECG: A Preliminary Study"; IEEE, 1992).   How-ever, because derivatives are affected both by baseline wander and by noise, this technique is susceptible to error in the presence of either baseline wander or noise, both of which are common.

30 Laguna, et al use the signal slope to identify the QRS wave, use derivatives to find the peaks of the P and T waves, and use derivatives and thresholding to find the onsets and offsets of the P and T waves (see Laguna, et al.; "Automatic Detection of Wave Boundaries on Multilead
35 ECG Signals: Validation with the CSE Database"; Computers and Biomedical Research, vol. 27, pp. 45-60, 1994). This

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method is also error-prone in the presence of baseline wander or noise.

Koski, et al use syntactic methods based on signal slope to identify P, QRS, and T waves (see Koski, et al; "Syntactic Recognition of ECG Signals by Attributed Finite Automata"; 1995). This method is also believed to be error-prone in the presence of baseline wander or noise.

United States Patent No. 4,945,917 Akselrod, et al discloses a technique for detecting fetal QRS waves in which maternal QRS waves are first detected in an operator-assisted "learning" phase by deriving first and second derivatives of a portion of the maternal ECG signal. A "template" representative of the maternal QRS wave is then constructed and subtracted from a composite maternal-fetal ECG signal to derive the fetal QRS wave. This technique is subject to a number of disadvantages, including the need for operator intervention, and reliance upon a fixed template which may be a poor representation of the continuously variable QRS wave as the patient's heart beat conditions vary.

United States Patent No. 4,704,681 Shimuzu, et al discloses an apparatus for detecting certain "delta waves" within previously detected QRS waves. No provision is made for detecting P or T waves.

The present invention provides a method and apparatus for reliably, automatically detecting P, QRS and T waves in high speed processing of large volumes of ECG signal data representative of multiple leads and many heart beat cycles.

Summary of the Invention

The invention provides a method and apparatus for detecting P or T waves in an electrocardiogram signal in intervals before and after each (previously) detected QRS wave. Within each interval, a candidate pair of samples are selected. If the candidate pair are separated by a time duration which does not exceed a predefined time

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duration then that pair is rejected and the process repeats. Otherwise, the area "A" of a closed polygon bounded by all of the samples between and including the candidate pair is derived (the polygon's base line extends linearly a distance "d" between the candidate pair of samples). The maximum vertical displacement "h" between the base line and any portion of the polygon above the base line is derived. If "h" does not exceed a predefined minimum vertical displacement, then the candidate pair is rejected and the process repeats. Otherwise, a value Gamma = A*h/d is derived for the candidate pair. If Gamma does not exceed any value of Gamma derived previously in respect of any previously selected candidate pair, then the candidate pair is rejected and the process repeats. Otherwise, a value BestGamma is set equal to the candidate pair's value Gamma. Another candidate pair is then selected and the process repeats. The P or T wave is selected as that whose value Gamma equals the value BestGamma.

20   Brief Description of the Drawings

Figure 1 depicts a typical ECG signal consisting of several heart beat cycle segments.

Figure 2 depicts a single heart beat cycle segment of the Figure 1 ECG signal.

Figure 3 depicts a single heart beat cycle segment of the Figure 1 ECG signal in which the ECG baseline is wandering.

Figure 4 depicts a single heart beat cycle segment of the Figure 1 ECG signal in which the signal is contaminated by high frequency noise.

Figure 5 is a block diagram of a P, QRS, and T wave detector according to the invention.

Figures 6A and 6B together comprise a flowchart which depicts the sequence of steps performed in detecting QRS waves in accordance with the invention.

Figure 7 is a flowchart which depicts the sequence of steps performed in detecting P or T waves in accordance with the invention.

Figure 8 is a flowchart which depicts the sequence of wave detection sub-steps performed during either P or T wave detection in accordance with the invention.

Figures 9A through 9S are signal waveforms which respectively depict successive stages of the operation of the preferred embodiment of the invention.

Detailed Description of the Preferred Embodiment

Introduction

Figure 5 is a block diagram representation of an apparatus for processing previously measured and stored ECG samples 20 in accordance with the invention. Each ECG sample waveform is generally of the form shown in Figure 9A, which is identical to the previously discussed Figure 2 waveform. Buffer 21 stores a selected group of ECG samples while approximations to the first and second derivatives of those samples are derived.

Specifically, filter 23 receives the Figure 9A ECG sample waveform as input, and produces as output a signal representative of the first derivative ("D1") thereof, as shown in Figure 9B. Filter 26 also receives the Figure 9A ECG sample waveform as input, and produces as output a signal representative of the second derivative ("D2") thereof, as shown in Figure 9C. Buffer 24 stores the first derivative representations output by filter 23, and buffer 27 stores the second derivative representations output by filter 26.

As hereinafter described in greater detail, QRS detector 22 applies the algorithm depicted in Figures 6A and 6B to the ECG samples stored in buffer 21, to the first derivative representations stored in buffer 24 and to the second derivative representations stored in buffer 27 to detect the onsets, peaks, and offsets of QRS waves in each

ECG sample waveform. P and T wave detector 25 applies the
algorithm depicted in Figure 7 to the output of QRS
detector 22 and to the ECG samples stored in buffer 21 to
detect the onsets, peaks, and offsets of the P and T waves
5   in each ECG sample waveform. The onsets, offsets, and
peaks of the P, QRS, and T waves output by QRS detector 22
and by P and T detector 25 are stored as a sequential
record 28, which can be on a computer disk, tape, memory,
or communications channel.
10

QRS Wave Detection
        The operation of QRS detector 22 will now be described
with reference to Figures 6A and 6B. Such operation is
conveniently characterized in terms of the following
15   definitions:

MaxQRSSep	absolute maximum distance between QRS waves
MaxSep	maximum distance between QRS waves
MinQRSSep	absolute minimum distance between QRS waves
MinSep	minimum distance between QRS waves
MinQRSWidth	absolute minimum time between QRS wave onset and offset
MaxQRSWidth	absolute maximum time between QRS wave onset and offset
MinQRSHeight	absolute minimum height from onset or offset to peak
MaxWidth	maximum time between QRS wave onset and offset
MinWidth	minimum time between QRS wave onset and offset
MinHeight	minimum height from onset or offset to peak
D2Thresh	minimum value of second derivative at QRS peak
MinD2Height	minimum height from onset or offset to peak in second derivative
QRSPeak	peak of current candidate QRS wave
QRSOn	onset of current candidate QRS wave
QRSOff	offset of current candidate QRS wave
LastQRSPeak	peak of previously detected QRS wave
LastQRSOn	onset of previously detected QRS wave
LastQRSOff	offset of previously detected QRS wave

45   An initialization step 40 is first performed to set
the following initial values:

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```
              MaxQRSSep        : =   2 seconds
              MaxSep           : =   MaxQRSSep
              MinQRSSep        : =   0.2 seconds
              MinSep           : =   MinQRSSep
    5         MinQRSWidth      : =   25 milliseconds
              MaxQRSWidth      : =   240 milliseconds
              MinQRSHeight     : =   0.25mV
              MaxWidth         : =   MaxQRSWidth
              MinWidth         : =   MinQRSWidth
   10         MinHeight        : =   MinQRSHeight
              D2Thresh         : =   0
              MinD2Height      : =   0
              D1Lthresh        : =   0
              D1Rthresh        : =   0
   15         D2LRThresh       : =   0
              LastQRSPeak      : =   nil
              LastQRSOn        : =   nil
              LastQRSOff       : =   nil
```

20   At step 41, the next ECG sample is retrieved from buffer 21, and that sample (called "QRSPeak") is evaluated to determine whether a QRS wave can be detected therein. Step 41 is the first step in a loop. QRSPeak is increment-ed by one with each repetition of step 41. At step 44, a

25   test is performed to determine whether the distance 90 (Figure 9D) between the peak of the current candidate QRS wave (i.e. QRSPeak) and the peak of the previously detected QRS wave (i.e. LastQRSPeak) is less than the maximum distance between QRS waves (i.e. MaxSep), or whether

30   LastQRSPeak is nil (as it will be if the current candidate QRS wave is the first sample processed from buffer 21).

       If distance 90 is not less than MaxSep, or if LastQRS-Peak is nil, then a further test step 45 is performed to determine whether threshold values D2Thresh, MinD2Height,

35   MinHeight and MinWidth are minimal. These threshold values are minimal if the following conditions are met:

```
              D2Thresh        ≤    0
              MinD2Height     ≤    0
              MinHeight       ≤    MinQRSHeight
   40         MinWidth        ≤    MinQRSWidth
```

If the threshold values D2Thresh, MinD2Height, MinHeight and MinWidth are not minimal, then step 43 is performed to relax those threshold values, as well as the threshold

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values MaxSep, MinSep, MaxWidth by resetting their respect-
ive values as follows:

MaxSep	:=	Min(MaxQRSSep, MaxSep*2)
MinSep	:=	Max(MinQRSSep, MinSep/2)
MaxWidth	:=	MIN(MaxQRSWidth, MaxWidth*2)
MinWidth	:=	MAX(MinQRSWidth, MinWidth/2)
MinHeight	:=	MAX(MinQRSHeight, MinHeight/2)
D2Thresh	:=	2
MinD2Height	:=	2

After relaxation step 43, step 42 is performed to reset the
previously detected QRS wave (i.e. LastQRSPeak) as the
sample to be evaluated, commencing with step 41, to deter-
mine whether a QRS wave can be detected therein. Accord-
ingly, the candidate QRS wave which was unsuccessfully
processed during the previously described steps will again
be processed, with different threshold values, to determine
whether a QRS wave can be detected therein. If test step
45 determines that threshold values D2Thresh, MinD2Height,
MinHeight and MinWidth are minimal, then step 46 is per-
formed to output the last QRS and to set LastQRSPeak to
nil.

At this point, QRS detector 22 has reached a stage at
which the QRS wave following an earlier-detected QRS wave
can not be detected. A detected QRS wave is not immediate-
ly output, because it may be invalidated by a subsequently
detected QRS wave. If no following QRS wave is detected,
then the last detected QRS wave is accepted as valid and
its onset, offset and peak values are output. Once a QRS
wave is output, it need not be retained in memory. Since
no new QRS wave has been detected, LastQRSPeak is set to
nil.

After performance of step 46; or, if test step 44
determines that distance 90 is less than MaxSep, and that
LastQRSPeak is not nil, then a further test step 47 is
performed on the second derivative representation (input to
QRS detector 22 from buffer 27) of the ECG sample currently
being processed by QRS detector 22. As depicted in Figure
9E, test step 47 determines whether the second derivative
at QRSPeak is a local extrema. If the ECG sample currently

being processed by QRS detector 22 is sample "i", then its second derivative is a local extrema if and only if $D2[i-1] \leq D2[i] \geq D2[i+1]$; or, $D2[i-1] \geq D2[i] \leq D2[i+1]$.

If test step 47 determines that the second derivative at QRSPeak is not a local extrema, then the loop is repeated commencing with step 41. Otherwise, if test step 47 determines that the second derivative at QRSPeak is a local extrema, then a further test step 48 is performed to determine whether the absolute value of the second derivative at QRSPeak is less than D2Thresh, as shown in Figure 9F. If test step 48 determines that the absolute value of the second derivative at QRSPeak is less than D2Thresh, then the loop is repeated commencing with step 41. Otherwise, if test step 48 determines that the absolute value of the second derivative at QRSPeak is less than D2Thresh, step 49 is performed to set indices D2On, D2Off (Figure 9F) equal to the indices of the local extrema adjacent QRSPeak in the second derivative of the ECG sample currently being processed by QRS detector 22.

After performance of step 49, a further test step 50 is performed to determine whether the time "t1" (Figure 9G) between D2Off and D2On is less than MaxWidth. If test step 50 determines that the time between D2Off and D2On is not less than MaxWidth, then the loop is repeated commencing with step 41. Otherwise, if test step 50 determines that the time between D2Off and D2On is less than MaxWidth, then a further test step 51 is performed to determine whether the minimum difference in the values "a", "b" (Figure 9G) of the second derivative between D2On and D2Peak or between D2Off and D2Peak are less the MinD2Height.

If test step 51 determines that the minimum difference in the values of the second derivative between D2On and D2Peak; or, between D2Off and D2Peak are not less the MinD2Height, then the loop is repeated commencing with step 41. Otherwise, if test step 51 determines that the minimum difference in the values of the second derivative between D2On and D2Peak; or, between D2Off and D2Peak are less the

MinD2Height then step 52 is performed to set threshold
values D1LThresh, D1RTthresh for the first derivative, and
to set threshold value D2LRThresh for the second derivative
between D2On and D2Off, as shown in Figure 9H.   More
5   particularly, the threshold values are set as follows:

D1LThresh := ¼ the maximum value in the first deriv-
ative between D2On and QRSPeak
D1RThresh := ¼ the maximum value in the first deriv-
ative between QRSPeak and D2Off
10   D2LRThresh := ¼ the maximum value in the second
derivative between D2On and D2Off

After performance of step 52, step 53 is performed, as
depicted in Figure 9I, to set QRSOn and QRSOff to the indi-
ces near QRSPeak where the values of the first and second
15   derivatives are below D1Lthresh and D2LRThresh for QRSOn,
and below D1RThresh and D2LRThresh for QRSOff.

After performance of step 53, test step 54 is per-
formed to determine whether the time "t2" (Figure 9J)
between QRSOn and QRSOff is less than MaxWidth.   If test
20   step 54 determines that the time between QRSOn and QRSOff
is not less than MaxWidth, then step 55 is performed to set
QRSOn and QRSOff equal to D2On and D2Off respectively
(Figure 9K).   If test step 54 determines that the time
between QRSOn and QRSOff is less than MaxWidth; or, after
25   performance of step 55 if needed, test step 56 is performed
to determine whether the average height difference from
QRSOn to QRSPeak (i.e. distance "a" in Figure 9L); and,
from QRSOff to QRSPeak (i.e. distance "b" in Figure 9L) is
less than MinHeight.   If test step 56 determines that the
30   average height difference aforesaid is not less than Min-
Height, then the loop is repeated commencing with step 41.

Otherwise, if test step 56 determines that the average
height difference aforesaid is less than MinHeight then a
test step 57 is performed to determine whether LastQRSPeak
35   is nil (i.e. to determine whether LastQRSPeak has been
accepted as a QRS wave).   If test step 57 determines that
LastQRSPeak is not nil, then a further test step 58 is
performed to determine whether the time "t3" (Figure 9M)

between LastQRSPeak and QRSPeak is greater than MinSep. If test step 58 determines that the time between LastQRSPeak and QRSPeak is greater than MinSep, then LastQRSPeak is accepted as a valid QRS wave and is as such at step 59.

5   Otherwise, if test step 58 determines that the time between LastQRSPeak and QRSPeak is not greater than MinSep, then a further test step 60 is performed as depicted in Figure 9N to determine whether the absolute value "V1" of the second derivative at QRSPeak is greater than its absolute value

10   "V2" at LastQRSPeak. If test step 60 determines that V1 is not greater than V2, then the loop is repeated commencing with step 41. Otherwise, if test step 60 determines that V1 is greater than V2; or, if test step 57 determines that LastQRSPeak is nil; or, after performance of step 59; step

15   61 is performed to derive a QRS model from the current QRS candidate as follows:

MaxSep	:=	2*(QRSPeak - LastQRSPeak), or MaxQRSSep if LastQRSPeak is nil
MinSep	:=	½*(QRSPeak - LastQRSPeak), or MinQRSSep if LastQRSPeak is nil
MaxWidth	:=	Min(2*(QRSOff - QRSOn), QRSMaxWidth)
MinWidth	:=	Max(½*(QRSOff - QRSOn), QRSMinWidth)
MinHeight	:=	Max(½*(height of QRS), QRSMinHeight)
D2Thresh	:=	½*(Abs(D2) at QRSPeak)
MinD2Height	:=	½*(height of QRS in D2)

After performance of QRS model derivation step 61, step 62

30   is performed to set LastQRSPeak, LastQRSOn, and LastQRSOff equal to the values of QRSPeak, QRSOn, and QRSOff respectively. After performance of step 62, the loop is repeated commencing with step 41.

35   P and T Wave Detection

The operation of P and T detector 25 will now be described with reference to Figure 7. As previously mentioned, P and T wave detector 25 applies the Figure 7 algorithm to the output of QRS detector 22 and to the ECG

40   samples stored in buffer 21 to detect the onsets, peaks,

and offsets of the P and T waves in each ECG sample
waveform. It is however important to understand that usage
of the previously described QRS detector 22 is not essen-
tial to the operation of P and T detector 25. The prior
5   art has evolved a variety of QRS detectors, many of which
can detect onsets, peaks, and offsets of QRS waves in ECG
sample waveforms. Any such QRS detector could readily be
adapted and substituted for QRS detector 22 to serve as an
input source of onsets, peaks, and offsets of QRS waves for
10   P and T detector 25.

        The operation of P and T detector 25 is conveniently
characterized in terms of the following definitions:

        MinPWidth   absolute minimum time between P wave
                         onset and offset
15   MinPHeight   absolute minimum height from onset or
                         offset to peak of P wave
        MinTWidth   absolute minimum time between T wave
                         onset and offset
        MinTHeight   absolute minimum height from onset or
20   offset to peak of T wave

        With reference to Figure 7, step 70 defines a time
interval "MaxPR" (Figure 9O) seconds prior to the onset of
the selected input QRS wave; and, a time interval "MaxST"
seconds after the offset of the selected input QRS wave.
25   Step 71 narrows the MaxPR interval, as shown in Figure 9P,
so that it does not overlap any previously detected T or
QRS wave, and narrows the MaxST interval so that it does
not overlap the following QRS wave. Step 72 filters the
input ECG samples obtained from buffer 21 to remove noise.
30   As hereinafter described with reference to Figure 8, step
73 detects, in the narrowed MaxPR interval, the best candi-
date P wave which satisfies the MinPWidth and MinPHeight
thresholds; and, step 74 detects, in the narrowed MaxST
interval, the best candidate T wave which satisfies the
35   MinTWidth and MinTHeight thresholds. Step 75 then outputs
the P wave detected by step 73, if any; the T wave detected
by step 74, if any; and the QRS wave previously detected by
QRS detector 22.

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Figure 8 provides greater detail of the operations performed during steps 73 and 74. The same operations are performed during each of steps 73 and 74, the only difference being that step 73 is performed with respect to the

5   narrowed MaxPR interval to detect the best candidate P wave, and step 74 is performed with respect to the narrowed MaxST interval to detect the best candidate T wave. Accordingly, in the following description, reference is made to the "candidate wave", which those skilled in the

10 art will understand to mean a candidate P wave if the Figure 8 operations are performed during step 73, and to mean a candidate T wave if the Figure 8 operations are performed during step 74.

The Figure 8 operations are conveniently characterized

15 in terms of the following definitions:

MinWidth   minimum time between onset and offset of candidate wave
MinHeight   minimum height from onset or offset to peak of candidate wave

20 BestPeak   location of best candidate wave's peak
BestOn   location of best candidate wave's onset
BestOff   location of best candidate wave's offset
BestGamma   measure of best candidate wave's validity

Initialization step 80 sets the values of BestOn, BestOff,

25 BestPeak, and BestGamma to nil, and sets the values of MinWidth and MinHeight to equal parameters passed into P and T detector 25. Step 81 initiates a loop which iteratively evaluates the "On" and "Off" values (Figure 9Q) for every pair of sample points within the input interval

30 of the candidate wave (i.e. the narrowed MaxPR interval in the case of step 73, or the narrowed MaxST interval in the case of step 74) and selects the BestOn, BestOff, and BestPeak values for the candidate wave.

More particularly, a candidate onset value "On", and

35 a candidate offset value "Off" are selected during step 81. Test step 82 then determines whether the time "T" (Figure 9Q) between the On and Off values is greater than MinWidth. If test step 82 determines that T is not greater than MinWidth then the loop is repeated commencing with step 81.

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Otherwise, if test step 82 determines that T is greater than MinWidth, then step 83 is performed to determine the area "A" (Figure 9R) of the closed polygon bounded by all of the sample intervals between and including the On and
5 Off values, the polygon having a base line "B" (Figure 9R) extending linearly between the On and Off values.

Step 84 then selects as the "Peak" sample (Figure 9S) the ECG sample which has the maximum height "h" above base line B. In this context, "height" refers to the distance
10 in ECG samples from Peak to base line B. A test step 85 is then performed to determine whether h is greater than Min-Height. If test step 85 determines that h is not greater than MinHeight then the loop is repeated commencing with step 81.

15   Otherwise, if test step 85 determines that h is greater than MinHeight, step 86 is performed to determine the Euclidean distance "d" (Figure 9S) between the candidate On and Off values in terms of both ECG samples and time. Step 87 is then performed to determine a candidate
20 value "Gamma" = A*h/d. Test step 88 is then performed to determine whether Gamma is greater than BestGamma. If test step 88 determines that Gamma is not greater than BestGamma then the loop is repeated commencing with step 81. Other-wise, if test step 88 determines that Gamma is greater than
25 BestGamma, then the values of BestOn, BestOff, BestPeak, and BestGamma are replaced with the values of On, Off, Peak, and Gamma and the loop is then repeated commencing with step 81.

30 <u>Summary</u>

It will thus be understood that the apparatus depicted in Figure 5 receives input ECG samples, detects QRS waves in such samples, and then detects the P and T waves adjac-ent each QRS wave. The ECG samples are read from a se-
35 quential storage device and buffered in a computer memory. Approximations to the first and second derivatives of the ECG samples are also computed and buffered. The ECG

samples and the first and second derivative approximations
are input to a QRS detector, which outputs the onsets,
offsets and peaks of detected QRS waves.

The QRS detector maintains records of the last
5   detected QRS (which is a provisional candidate for output
as a valid QRS wave, until its final acceptance), and a QRS
model derived from the last detected QRS. Final acceptance
of the last QRS wave as a valid QRS wave depends upon the
outcome of tests which involve the next candidate QRS wave.
10   The QRS detector iterates over every ECG sample in the
candidate wave, comparing each sample to the QRS model to
determine whether the selected sample is the peak of a QRS
wave. If no QRS is detected after a maximum expected QRS
interval, the model parameters are relaxed and the ECG
15   samples subsequent to the last valid QRS are re-examined.
If the model is already fully relaxed, no new QRS is
detected and the last detected QRS is accepted as valid and
output.

Once an ECG sample is determined to be a candidate QRS
20   peak, the candidate QRS wave's onset and offset are deter-
mined by setting thresholds and examining the first and
second derivatives near the peak. The candidate peak,
onset, and offset must satisfy the QRS model thresholds.
If the candidate satisfies the model and is sufficiently
25   far from the previous QRS, the previous QRS is output as a
detected QRS wave. If the candidate satisfies the model
but is too close to the previous QRS, the QRS having the
lesser second derivative value at its peak is rejected. If
the current candidate passes all tests, the last QRS is
30   accepted as valid and output, and the current QRS candidate
is recorded as the last QRS.

Once a QRS has been detected (either by QRS detector
25 or by a suitable substitute QRS detector), a P and T
wave detector looks for a P wave preceding the QRS wave and
35   for a T wave following it. These waves are found by
finding waves in the ECG samples which satisfy minimum
height and width requirements and lie near the QRS. The

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ECG samples in these ranges are first filtered to remove noise. The onset and offset of the P and T waves are chosen according to their height relative to their onset and offset, the distance between their onset and offset, and the area of a closed polygon bounded by the ECG samples between their onset and offset. The P and T wave detector outputs include the onset, offset, and peaks of the P and T waves.

As will be apparent to those skilled in the art in the light of the foregoing disclosure, many alterations and modifications are possible in the practice of this invention without departing from the spirit or scope thereof. Accordingly, the scope of the invention is to be construed in accordance with the substance defined by the following claims.

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WHAT IS CLAIMED IS:

1. A method of detecting P and T waves in an electro-
    cardiogram signal containing said P and T waves and
    containing previously detected QRS waves, said method
    characterized by the steps of:

    a. selecting (41) a next one (QRSPeak) of said
        previously detected QRS waves;

    b. defining (70) a first time interval (MaxPR)
        within said electrocardiogram signal, said first
        time interval preceding said selected QRS wave
        and containing a plurality of samples of said
        electrocardiogram signal;

    c. defining (70) a second time interval (MaxST)
        within said electrocardiogram signal, said second
        time interval following said selected QRS wave
        and containing a plurality of samples of said
        electrocardiogram signal;

    d. narrowing (71) said first time interval to
        exclude QRS and previously detected T waves
        preceding said selected QRS wave;

    e. narrowing (71) said second time interval to
        exclude QRS waves following said selected QRS
        wave;

    f. for each pair of said samples in said first time
        interval:

        i.   proceeding (82) to step 1(f)(iv) if said
             pair of samples are separated by a time
             duration which does not exceed a predefined
             time duration (MinPWidth);

        ii. deriving (83) the area, width, and height of
             a closed polygon having vertices defined by
             all samples within said first time interval
             between and including said pair of samples;

        iii. deriving (86, 87) a rating for said polygon
             as a function of said area, width and
             height;

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    iv.   selecting (81) another pair of said samples and proceeding to step 1(f)(i);

  g.   selecting (73) as said P wave that one of said step 1(f)(iii) polygons for which said rating is maximal;

  h.   for each pair of said samples in said second time interval:

    i.   proceeding (82) to step 1(h)(iv) if said pair of samples are separated by a time duration which does not exceed a predefined time duration (MinTWidth);

    ii.   deriving (83) the area, width, and height of a closed polygon having vertices defined by all samples within said second time interval between and including said pair of samples;

    iii. deriving (86, 87) a rating for said polygon as a function of said area, width and height;

    iv.   selecting (81) another pair of said samples and proceeding to step 1(h)(i); and,

  i.   selecting (74) as said T wave that one of said step 1(h)(iii) polygons for which said rating is maximal.

2.   A method as defined in claim 1, further comprising, before said step 1(f), the further step of filtering (72) those portions of said electrocardiogram signal containing said first and second time intervals to remove noise.

3.   A method as defined in claim 1, wherein said previously detected QRS waves are respectively characterized by onset (QRSOn), offset (QRSOff) and peak (QRSPeak) values, said method further comprising detecting said onset, offset and peak values by:

  a.   deriving first and second derivative approximations (D1, D2) of said electrocardiogram signal;

  b.   deriving from said previously detected QRS waves a plurality of threshold values (D2Thresh, MinD2-

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Height, MinHeight, MinWidth) which collectively characterize acceptable bounds for said onset, offset and peak values;

c.   for each of said previously detected QRS waves, selecting candidate values for said onset, offset and peak values;

d.   comparing said candidate values to said threshold values to derive a measure of difference there-between;

e.   accepting said candidate values as said onset, offset and peak values respectively if said difference does not exceed a predefined minimum; and,

f.   if said difference exceeds said predefined mini-mum, increasing said respective threshold values and proceeding to said step 3(c).

4.   A method as defined in claim 1, wherein said steps 1(f)(ii) and 1(h)(ii) each further comprise:

a.   deriving said closed polygon area as that area bounded by all of said samples between and in-cluding said pair of samples, said polygon having a base line extending linearly a distance "d" between said pair of samples;

b.   deriving a maximum vertical displacement "h" between said base line and any portion of said polygon above said base line; and,

c.   comparing said maximum vertical displacement to a predefined minimum vertical displacement; and,

d.   if said maximum vertical displacement exceeds said predefined minimum vertical displacement then defining said rating = A*h/d for said pair of samples.

5.   A method as defined in claim 1, wherein:

a.   said narrowing step 1(d) further comprises:

i.   if said first time interval overlaps a time interval occupied by a previously detected T wave portion of said electrocardiogram

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signal preceding said first time interval,
reducing (71) said first time interval to
exclude said previously detected T wave
portion;

ii.   if said first time interval overlaps a time
interval occupied by a previously detected
QRS wave portion of said electrocardiogram
signal preceding said first time interval,
reducing (71) said first time interval to
exclude said previously detected QRS wave
portion; and,

b.   said narrowing step 1(e) further comprises:

i.   if said second time interval overlaps a time
interval occupied by a previously detected
QRS wave portion of said electrocardiogram
signal following said second time interval,
reducing (71) said second time interval to
exclude said previously detected QRS wave
portion.

6.   A method as defined in claim 1, wherein said previ-
ously detected QRS waves are detected by, for each
pair of samples within said respective first and
second time intervals:

a.   deriving first and second derivative approxima-
tions (D1, D2) of said electrocardiogram signal;

b.   comparing (47, 48) said second derivative approx-
imations and selecting as a first peak that one
of said samples for which said second derivative
approximation is greatest;

c.   proceeding to step 6(q) if said first peak second
derivative approximation does not exceed a prede-
fined minimum second derivative approximation
value;

d.   comparing (47, 48) said second derivative approx-
imations for said samples immediately preceding
said first peak and selecting as a second peak

that one of said preceding samples for which said second derivative approximation is greatest;

e. comparing (47, 48) said second derivative approximations for said samples immediately following said first peak and selecting as a third peak that one of said following samples for which said second derivative approximation is greatest;

f. proceeding (50) to step 6(q) if said second and third peaks are separated by a time duration which exceeds a predefined maximum onset-offset time duration;

g. proceeding (51) to step 6(q) if the difference between said first and second peak second derivative approximations does not exceed a predefined minimum peak separation value or if the difference between said first and third peak second derivative approximations does not exceed said predefined minimum peak separation value;

h. defining (52) a first threshold D1L as a function of said first derivative approximations for said samples between said first and second peaks;

i. defining (52) a second threshold D1R as a function of said first derivative approximations for said samples between said first and third peaks;

j. defining (52) a third threshold D2LR as a function of said second derivative approximations for said samples between said first and third peaks;

k. selecting (53) as a QRSOn value that one of said samples for which said first and second derivative approximations respectively do not exceed said D1L and D2LR thresholds;

l. selecting (53) as a QRSOff value that one of said samples for which said first and second derivative approximations respectively do not exceed said D1R and D2LR thresholds;

m. proceeding (54) to step 6(q) if said selected QRSOn and QRSOff values are separated by a time

duration which does not exceed a predefined QRS
time duration;

n. if said selected QRSOn and QRSOff values are
separated by a time duration which exceeds said
predefined QRS time duration then selecting (55)
said second peak as said QRSOn value and select-
ing said third peak as said QRSOff value;

o. proceeding (56) to step 6(q) if the average
values of:

i.   said samples between said first peak and
said QRSOn value;

ii. said samples between said first peak and
said QRSOff value;

do not exceed a predefined average value;

p. if said first peak is not separated from said
first peak of an immediately preceding, previous-
ly detected QRS wave then rejecting (59) that one
of said samples for which said second derivative
approximation is lowest; and,

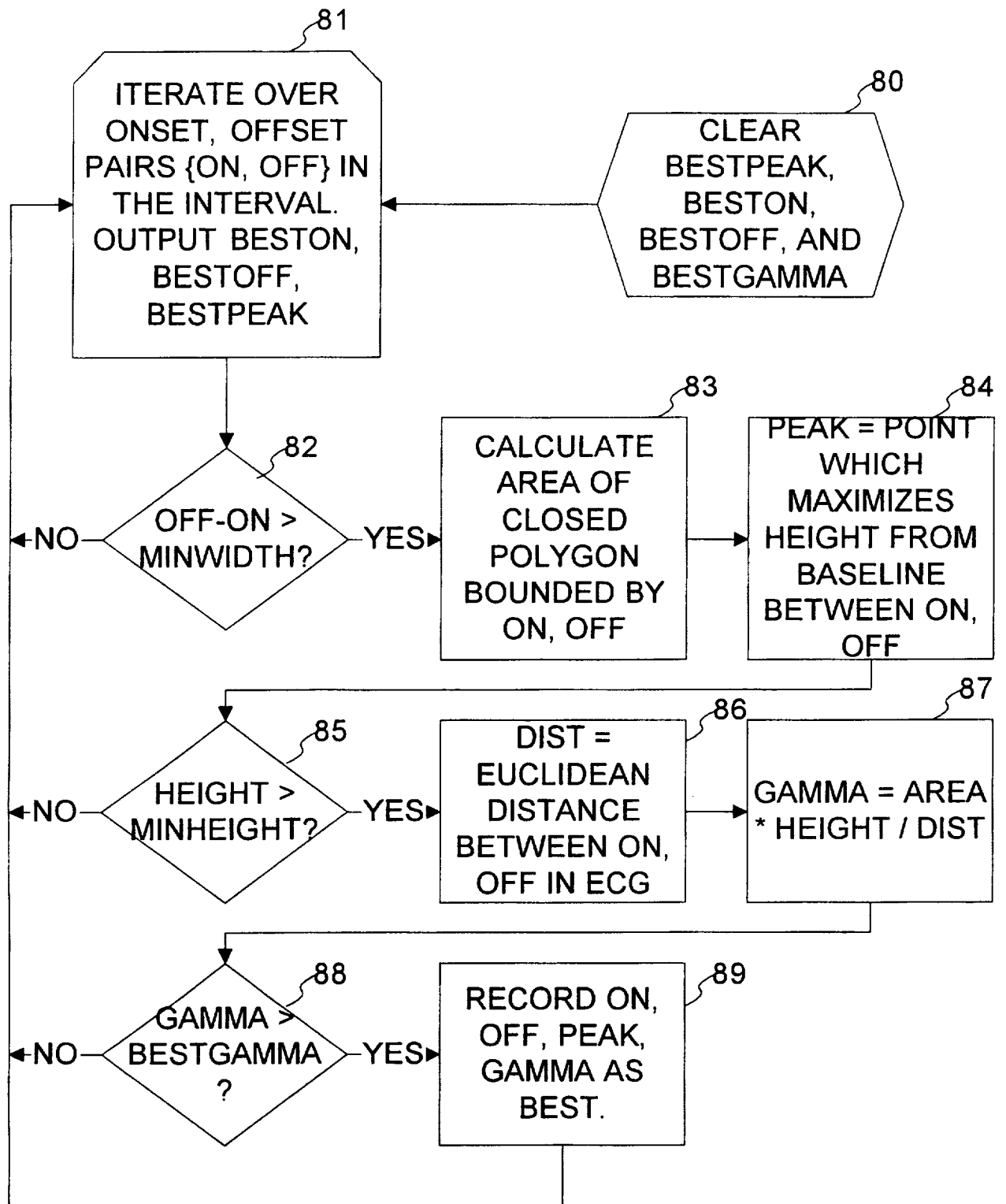q. selecting (41) a next pair of said samples and
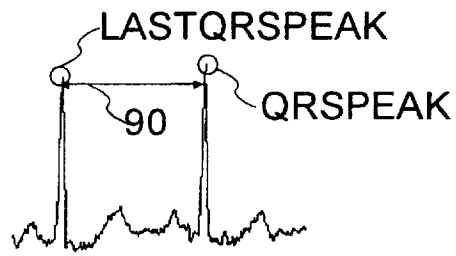repeating steps 6(a) through 6(p) until none of
said samples remain.

FIGURE 1
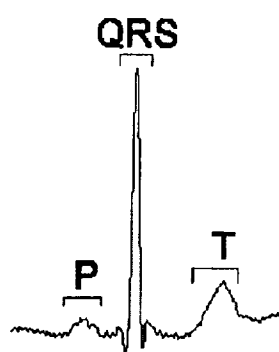
FIGURE 2

FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6A

FIGURE 6B

```
         ┌─70            ┌─71            ┌─72
┌──────────────┐  ┌──────────────┐  ┌──────────────┐
│   DEFINE     │  │   NARROW     │  │              │
│  INTERVAL    │  │ INTERVAL IF IT│  │  FILTER ECG  │
│ AROUND QRS   │  │ CONTAINS THE │  │  SAMPLES IN  │
│  WAVE AS:    │─▶│  PREVIOUS T  │─▶│ INTERVAL TO  │
│ [ON - MAXPR, │  │ WAVE OR THE  │  │REMOVE NOISE  │
│ OFF + MAXST] │  │ PREVIOUS OR  │  │              │
│              │  │  FOLLOWING   │  │              │
│              │  │   QRS WAVE   │  │              │
└──────────────┘  └──────────────┘  └──────────────┘
```

```
         ┌─73            ┌─74            ┌─75
┌──────────────┐  ┌──────────────┐  ┌──────────────┐
│  DETECT P    │  │  DETECT T    │  │              │
│ WAVE IN THE  │  │ WAVE IN THE  │  │              │
│ SUB-INTERVAL │  │ SUB-INTERVAL │  │  OUTPUT P,   │
│ BEFORE QRS   │─▶│ AFTER QRS    │─▶│ QRS, T IF ANY│
│ ONSET USING  │  │ OFFSET USING │  │   FOUND      │
│  MINPWIDTH   │  │  MINTWIDTH   │  │              │
│    AND       │  │    AND       │  │              │
│ MINPHEIGHT   │  │ MINTHEIGHT   │  │              │
└──────────────┘  └──────────────┘  └──────────────┘
```

FIGURE 7

ITERATE OVER
ONSET, OFFSET
PAIRS {ON, OFF} IN
THE INTERVAL.
OUTPUT BESTON,
BESTOFF,
BESTPEAK
`81`

CLEAR
BESTPEAK,
BESTON,
BESTOFF, AND
BESTGAMMA
`80`

OFF-ON >
MINWIDTH?
`82`

CALCULATE
AREA OF
CLOSED
POLYGON
BOUNDED BY
ON, OFF
`83`

PEAK = POINT
WHICH
MAXIMIZES
HEIGHT FROM
BASELINE
BETWEEN ON,
OFF
`84`

HEIGHT >
MINHEIGHT?
`85`

DIST =
EUCLIDEAN
DISTANCE
BETWEEN ON,
OFF IN ECG
`86`

GAMMA = AREA
* HEIGHT / DIST
`87`

GAMMA >
BESTGAMMA
?
`88`

RECORD ON,
OFF, PEAK,
GAMMA AS
BEST.
`89`

←NO

←NO

←NO

YES▶

YES▶

YES▶

FIGURE 8

FIGURE 9A

FIGURE 9B

FIGURE 9C

FIGURE 9D
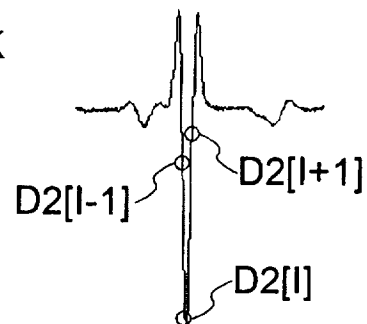
FIGURE 9E
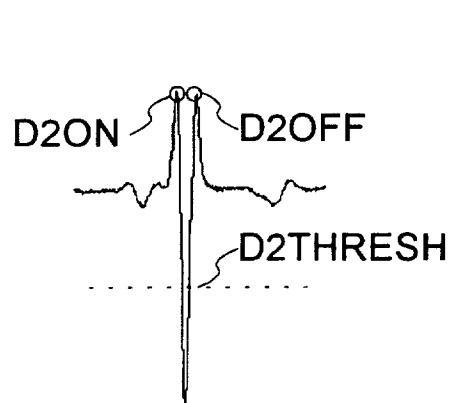
FIGURE 9F
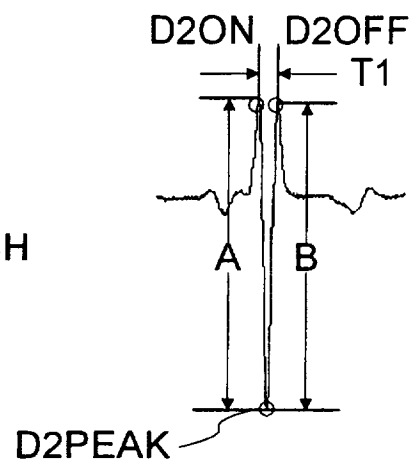
FIGURE 9G
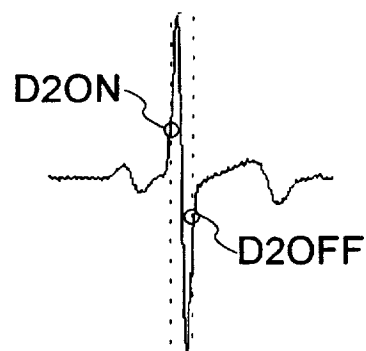
FIGURE 9H
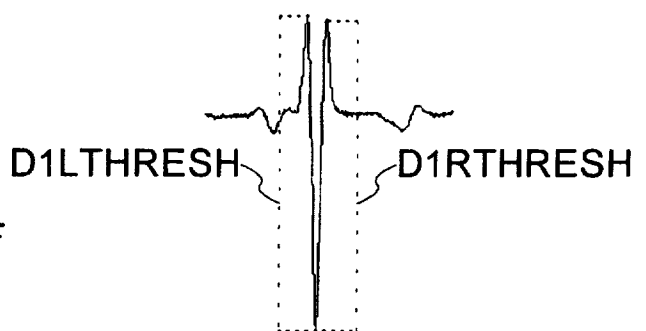
FIGURE 9I
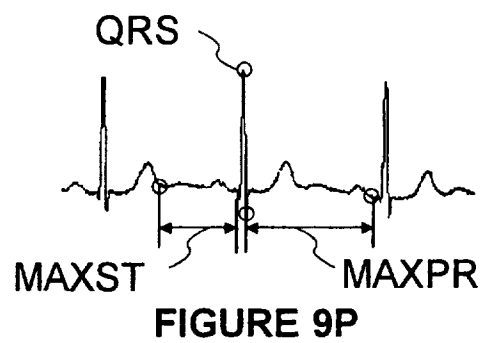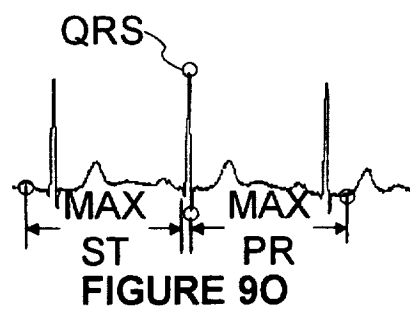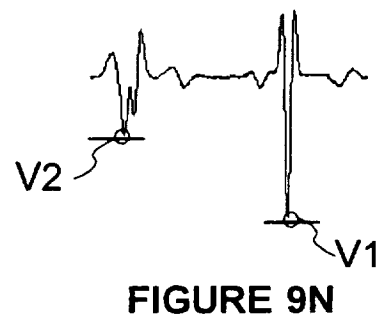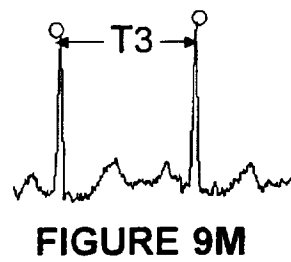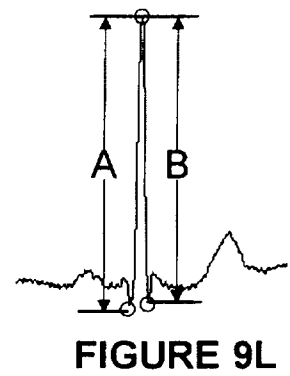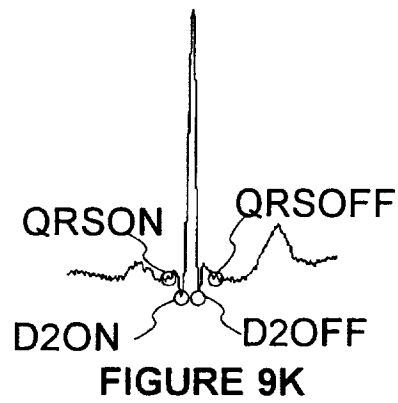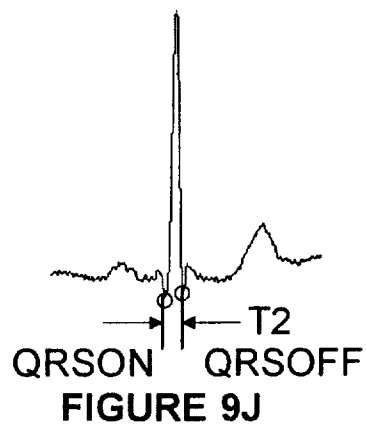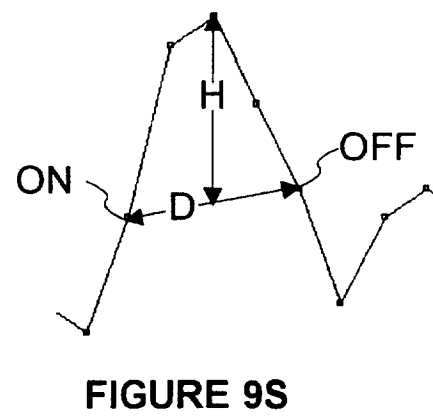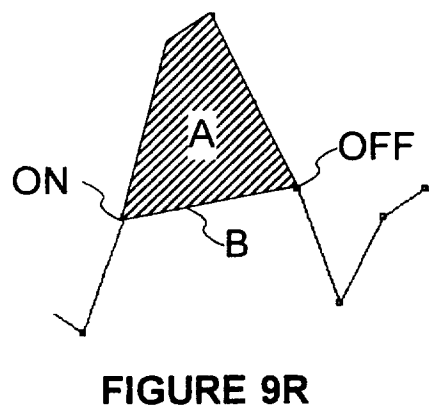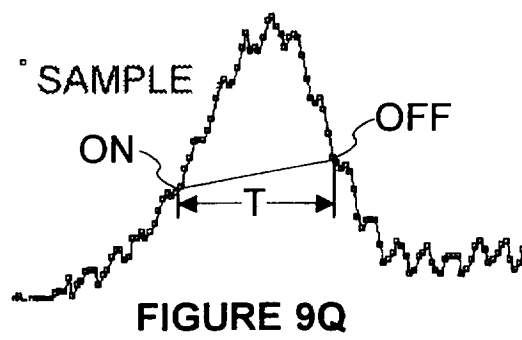
FIGURE 9J

FIGURE 9K

FIGURE 9L

FIGURE 9M

FIGURE 9N

FIGURE 9O

FIGURE 9P

FIGURE 9Q

FIGURE 9R

FIGURE 9S

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6   G06F19/00   A61B5/042

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6   G06F   A61B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	ANONYMOUS: "Selective Filter for Electrocardiograph" IBM TECHNICAL DISCLOSURE BULLETIN, vol. 29, no. 4, September 1986, NEW YORK, US, pages 1797-1798, XP002046705 see the whole document ---	1
A	HEE-KYO JOENG ET AL: "A NEW ALGORITHM FOR P-WAVE DETECTION IN THE ECG SIGNAL" IMAGES OF THE TWENTY FIRST CENTURY, SEATTLE, NOV. 9 - 12, 1989, vol. 11 PART 1/06, 9 November 1989, YONGMIN KIM;SPELMAN F A, page 42/43 XP000129189 see the whole document ---	1

-/--

[X] Further documents are listed in the continuation of box C.   [X] Patent family members are listed in annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
13 November 1997	27. 11. 97

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Deane, E

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category°	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 3 832 994 A (BICHER H ET AL) 3 September 1974 see column 13, line 18 - column 15, line 22; figure 6 ---	1
A	FOKAPU O ET AL: "A NEW APPROACH FOR P WAVE DETECTION USING ANALYTIC SIGNAL" VISUALIZATION, IMAGING, SIGNAL PROCESSING, MODELING, NEURAL NETWORK, SAN DIEGO, OCT. 28 - 31, 1993, vol. 15 PART 1, 28 October 1993, SZETO A;RANGARAJ M RANGAYYAN, page 400/401 XP000436800 see the whole document ---	1
A	FREEMAN K ET AL: "P WAVE DETECTION OF AMBULATORY ECG" PROCEEDINGS OF THE ANNUAL INTERNATIONAL CONFERENCE OF THE ENGINEERI IN MEDICINE AND BIOLOGY SOCIETY, ORLANDO, OCT. 31 - NOV. 3, 1991, vol. 13, 31 October 1991, NAGEL J;SMITH W M, pages 647-648, XP000348272 see the whole document ---	1
A	LAGUNA P. ET AL.: "Automatic Detection of Wave Boundaries in Multilead ECG Signals: Validation with the CSE Database" COMPUTERS AND BIOMEDICAL RESEARCH, vol. 27, 1994, pages 45-30, XP002046491 cited in the application see page 49, line 23 - page 51, line 13 -----	1

2

INTERNATIONAL SEARCH REPORT

Information on patent family members

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 3832994 A	03-09-74	NONE	