Respiratory Signal Derived from Eight-lead ECG

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Abstract

Several techniques are actually used for respiratory monitoring (spirometers, nasal thermocouples, transthoracic inductance, impedence plethysmography, strain gauge). Each of these techniques require a special device. The method here proposed derives the EDR values (ECG-Derived-Respiratory signal) from ordinary ECGs. Eight ECG leads are utilized. The method is based on the verified hypothesis that the breath-representative "points" are disposed around the preferred direction in a 8-D space. Once the "respiratory direction" is located, the method produces the EDR values. The respiratory waveform is obtained through an interpolation of such values.

The method has been tested on 10 voluntary subjects in different conditions (deep breath, short breath, held breath to simulate apnea). The EDR trace obtained has been compared with a reference signal acquired from strain gauge measurement of thoracic circumference.

This technique is applicable to any type of automated ECG analysis, in real-time and without the need for additional transducers or hardware.

1. Introduction

The knowledge of respiratory waveforms associated to the ECG can be useful above all when the clinical significance of certain cardiac arrhythmias can be understood only with reference to respiration.

The recording techniques are available for the monitoring of numerous physiological variables. The ones tied to the respiration are multiple, the choice is tied to the type of pathology given to study and to the aim of the study. Devices such as spirometers and nasal thermocouples measure air flow into and out of the lungs directly, carrying out careful measures but they interfere with respiration. The breathing can also be monitored indirectly by measures of the variation of body volume. At this aim, the transthoracic inductance and inpedance plethysmographs, whole-body plethysmographs, strain gauge measurement of thoracic circumference and pneumatic respiration transducers are utilized. All these methods require dedicated devices.

The method here proposed derives respiratory waveform from ordinary ECGs permitting reliable detection of respiratory efforts. It's a technique of signal processing, it doesn't require any devices besides the electrodes utilized to acquire the ECG. This method is particularly useful in situation where the ECG is the only available information source (like a Holter recording).

2. The breathing influence on the cardiac electrical vector

ECGs recorded from the surface of the chest are influenced by the motion of electrodes with respect to the heart and by changes in the impedence of the thoracic cavity. The expansion and contraction of the chest which accompanies respiration results in motion of chest electrodes with respect to the heart. During inspiration, the apex of the heart is stretched towards the abdomen because of the filling of the lungs, helped by the shifting down of the diaphragm. During expiration the elevation of the diaphragm which helps the emptying of the lungs compresses the apex of the heart toward breast.

These anatomical influences of respiration result in amplitude variation in the ECG signal. The respiration induces a modulation of cardiac electrical axis. Therefore, the respiration changes the angle that the electrical cardiac vector makes with the reference line. These changes produce the amplitude modulation of the ECG signal. The modulation of QRS amplitude is particularly significant.

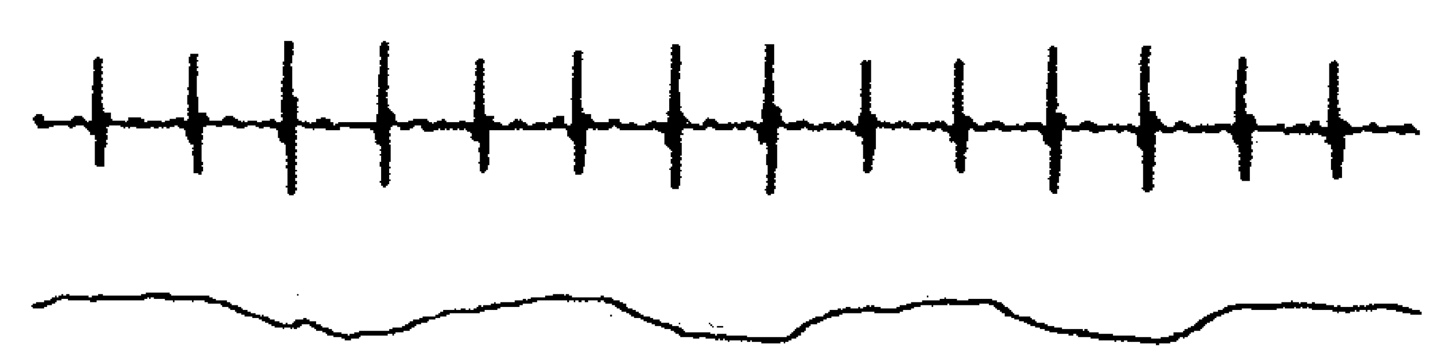

Figure 1. Upper trace: ECG; lower trace: respiration measured by pneumatic respiration transducer (PRT).

3. The method

Eight leads are utilized: I, II, V1, V2, V3, V4, V5, V6. This method is based on the verified hypothesis that the breath-representative "points" are arranged around the preferred direction in 8-D space. Once this main direction, called "respiratory direction", is located, the method produces the EDR (ECG-derived- respiratory-signal) values. The respiratory waveform is obtained through an interpolation of such values.

There is a learning stage. The first 16 heart beats are elaborated. The area of each QRS complex in each of the eight leads is measured over a fixed window. The width of the window is determined during the learning phase of ECG analysis program (by acquisition board). The QRS area, so calculated, is proportional to QRS amplitude. The baseline is calculated as the average of the eight samples (250 samples/s) that precede the QRS and it is subtracted for QRS area in order to reduce the phenomenon know as "baseline wandering".

Every beat is represented by a vector of eight elements, one element for every lead.

The center of gravity is calculated for every lead:

for i=1,...8; $G_{X_i}=\frac{1}{16}\sum_{h=1}^{16}Xi_h$

so $G=(G_{x1},...,G_{x8})$

At this point we change the coordinates:

$$\begin{cases} y_1 = x_1 - G_{X_1} \\ \dots \\ y_8 = x_8 - G_{X_8} \end{cases}$$

In order to produce the "respiratory direction", we consider the inertia hyper-ellipsoid relative at 16 vectors obtained. This is the correspondent equation:

$$A_{11}y_1^2+...+A_{88}y_8^2+2A_{12}y_1y_2+...+2A_{78}y_7y_8 =$$

$$A_{11}=\sum_{s=1}^{16}(y_{s,2}^2+...+y_{s,8}^2)$$

$$\dots$$

$$\dots$$

$$A_{88}=\sum_{s=1}^{16}(y_{s,1}^2+...+y_{s,7}^2)$$

A_{ij} are the elements of the inertia matrix:

for i≠j $A_{ij}=-\sum_{s=1}^{16}(y_{s,i}y_{s,j})$

The solution of the following system:

$$|Aij-\lambda I|=0$$

produces the eigenvalues of the inertia matrix.

The matrix is symmetric and is defined positive; therefore, all eigenvalues are positive.

During all tests the eigenvalues calculated have unitary multiplicity. The length of main semi-axis is associated with the smaller eigenvalue $(\bar{\lambda})$. The corresponding eigenvector locates the main direction.

The solution of following system:

$$(A_{ij}-\bar{\lambda}I)\begin{pmatrix} X_1 \\ \vdots \\ X_8 \end{pmatrix}=\begin{pmatrix} 0 \\ \vdots \\ 0 \end{pmatrix}$$

produces infinity eigenvectors.

Among these eigenvectors we choose a normalized one: $\bar{v}=(l_1,...,l_8)$.

The main direction is located by the straight line r:

$$\frac{x_1-G_{X_1}}{l_1}=...=\frac{x_8-G_{X_8}}{l_8}$$

The main direction of hyper-ellipsoid coincides to the "respiratory direction". This direction will be the reference for all the next calculations.

When the learning stage is finished every heart-beat produces an EDR value useful for the construction of the respiratory wave.

For every lead of the new heart-beat we calculate the area of the QRS complex. We obtain a vector of 8 elements, every element represents the QRS complex area of the corresponding lead:

$$\bar{B}=(\bar{X}_1,...,\bar{X}_8)$$

The free vector is:

$$\overline{GB}=(\bar{X}_1-G_{x_1},...,\bar{X}_8-G_{x_8})$$

The length with sign of the vector projection (Figure 2) on the main direction (r) is the EDR value:

$$EDR\_value=l_1(\bar{x}_1-G_{x_1})+...+l_8(\bar{x}_8-G_{x_8})$$

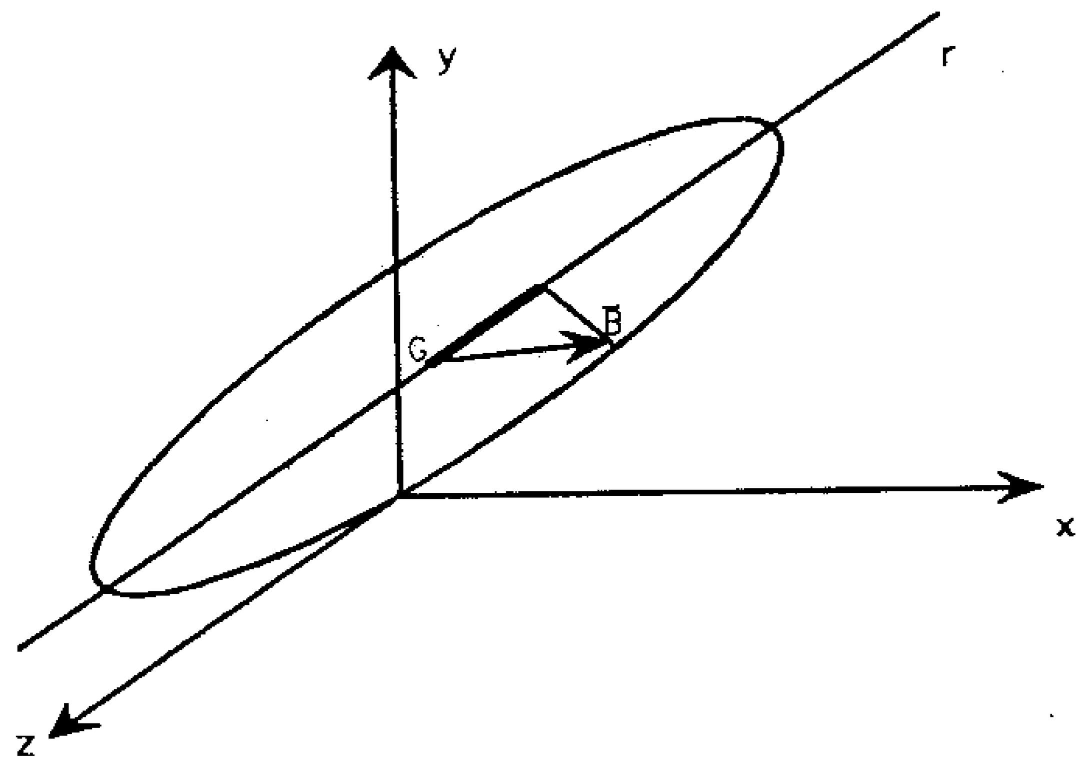

Figure 2. The vector projection on the main direction in 3-D space.

The respiratory waveform is obtained through an interpolation of such values.

The following diagram (Figure 3) schematizes the described method.

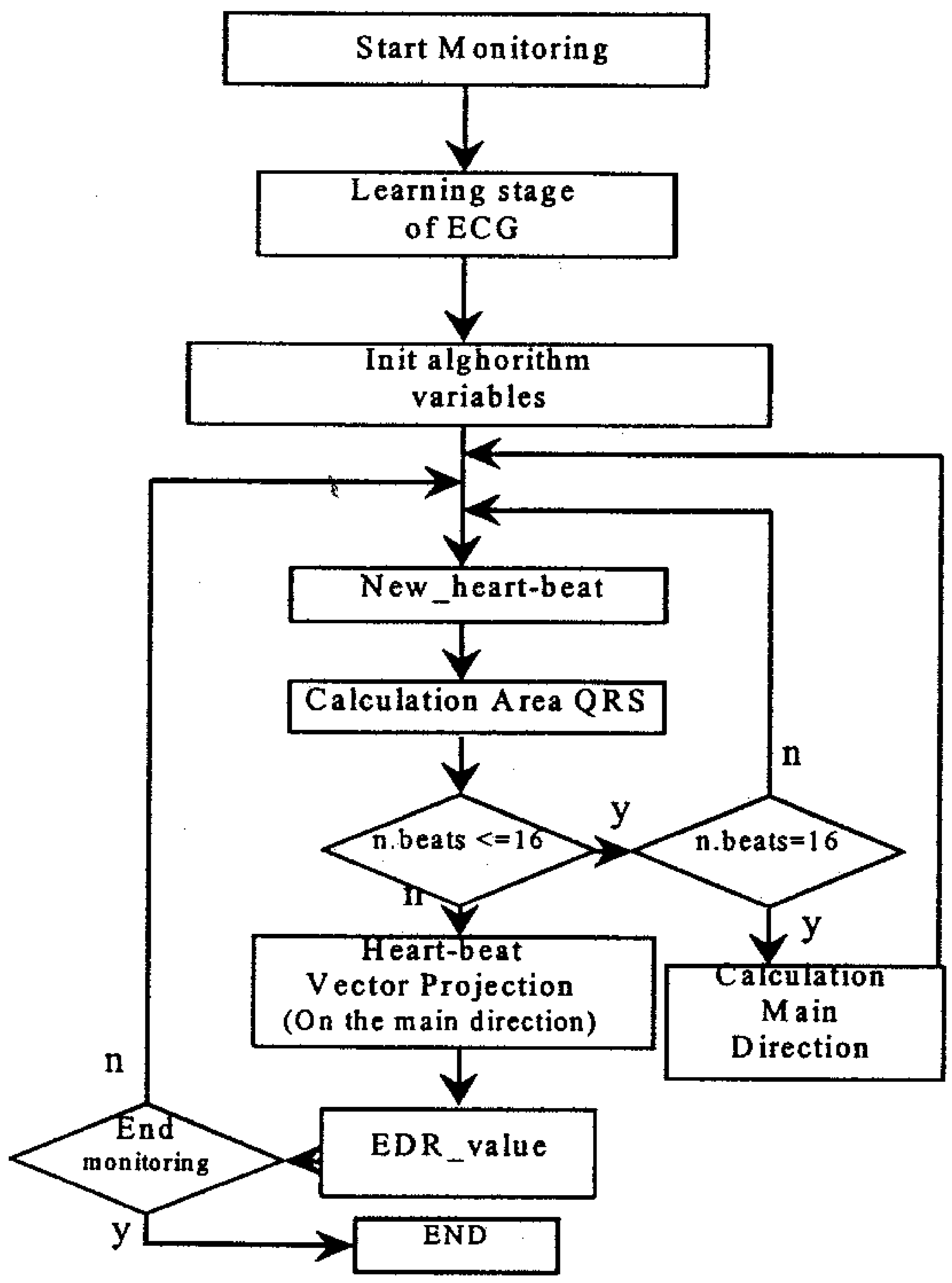

Figure 3. The diagram of the method.

4. Test of method

The method has been tested on 10 voluntary subjects in different conditions. At the subject, besides the electrodes a strain gauge measurement of thoracic circumference is applied, in order to obtain the respiratory reference signal to compare with the EDR trace.

The examined subjects breathed normally before, modified their breath alternating deep and light breaths and fast breaths. To test the method it was also necessary to simulate apneas. There were two different apneas. We asked subjects to execute a deep inspiration and subsequently to withhold the breath. This type of apnea was called APNEA I. The apnea preceded by a complete expiration was called APNEA E.

During each test the characteristics (age, height, weight and HR) of the subject are noted down.

5. Results

The following figures represent the respiratory dynamic of some subjects. In Figure 4 and Figure 5 the upper trace reports the ECG signal, the middle trace the EDR waveform and the lower trace the measured waveform. It's clear how each heart-beat corresponds an EDR value. We obtain the EDR waveform interpolating the EDR values. In the other figures, the upper is the EDR waveform and the lower is the "reference waveform". All the results here presented are part of studies done on different subjects.

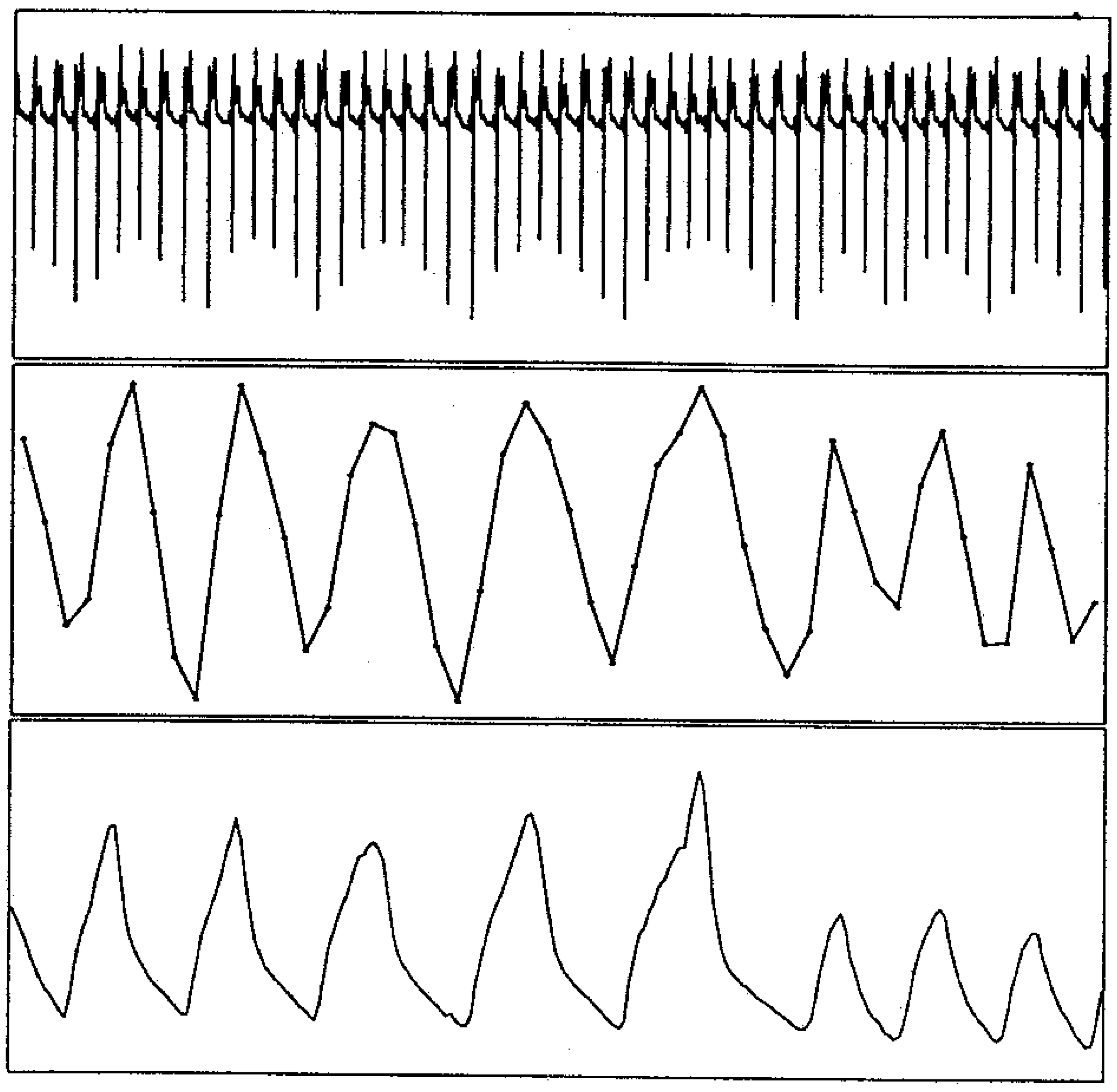

Figure 4. The first waves represent deep breaths and the other, regular breaths. Duration: 56 seconds.

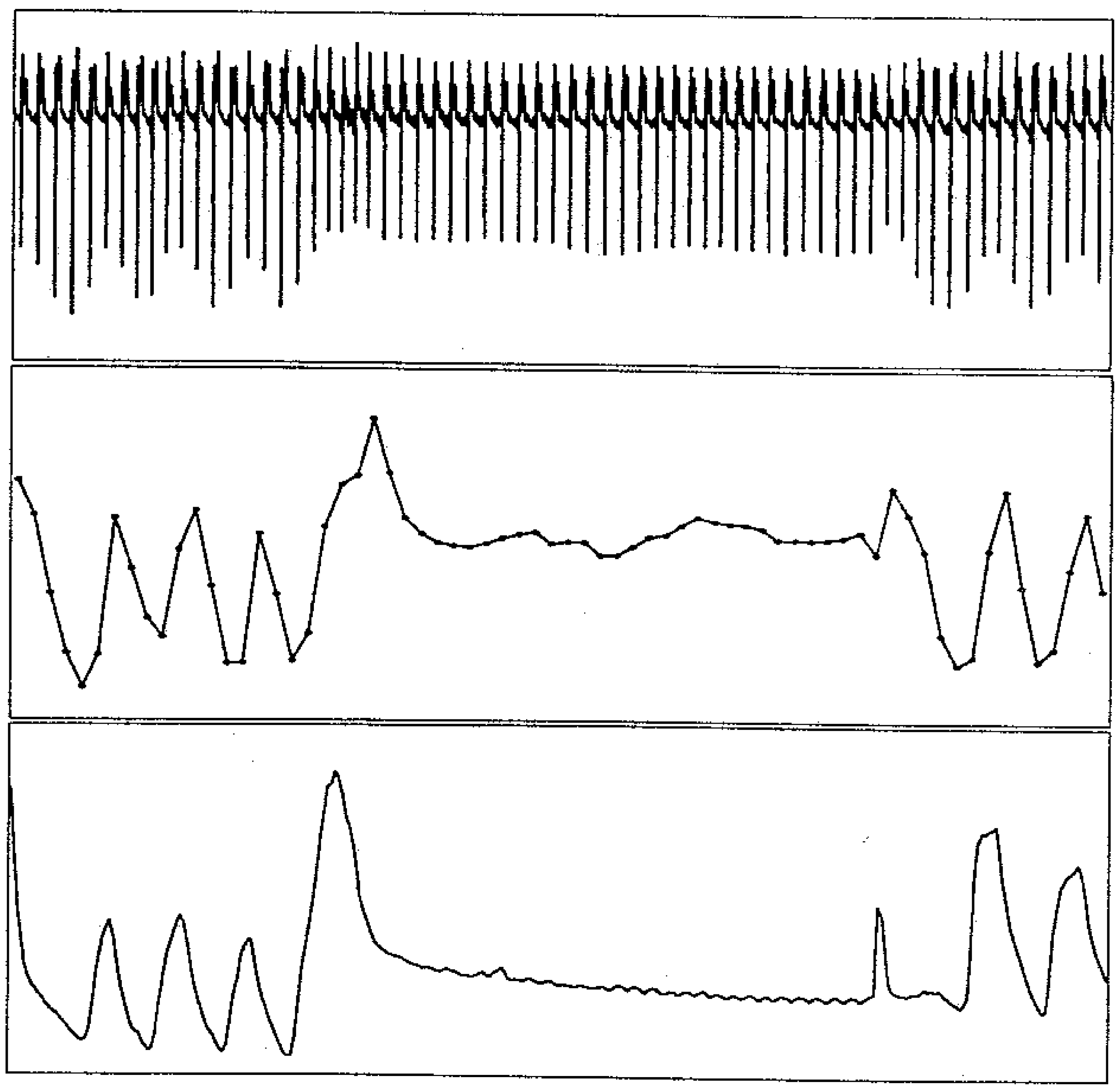

Figure 5. After some regular breaths, the subject executed a deep inspiration and held the breath. The apnea duration is 32 seconds. Duration: 77 seconds.

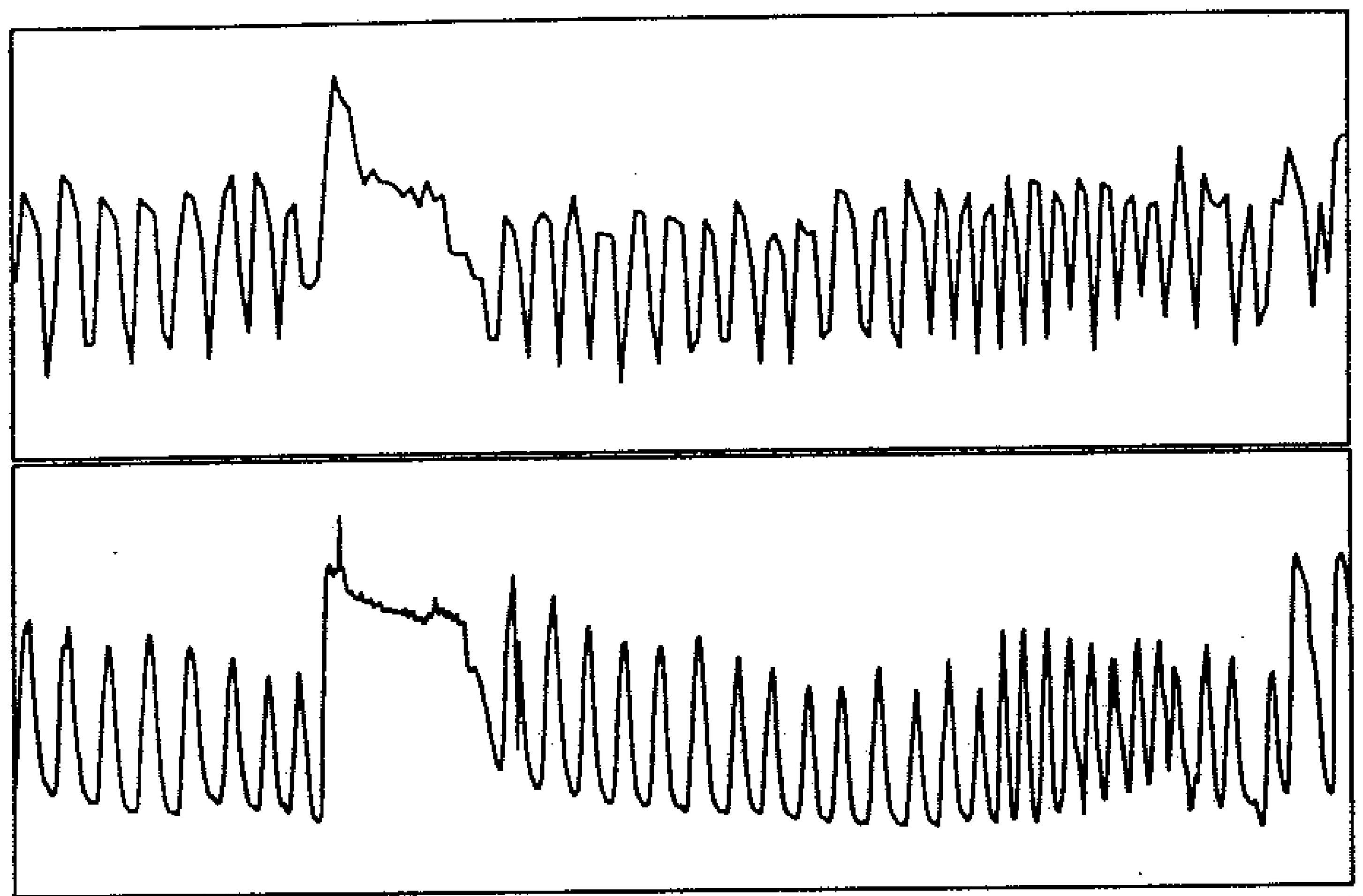

Figure 6. The upper is the EDR waveform; the lower is the respiration reference waveform. The apnea is preceded by deep breaths. After apnea, regular breaths are followed by fast breaths. Duration: 137 seconds.

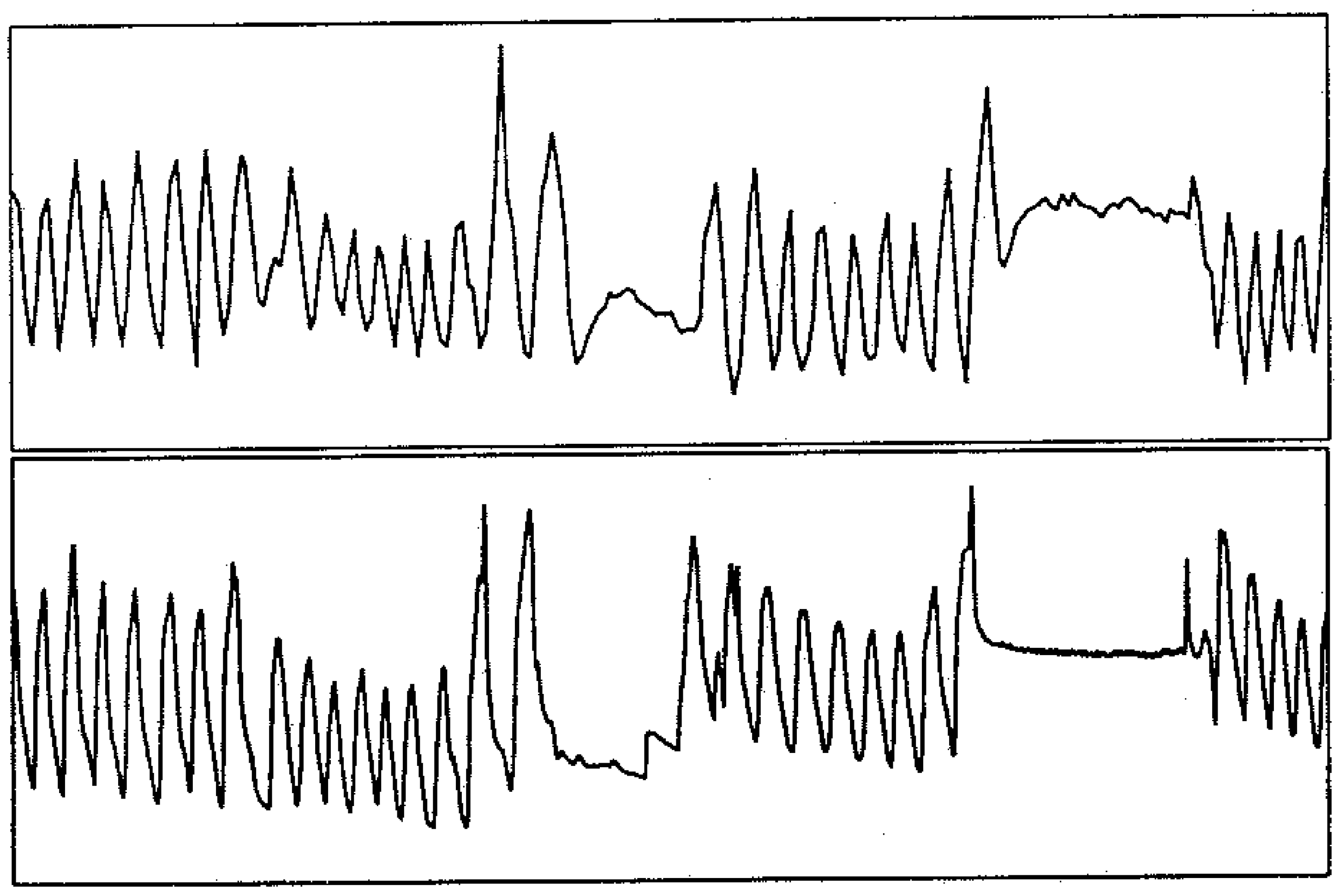

Figure 7. The upper is the EDR waveform; the lower is the respiration reference waveform. The first waves represent breaths done moderately slow. It's possible to distinguish two different apneas. The first (20s) is preceded by total expiration and the second (33s) is preceded by a deep inspiration.
Duration: 200 seconds.

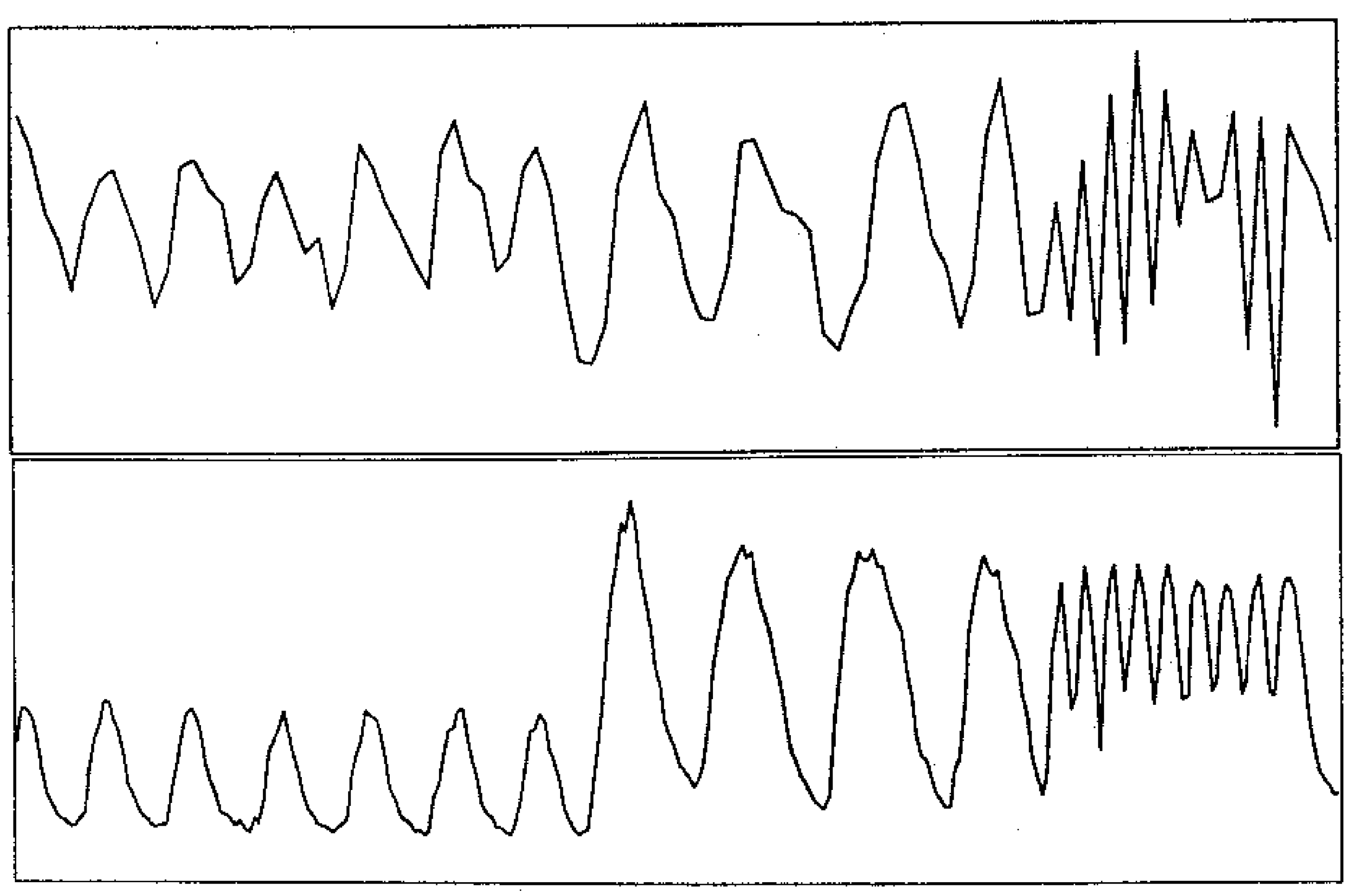

Figure 8. The upper is the EDR waveform; the lower is the respiration reference waveform. Some regular breaths are followed by some deep and slow breaths. The last waves represent fast breaths.
Duration: 56 seconds

6. Conclusions

The results obtained have shown to be strongly correlated with conventional measurements of respiration.

The frequency of respiratory efforts may be measured easily and accurately from EDR signal obtained by the method presented. Respiratory disturbance which are reflected in changes of respiration frequency are clearly revealed in the EDR wave. It is possible also to distinguish the different respiratory efforts.

The technique is applicable to any type of automated and multilead ECG analysis. It can be incorporated into real-time arrhythmia monitors as well as Holter scanning systems without the need for additional transducers or hardware. The method is characterized by high flexibility and does not depend on the lead system or number. The use of eight leads reduces only the present noise.

The advantages of this method are to utilize the existing hardware to obtain additional information without the need for additional devices. This method is particularly useful in situation where the ECG is the only available information source (like a Holter recording).

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