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Fuzzy Logic Applied to Apnoea Monitoring in Infants

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Abstract: - A unit has been designed which monitors newborn infants at risk of Sudden Infant Death Syndrome (SIDS) in a home environment. The unit monitors respiration, electrocardiogram (ECG) and haemoglobin oxygen saturation (SpO_2), using an intelligent fuzzy logic algorithm to process the signals in order to detect any potentially life threatening event at an early stage. Provision is made for the generation of both audible and silent alarms and for the storage of signals and other information before, during and after an alarm episode for diagnostic purposes.

Key-Words: - Fuzzy Logic, Apnoea, SIDS, Home Monitoring.

1 Introduction

The past few decades have seen major advances in the field of medicine. Despite these advances, a number of fatal conditions remain largely a mystery to the medical profession. One such condition is that of sudden and unexplained death among newborn and young infants, generally known as "cot-death" and referred to clinically as Sudden Infant Death Syndrome or SIDS[1-2].

In an attempt to prevent deaths in such circumstances, and faced with the absence of an effective alternative, many clinicians have resorted to using home monitoring techniques on infants thought to be at risk. The SIDS monitors currently available, however, have a number of serious drawbacks, namely: their inability to reliably detect life-threatening events; their high rate of false alarms; the lack of information they provide to determine the cause of alarms; and the lack of flexibility for setting individual alarm limits [3-7].

The authors have developed an apnoea monitor for use with newborn infants which overcomes these drawbacks. It measures ECG and heart-rate in a standard manner and respiration by means of impedance plethysmography. Oxygen saturation is monitored through the integration of a commercially available pulse oximeter module. A fuzzy logic algorithm is employed to process the information obtained from these signals in order to provide reliable indication of life threatening events. In the event of an alarm condition, all of the data in a period preceding and following the event are stored for subsequent retrieval and analysis by the physician. Finally, the monitor has a user-friendly, menu-based interface that allows two-level interaction with the user, one level for simple set-up by the home carer and a second for analytical or diagnostic use by clinical personnel.

2 Monitor Design

A block diagram of the monitor designed by the authors is shown in Fig. 1. The heart of the system is the SAB80C535 microcontroller (Siemens Ltd.), which belongs to the Intel 8051 family and has 64kbytes of accompanying EPROM as programme memory and 64kbytes of static RAM for operating data storage. The microcontroller has a multiplexed, 8-channel, 8-bit, on-chip, analogue-to-digital converter and an on-chip multi-digit liquid crystal display (LCD) driver. It interfaces with the user-control keypad, the front panel LCD, the alarm buzzers and LEDs, a real-time clock chip, a multimedia flash memory card for signal and alarm information storage and an RS232 serial port for communication with a PC. The microcontroller platform monitors all sensor inputs, controls all operations, responds to user inputs, runs the fuzzy logic algorithm, generates the alarms and stores the resulting information required.

2.1 System Management

Table 1 gives a list of the life-threatening alarm conditions that the monitor detects. An audible alarm is generated when any of the conditions listed occurs. Provision is also made for a silent alarm feature, which allows separate limits to be specified that provoke events to be stored without actually generating an acoustic alarm. This feature provides the physician with useful information without giving rise to excessive acoustic alarms in operation. Under normal circumstances, an alarm will be reset automatically when the alarm condition no longer exists, e.g. when the child starts to breathe again or the heart rate returns to within the allowed limits. To avoid the possibility that the system keeps resetting the alarm itself even though the child may still be in the alarm state, a safety feature is incorporated which

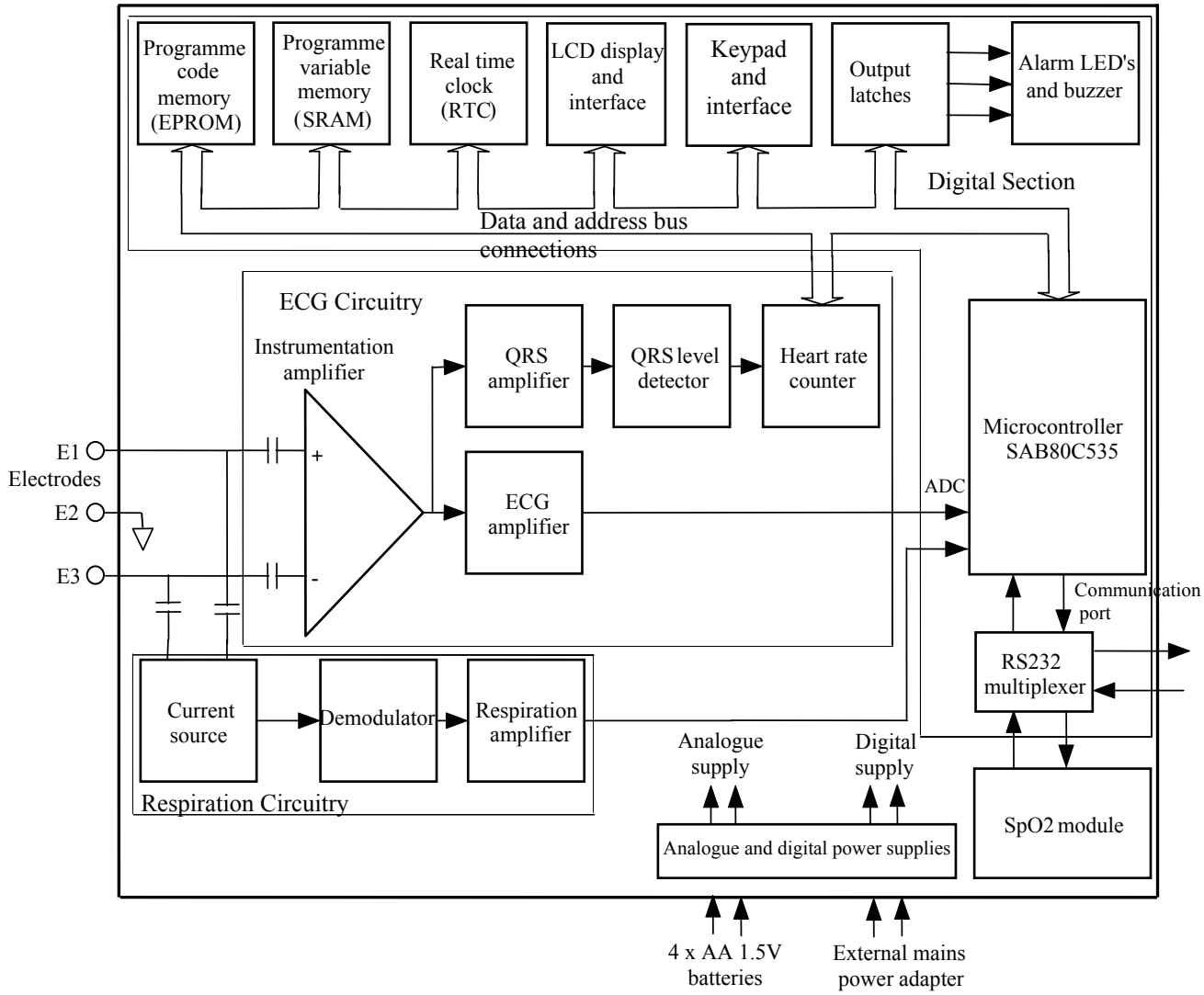

Fig. 1 Block diagram of the SIDS monitor

ensures that if two alarms occur within a period of one minute, then the alarm can only be reset manually by the operator.

Table 1 Acoustic alarm criteria

Alarm	Criteria
Apnoea	no respiration signal for period: 8-30s, step 2s
Tachycardia	heart rate above limit: 100-260, step 5bpm
Bradycardia	heart rate below limit: 40-140, step 5bpm
Asystole	no ECG signal for period: 8-30s ,step 2s
HR Change	Sudden change in HR: 5-100%, step 5%
SpO_2 High	O_2 saturation above limit: 95-100%, step1%
SpO_2 Low	O_2 saturation below limit: 50-95%, step 1%
Safety alarm	2 alarms within 1 minute (manual reset)
Sensor	loose or dislodged electrode

The monitor incorporates 8Mbytes of flash memory to store the respiration and ECG signals, the heart rate, the oxygen saturation level, the plethysmogramme signal and the transthoracic impedance for up to 8 hours in continuous mode. When not in continuous mode, the monitor can store up to 200 alarm episodes. Each episode includes all of these signals for a preset period leading up to the alarm, during the alarm phase itself and for a preset period after the alarm event. A compliance log stores the time and the date when the monitor is switched on or off along with the monitor settings. The physician can download this information through the RS232 interface to gain access to the stored records and to check that the monitor is being utilised correctly.

2.2 ECG and Heart Rate Monitoring

The ECG section of the monitor as shown in Fig. 1 has two distinct channels. The electrodes are connected through a protection network to the input differential stage. The top channel has a 3dB bandwidth of 0.07-40Hz and a fixed gain of 60dB and feeds, via a level shifting stage, into one of the analogue-to-digital converter channels of the microcontroller, where it is sampled at a rate of 128Hz. This provides an ECG signal of sufficient fidelity for a physician to obtain diagnostic value from recordings stored during alarm episodes. The

lower channel has a much narrower 3dB bandwidth of 10-30Hz for the purpose of determining the heart rate. In this case only the QRS complex of the ECG signal is of interest, and the narrower bandwidth significantly reduces movement components and muscle artefact. A 50Hz notch filter is also included to suppress mains interference. After filtering, the signal is applied to a variable gain stage, so that an electrode signal level ranging from 200μV-8mV can be accommodated. The output of this stage is in turn applied to a trigger level detection circuit, which provides a logic level output pulse for each QRS complex occurring in the ECG. This logic signal is fed to one of the 16-bit counters in the microcontroller so that the R-R interval can be measured and used to determine the heart rate, which lies within the range 40 – 300 beats per minute.

2.3 Respiration Monitoring

The respiration monitoring unit uses the same electrodes as are used to record the ECG signal and is connected in parallel via a transformer. An r.f. oscillator operating at a frequency of 38.5kHz feeds the transformer from a high impedance source so that the current injected at the electrodes is essentially constant. This r.f. signal does not interfere with the ECG unit as it is suppressed by its matching network and is well outside the ECG signal bandwidth. Respiration is then measured by way of the changes in trans-thoracic impedance of the infant, which are reflected back to the primary side of the transformer and can be detected by monitoring the signal here. This appears as an r.f. sinusoidal signal, amplitude modulated at the respiration rate of the infant, which is between 10 and 100 breaths per minute. The signal is envelope demodulated, amplified by 80dB and filtered in a 3rd-order bandpass filter with a 3dB bandwidth of 0.2 - 2Hz, to give a signal representing respiration. The dc component is removed but is used to determine the quality of electrode contact and will indicate when an electrode has become loose. The respiration signal is then sampled in a second channel of the analogue-to-digital converter of the microcontroller at a rate of 128Hz.

2.4 Oxygen Saturation Monitoring

Haemoglobin oxygen saturation is measured by a commercial pulse oximeter, the MS-5 module (Masimo Inc.) which is fully incorporated into the main monitor. This module determines oxygen saturation non-invasively by passing red light of wavelength 660nm and infrared light of 905nm through a capillary bed and measuring relative changes in light absorption at the two wavelengths during the cardiac cycle. Healthy humans have an arterial oxygen saturation of between 94% and 98%. The module outputs a value once every second via an RS232 serial link to the microcontroller.

3. The Fuzzy Logic Algorithm

During the course of monitoring the parameters namely; respiration, ECG, heart rate and SpO_2, apnoea is considered present based on the following five criteria:

(i) if the amplitude of the respiration signal suddenly drops to near the baseline,
(ii) if the amplitude of the respiration signal is constant at the occurrence of each QRS complex in the ECG signal,
(iii) if the frequency of the respiration signal is approximately equal to the heart rate,
(iv) if there is a sudden change in the heart rate i.e. bradycardia or tachycardia,
(v) if there is a sudden drop in the oxygen saturation value i.e. desaturation.

The first criterion is based on the fact that cessation of breathing will ideally cause the respiration curve to drop to zero. However, in the event of apnoea, there is often a residual component of cardiogenic artefact present in the respiration signal due to transthoracic impedance changes caused by the heart beat. The second criterion is used to detect this condition. When the respiration signal is present, its amplitude at the instant a QRS complex occurs in the ECG varies from beat to beat. Once respiration ceases, the amplitudes of the cardiogenic artefacts become constant. The third criterion also helps to detect these cardiogenic artefact components. If the frequency of the respiration signal suddenly becomes equal to the heart rate, then this is a strong indication that the respiration signal is in fact simply the cardiogenic artefact and not a true indication of respiration. Finally the fourth and fifth criteria stem from the fact that central apnoea is often accompanied by a sudden change in the heart rate and/or a drop in the oxygen saturation value.

The task of the fuzzy logic algorithm is to monitor all measured parameters, as well as the user inputs such as delay times and variable limits and to generate both audible and silent alarms and store recordings of the required signals when necessary. To this end, decisions as to the status of each parameter have to be made, e.g. whether the respiration amplitude is considered low or not, and an assessment of the risk of apnoea being present made based on these decisions.

An extended set of variables was established from the measured parameters and fuzzy sets were then constructed based on the ranges of values of these variables as shown in Fig. 2. These functions are stored as arrays in the form of look-up tables in the microcontroller memory. Signals were level-shifted and variables scaled as required so that values would occupy the 8-bit integer range of 0 – 255 used by the microcontroller, e.g. membership values were coded as integers between 0 and 100.

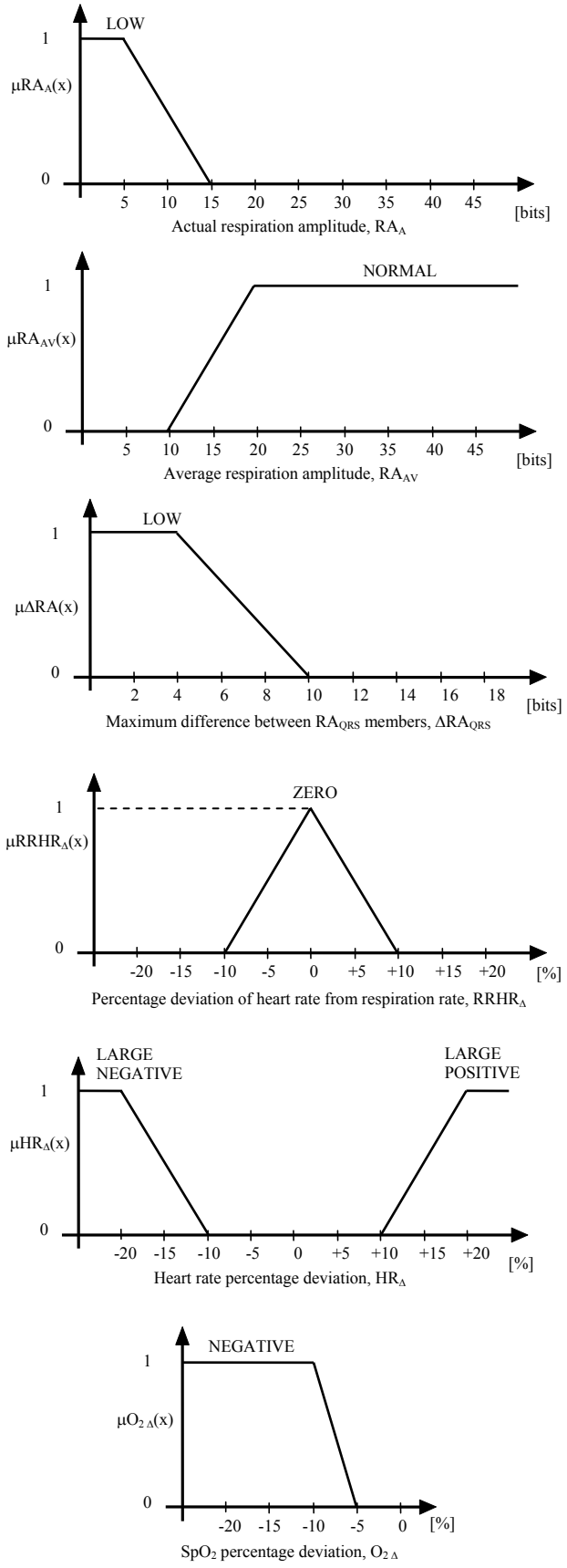

Fig. 2 Fuzzy sets for the fuzzy logic algorithm

Fuzzy modelling is based on evaluating the truth of a set of propositions concerning the input variables. Each proposition will have a degree of truth based on the membership value defined by the fuzzy set for the particular values of its input variables. The set of propositions used in the algorithm is given below in Table 2.

Table 2 Fuzzy algorithm propositions

Rule	Proposition
Rule 1	IF actual respiration amplitude RA_A is LOW AND average amplitude RA_{AV} is NORMAL THEN apnoea probability is HIGH
Rule 2	IF deviation between values of ΔRA_{QRS} is LOW THEN apnoea probability is HIGH
Rule 3	IF deviation of $RRHR_\Delta$ is ZERO THEN apnoea probability is HIGH
Rule 4	IF heart rate deviation HR_Δ is LARGE NEGATIVE THEN apnoea probability is HIGH
Rule 5	IF heart rate deviation HR_Δ is LARGE POSITIVE THEN apnoea probability is HIGH
Rule 6	IF oxygen saturation deviation $O_{2\Delta}$ is NEGATIVE THEN apnoea probability is HIGH

Rule 1 detects a sudden drop in the amplitude of the respiration signal by comparing the actual value RA_A with the average value RA_{AV}. Rule 2 checks the difference between the respiration amplitudes measured at each QRS complex. The lower the spread in these values, the higher the probability that an apnoea phase is present. Rule 3 determines to what degree the respiration rate is equal to the heart rate. If the difference between them is small, then the probability of a central apnoea phase with strong cardiogenic artefacts superimposed being present is increased. Rule 4 is used to detect a sudden drop in the heart rate compared to the moving average. A drop of 15% or more is another indication of an apnoea phase. Rule 5, on the other hand, detects any sudden increase in the heart rate. Finally, rule 6 detects any sudden drop in the oxygen saturation level. Oxygen saturation is generally constant at between 96% and 98%. A value of less than 90% is considered critically low. Thus, even a drop of 5% or more is an indication that something is astray.

The truth values associated with all of the propositions are then combined to give an output fuzzy set, the process known as output composition. The method of composition used in the authors' algorithm is the 'fuzzy additive' method [8, 9]. This method sums the truth values determined for each proposition across the range of input values, with the maximum resulting value limited to unity. Once this is accomplished, the output fuzzy region must be defuzzified or decomposed to find a single value of output 'truth'. This is done using the 'centre of gravity' technique [8, 9] and involves finding the centroid of the composed output fuzzy region by calculating the weighted mean of the function over this region given as:

$$\Re = \frac{\sum_{i=0}^{N-1} d_i \mu_A(d_i)}{\sum_{i=0}^{N-1} \mu_A(d_i)} \qquad (1)$$

where d_i is the i^{th} value of the output domain range and $\mu_A(d_i)$ is the membership value at d_i. The resulting output truth value $\Re$ is then used as input to the output fuzzy set which will generate the value of the final output variable based on the description of this set. The output fuzzy set representing a HIGH Probability of Apnoea used in the authors' algorithm was simply a linear proportionate function and as membership values are already scaled by a factor of 100 in the microcontroller, the value of $\Re$ is automatically generated as a percentage.

In practice, the shape of the fuzzy sets defined and the nature of the centroid technique means that when any proposition contributes a non-zero membership value to the output composition, the resulting value of $\Re$ will lie between 50 and 67. Therefore, a value of 50 is subtracted from the value of $\Re$ when it is non-zero to give an output range AP of 0–17 as representing the risk of apnoea being present. This final output value is then used to control the rate at which the alarm timer in the microcontroller is decremented. The timer is initially loaded with a value three times the time limit set by the user and once an apnoea event is recognised it is decremented at a rate determined as follows:
LOW: AP<5, alarm timer decremented once/sec,
MEDIUM: 5≤AP<10, timer decremented twice/sec,
HIGH: AP≥10, timer decremented three times/sec.

An alarm is generated when the timer value reaches zero. If AP < 10, then the probability that a dangerous apnoea event is in progress is less likely and the time taken before the monitor generates an alarm is longer than the limit set, thus avoiding excessive false alarms.

4. Testing and Validation

Initially, rigorous bench testing of the monitor was carried out using the appropriate signal generator, oscilloscope, patient simulators (Model 214B and Oxitest Plus, DNI Nevada Inc.) and a data recording system (LabView™, National Instruments Inc.). This verified that all measured signals were being reliably detected and that user selectable limits and settings were operating correctly, with the appropriate alarms generated. Correct operation of each of the rules of the fuzzy logic algorithm was also verified in the bench environment.

Once this was completed, clinical data were gathered using a cardio-respiratory monitor (VitaGuard VG-2000, Getemed AG.) which can record respiration and ECG signals. The Oxitest Plus was used to generate an SpO_2 signal. A wide range of test scenarios which included intermittent and long-lasting apnoea episodes was generated using the LabView™ framework to replay the recorded signals

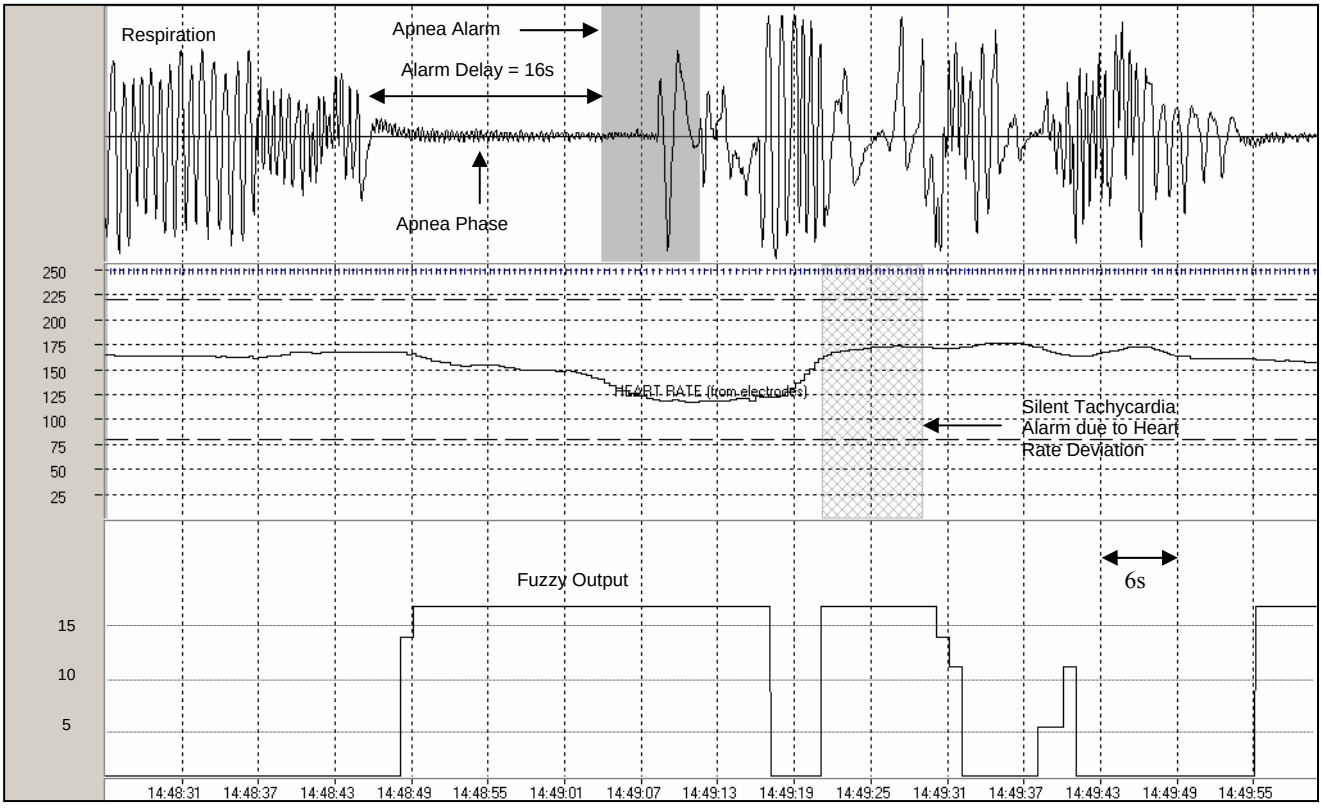

Fig. 3 Output of fuzzy algorithm generating an acoustic apnoea alarm and a silent alarm.

via a digital-to-analogue conversion card in a PC. A range of alarm conditions were established which did not depend on the fuzzy algorithm for detection, such as simple excursions of the heart rate outside of the user-defined limits. In addition, a range of alarm conditions which relied exclusively on the fuzzy logic algorithm for their detection were established, with a final set of 5 tests for each of the 6 fuzzy algorithm propositions. All of these conditions were correctly detected.

Fig. 3 shows an example of a record having a genuine apnoea phase lasting approximately 20s with an accompanying tachycardia immediately afterwards during a period of irregular breathing. The apnoea event is detected immediately by the algorithm which generates a maximum output value to decrement the alarm timer at the maximum rate. An audible alarm is then generated after the set delay period of 16s. Respiration is then temporarily restored so that this alarm is deactivated. However, respiration is irregular and is accompanied by an abrupt tachycardia which the algorithm detects, generating a silent alarm and storing the signals during this event also.

5. Conclusion

After some fine-tuning during development, the monitor was successful in detecting all apnoea scenarios presented to it. The monitor gives increased detection of dangerous or life-threatening events because of the measurement of respiration, ECG and SpO_2 in combination. The fuzzy logic algorithm has made significant improvements in reducing the number of false alarms, while at the same time has allowed the generation of silent alarms to be used to store valuable diagnostic information without the need for user intervention. It is hoped to proceed to full-scale clinical trials on the unit in the near future but time is needed to ensure that all ethical and legal requirements have been complied with when carrying out home monitoring studies.

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