AN INTELLIGENT ALARM SYSTEM BASED ON TEMPORAL EPISODES FOR INTENSIVE CARE UNITS

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Abstract : This paper presents an alarm system based on temporal episodes. A temporal episode is semi qualitative information that describes the signal trend. The system developed is a limit alarm system based on episodes extracted on line. It is able to recognize specific signal behaviours such as probe disconnection or steady state near the alarm limit threshold. The system is implemented to run on line and was tested on 36 hours of data recorded on adult patients hospitalized in Intensive Care Units. The alarm periods generated are compared to those raised by a classical limit alarm system. The conclusion is that 33% of the alarms raised by the classical system would be filtered, without any clinically relevant alarm missed.

Keywords: Biomedical engineering, monitoring elements, alarm filtering, knowledge acquisition, trends analysis, qualitative signal representation.

1. INTRODUCTION

Intensive Care Units receive patients in critical condition, whose state requires considerable attention from medical staff. To help them in their surveillance task, patients are equipped with monitoring systems recording on line physiological parameters describing the patient's state. The number of these variables recorded at a high frequency rate has been constantly increasing thanks to technological advances. Though such technological advances hold great potential in improving patient care, the everyday reality is that the personnel is often overwhelmed by this continuous data flow. Monitoring systems are equipped with limit alarm systems, which generate a large number of alarms, unfortunately false more often than not, with the consequence to diminish the personnel vigilance. False alarms are due to variations occurring on the monitored signal generated by extraneous causes such as measurement artefacts, patient turning in bed, cough ... Tsien, *et al.*, (1997) report from a study made in a paediatric unit during a 10-weeks period that about 86% of the alarm soundings were false alarms. Their conclusion is that any attempt to improve these results seems worthwhile. Yet, until now, not much has been proposed to filter alarms, except applying moving average or median filters on the data (Makivirta, *et al.*, 1991), though research has been done to develop intelligent monitoring systems in the medical field (Lowe, *et al.*, 1999), and in industrial applications such as chemical processes (Colomer, *et al.*, 2002; Rengaswamy and Venkatasubramanian, 1995).

This paper presents an alarm system based on semi-qualitative temporal episodes. Such episodes are expressions such as :" systolic blood pressure has been steady at 120mmHg from time t_o until time t_1; it is increasing from 120mmHg to 160mmHg from

time t_1 to time t_2…". The temporal episode proposed in this paper is defined by information on the trend {steady, increasing, decreasing}, the time when the episode begins, the signal value at that time, the time when the episode ends, the signal value at the end. A methodology was developed previously (Charbonnier, 2003) to extract this information on line from ICU biological parameters. In this paper, a solution is proposed to use them in an alarm system. The advantage of using semi-qualitative episodes is that information on the trend enables to recognize specific situations, such as a steady state near the alarm limit threshold or a probe disconnection.
The on line episodes extraction methodology is briefly reminded and the alarm system is presented in section 2. Results obtained on 36 hours of data recorded on adult patients hospitalized in IC Units are analysed. Three variables are monitored: systolic blood pressure -SBP-, oxygen saturation -SpO2-, Maximal pressure in the airways -Pmax-, which are compared to the results obtained by a classical limit alarm system in section 3 and discussed in section 4.

2. DESCRIPTION OF THE ALARM SYSTEM

2.1. On line extraction of temporal episodes.

The methodology developed to extract on-line episodes from a biological time series is briefly described in this paragraph. An episode is defined by a set {linguistic term; time at the beginning; value at the beginning; time at the end; value at the end}. It corresponds to a time interval during which the property corresponding to the linguistic term holds. Three linguistic terms describing the signal trends are used: steady, increasing, decreasing. For instance, the episode SpO_2{increasing, 120s, 90%, 150s, 95%} expresses that the oxygen saturation (SpO_2) has increased from 120 seconds to 150 seconds from 90% to 95%. The time at which an episode ends is equal to the time at which the following episode starts. The end of the latest episode is the current time. The methodology to extract episodes consists of four successive steps, completed on-line, at each sampling time :

1. Segmentation of the data into line segments:
A segmentation algorithm has been developed that splits the data into successive line segments. The segments may be discontinuous. The segmentation algorithm uses the cumulative sum (CUSUM) technique to determine on line the moment when the linear approximation is no longer acceptable and when to calculate the new linear function that now best fits the data. The CUSUM consists in calculating and integrating at each sampling time, the difference between the signal and the linear model extrapolation. When the CUSUM value crosses a first threshold (th1, first tuning parameter), the corresponding signal is stored. When the CUSUM crosses a second threshold (th2, second tuning parameter), the new linear approximation is calculated that gives the best least squares approximation of the stored data (corresponding to CUSUM value between th1 and th2). The CUSUM is then reset to zero.

2. Classification: At each sampling time, the shape formed by the latest segment and the previous one is classified into one of 7 temporal shapes (the classification is tuned by one parameter) *: Steady, Increasing, Decreasing, Positive or Negative Step, Increasing/Decreasing or Decreasing/Increasing Transient.*

3. Episode generation: The shape obtained is transformed into semi-quantitative episodes, using 3 linguistic terms : {*Steady, Increasing, Decreasing*}.

4. Aggregation: The current episode, ending at the current time, is then aggregated, if possible, with the previous ones to form the longest possible episode.

The segmentation algorithm performs signal filtering. Yet, it does not distort quick changes, like a classical low pass filter would do, because successive segments may be discontinuous. Large signal discontinuities are detected thanks to the classification into discontinuous shapes, such as "step" or "transients", which model sudden and large increases or decreases in the signal. Figure 1 presents an example of the episodes extracted on a real Spo2 signal.

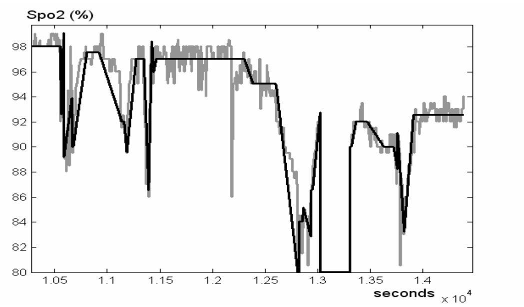

Fig. 1. Spo2 signal and the extracted episodes

2.2. Description of the temporal episode based alarm system.

The alarm system uses the temporal episodes extracted on line. The value at the end of the latest episode, updated at each sampling time, is used to raise the alarm or to stop it, as with a classical alarm system. Information on the signal trend is used to recognize specific events such as probe disconnections, signal discontinuities or steady states near the alarm threshold.

Sounding of the alarm. The alarm is raised when both the end value of the latest episode and the value of the signal cross the limit threshold. The end value of the latest episode corresponds to the signal extrapolation by the latest linear approximation calculated by the segmentation algorithm. The segmentation algorithm takes some time to detect a change in the data. When the value of the CUSUM is between thresholds th1 and th2, the extrapolation may be different from the signal. To prevent false alarms due to a difference between the extrapolation and the signal, the sounding of the alarm must be confirmed by the signal value.

The alarm is stopped when both the end value of the latest episode and the signal cross the threshold back. The alarm sequences generated by this method last longer than those generated by a classical limit alarm system. Indeed, the alarm may sound even if the signal is no longer above (or below) the limit threshold. Yet, the filtering effect of episode extraction avoids the succession of short alarms due to noise corrupting the signal, that may occur with a classical system when the monitored signal remains around the threshold value.

Detection of steady states near the limit threshold. With standard alarm systems, an alarm is raised when the value of the signal crosses the alarm threshold for more than 10s. When the signal is just below or just above the threshold, no information is given to the personnel, even if this state lasts some time. The temporal episode based alarm system detects a "near the threshold state" in the following way : if a steady episode is extracted whose beginning and end values do not cross the limit threshold but remain near the threshold (threshold +/- delta) for more than 2 minutes, a warning alarm is sound.

Detection of specific events associated with a discontinuity. The episode extraction methodology is able to detect signal discontinuities. The signal trend provides information on the shape of the signal when the threshold is crossed. If the end value of the latest episode and the value of the signal both cross the limit threshold (alarm raising) and if a discontinuity is detected at the same time, it means that the threshold crossing is due to a sudden and important signal variation. Specific events may be recognized using this information and specific actions can be taken by the alarm system.

1. Spo2 probe disconnection: If an Spo2 discontinuity is detected when the low limit threshold is crossed, the alarm is interpreted as a probe disconnection. This alarm is filtered, except if the disconnection lasts more than 2 minutes.

2. Rise in systolic blood pressure due to clinical care: If a SBP discontinuity is detected when the high limit threshold is crossed, the alarm is interpreted as a change of value due to medical care, such as a flush on a catheter, for example. The alarm is raised because a caregiver is present and can correctly react to the alarm sounding.

3. Rise in maximal pressure in the airways due to cough: If a Pmax discontinuity is detected when the high limit threshold is crossed, the alarm is interpreted as a cough. The system waits for 20s and raises the alarm if the value of the signal is still above the threshold.

4. Drop of maximal pressure in the airways due to ventilator disconnection: If a Pmax discontinuity is detected when the low limit threshold is crossed, and if the previous episode was a steady one, the alarm is interpreted as a disconnection from the ventilator. The alarm is raised because it is a patient's life threatening situation.

3. RESULTS

3.1. Presentation of the data base

The alarm system has been applied to data recorded every second on adult patients hospitalized in the Intensive Care Unit of Lyon-Sud Hospital. The results of nine recordings are analysed, from eight different patients. Each recording lasts four hours. The data were collected during specific clinical contexts: the weaning from mechanical ventilation and the ending of sedative drug administration. Data acquisition was achieved in real time, without interference from the usual daily care. During the data acquisition phase, an observer stayed at the patient's bed side and annotated all the clinical events that occurred during the recording (modification of drug therapy, of ventilator settings, change of alarms threshold settings, presence near the patient of a physician or a nurse, clinical care …).

3.2. Comparison with a classical alarm system

To analyse the results obtained with the temporal episode based alarm system, we compare them with the alarms periods generated by the classical alarm system. These periods correspond to time periods when the signal remains above (or below) the alarm threshold for more than 10s.

The temporal episode based alarm system was processed on line using the same alarm threshold settings than the classical alarm system. The time stamps (beginning; end) of the alarm periods were stored, as well as warning alarms ("near the threshold alarms") and specific event alarms. The parameter settings of the episode extraction procedure were the same for all the recordings.

We note **Al_CS**, the alarm periods generated by the classical alarm system, **Al_TEBS**, the alarm periods generated by the temporal episode based alarm system and **Al_NT**, "near the threshold" alarm periods.
To determine which of the Al_CS are concomitant to an Al_TEBS and which are not, we used the following off line procedure.

For every Al_CS,
Add a number of seconds (windowsize) to both sides of the alarm period.
 For every Al_TEBS
  Add a number of seconds (windowsize) to both sides of the alarm period.

Find if there is a time intersection between the two alarm periods
  If there is an intersection,
    the Al_CS is concomitant with an Al_TEBS (**Al_CS_TEBS**)
  Else
    the Al_CS is not concomitant with an Al_TEBS (**Al_CS_NTEBS**)

We used the same procedure to determine which of the Al_TEBS are concomitant to an Al_CS (**Al_TEBS_CS**) and which are not (**Al_TEBS_NCS**). To determine the delay between two concomitant Al_CS and Al_TEBS periods, we found the first Al_CS that intersects with the Al_TEBS and we calculated the difference between the beginning of the Al_CS and the beginning of the Al_TEBS .

The results which are presented in the next subsection were obtained using a window size of 30s to detect the Al_CS concomitant with Al_TEBS (left part of table 1) and a window size of 15s to detect the Al_TEBS concomitant with Al_CS (right part of table 2). We chose different window sizes to get the worst results in each case, ie to minimize Al_CS_NTEBS and to maximize Al_TEBS_NCS. Table 1 shows how the results are presented. (dur. stands for duration; the delay is defined as the delay between the AL_CS and AL_TEBS generation).

Table 1: Presentation of the results

Al_CS			Al_TEBS		
n° of Al_CS_TEBS			n° of Al_TEBS_CS		
Min dur.	Median dur.	Max dur.	Min dur.	Median dur.	Max dur.
			Min delay	Median delay	Max delay
n° of Al_CS_NTEBS			n° of Al_TEBS_NCS		
Min dur.	Median dur.	Max dur.	Min dur.	Median dur.	Max dur.

The procedure used to determine concomitant Al_CS and Al_TEBS was also used to determine how many Al_CS which were not concomitant with Al_TEBS (Al_CS_NTEBS), were concomitant with a "near the threshold period" (Al_NT). (cf. ℘2.2)

An Al_CS_NTEBS not concomitant with an Al_NT corresponds to an alarm period when the classical system sounds an alarm and the developed system does not. In the same way, we analysed the Al_NT and determined how much were not concomitant with an Al_CS (**Al_NT_NCS**). They correspond to alarm periods when the signal value remains near the alarm threshold for more than 2 minutes, but with no corresponding alarms from the classical system i.e. missed alarm periods.

3.3. Results

The values of delta chosen were: 10mmHg for the SBP, 2% for the Spo2 and 5 cmH_2O for the Pmax.

Systolic blood pressure (Table 2).

Table 2: Results for SBP

Al_CS			Al_TEBS		
	36			23	
12 s	80.5 s	558 s	25 s	122 s	1605 s
			-9 s	7 s	79 s
	26			1	
11 s	22 s	138 s	27 s	27 s	27 s

During the 36 hours of recording, the classical alarm system generated 62 alarm periods, and the temporal episode based alarm system 24.
26 alarm periods generated by the classical system are not concomitant with the temporal episode based alarm system (26 Al_CS_NTEBS). The median duration of these alarms are 22s, and the longest one lasts 138s. Considering the windowsize of 30s chosen to determine them, they correspond to alarm periods when the temporal episode based system did not raise an alarm even 1 minute later. Among these 26 alarm periods, 16 are concomitant with near the threshold alarm periods (Al_NT). Al_NT corresponds to periods when the signal is steady at a value close to the limit alarm threshold for more than 2 minutes. The longest Al_CS_NTEBS, lasting 138s, is concomitant with an Al_NT period. Among the 26 Al_CS_NTEBS, 10 were not concomitant with an Al_NT period. They correspond to periods when the temporal episode based alarm system would not warn the personnel. These periods, whose median duration is 20s, were analysed using the annotations made by the bed-side observer. None of them correspond to clinically relevant alarms needing medical intervention. All of them correspond to transient fluctuations that were filtered by the episode extraction procedure.
The median delay of detection of the temporal episode based alarm system is 7s, which is rather short. The 80^{th} percentile is equal to 17s (which means that 4 temporal episode based alarms out of 5 are raised with a delay of less than 17s) and the maximal value is equal to 79s. The min delay value of detection is -9s, because the latest episode crosses the limit threshold 1s after the signal, but the classical system waits 10s before generating alarms.
20 Al_NT_NCS were found. Their median duration is 250s, which means that SBP remained 10 times near the alarm limit threshold during more than 4 minutes, without any alarm from the classical system. One Al_TEBS_NCS is found, which corresponds to a period when the signal crosses the alarm threshold for less than 10s. No classical alarm is raised but the condition to raise the temporal episode based alarm is met. These periods correspond to periods when the signal increases or decreases with a certain magnitude; they are associated with a transitory state change.
6 Al_TEBS associated with a discontinuity were found. They are all concomitant with an Al_CS

period. The comparison with the annotations made by the bed-side observer showed that they all occurred when a caregiver was present and care was provided to the patient. An illustration of the alarm periods raised by the temporal episode based system and by the classical system is presented in Figure 2.

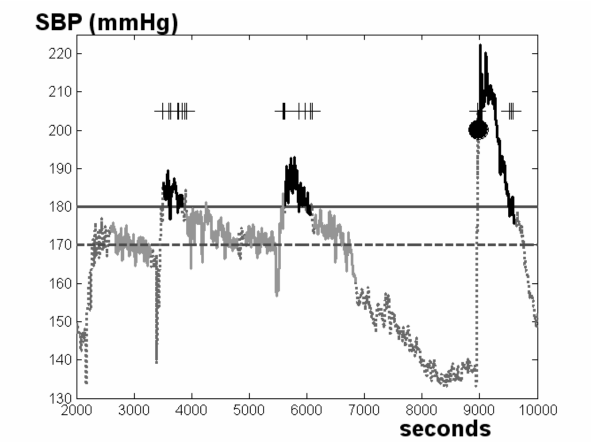

Fig. 2. SBP signal (dotted gray), Al_TEBS (black), Al_CS beginnings and ends (black crosses), Al_NT (gray) and alarms with discontinuity (black round).

Oxygen saturation rate Spo2 (Table 3)

Table 3 : Results for Spo2

Al_CS			Al_TEBS		
	67			50	
11 s	51.5 s	1340 s	10 s	128 s	1371 s
			-9 s	1 s	39 s
	8			8	
10 s	11.25 s	15 s	6 s	13 s	23 s

The classical alarm system has generated 75 alarm periods, and the temporal episode based alarm system 58. 8 Al_CS_NTEBS were found. They all correspond to artefact measurement when the signal drops below 90% for a short time (no more than 15s).

The median delay of detection of the temporal episode based alarm system is 1s, which means that half of the temporal episode based alarms are raised before the classical alarm system. Let us keep in mind that the classical alarm system waits 10s after the signal crossed the threshold before raising the alarm. The 80^{th} percentile is equal 1s and the maximal value is equal to 39s. 8 Al_TEBS are not concomitant with Al_CS. 3 of these alarms correspond to a decrease of Spo2 just below 90% due to a tracheal suction. They correspond to a patient's state change. The other five are observed on a patient during a period when Spo2 is submitted to large variations, and correspond to a period when the patient's state is unsteady. Among the 50 Al_TEBS concomitant with Al_CS, 24 were detected as a probe disconnection, which was confirmed by the comparison with the bed side observer's annotations. No "near the threshold" alarms were found for this signal.

Maximal pressure in the airways Pmax (Table 5)

Table 5 : Results for Pmax

Al_CS			Al_TEBS		
	87			54	
10 s	51 s	7471 s	8 s	25 s	7641 s
			-9 s	1.5 s	60 s
	5			5	
10 s	12 s	14 s	7 s	12 s	16 s

92 alarm periods were generated by the classical system. Only 5 of them are not concomitant with a Al_TEBS period. They correspond to very short periods of alarm. The temporal episode based alarm system generates 5 alarm periods not concomitant with the classical system. Thus the temporal episode based alarm system does not diminish the number of alarms generated for this biological parameter. This can be explained by the fact that Pmax is a biological parameter submitted to frequent and large variations and the tuning of the episode extraction procedure proposed for this parameter does not filter much these variations.

Among the five Al_CS not concomitant with an Al_TEBS, 3 were not concomitant with Al_NT alarm period. 5 Al_NT alarm period not concomitant with Al_CS periods were found. Their median duration is 319s and the maximal duration is 514s.
8 of the 61 Al_TEBS were interpreted as a ventilator disconnection by the temporal episode based alarm system, which is in complete agreement with the bedside observer annotations. After visual analysis of Pmax and of the bed side observer annotations, it appeared that 9 ventilator disconnections occurred. These disconnections are caused by a care giver, either to achieve a tracheal suction or to start the weaning procedure. The alarm system was able to recognize 8 out of 9 disconnections, the last one being detected as a standard alarm.

17 of the 61 Al_TEBS were detected as an increase in Pmax associated with a discontinuity. For 13 alarms among these 17 Al_TEBS, the value of Pmax went below the limit threshold during less than 20s, which means that no alarm is raised by the temporal episode based alarm system. The median delay of detection of the temporal episode based alarm system is 1.5s and the 80^{th} percentile is 9s.

4. DISCUSSION

It is difficult to go further in the comparison between the two alarm systems, the classical one and the temporal episode based one, because an on line medical expertise of the alarms that occurred on the patient is missing. The observer wasn't a physician and did not have the ability to determine wether an alarm was an important one, meaning the patient required an immediate intervention, or wehter it was a false alarm and should not have been raised by the alarm system. However, the bedside observations are informative and, at least, enable an analysis such as "this alarm was followed by a clinical intervention and this one wasn't" or such as "this alarm was caused by a probe disconnection". Using the annotations, it is possible to say that none of the alarms raised by the classical system that were not concomitant with an alarm raised by the temporal episode based system was an alarm followed by a clinical intervention, which means was clinically relevant. Actually, most of these alarms were due to transient variations, which were filtered by the episode extraction method. The number of this kind of alarms is important for SBP (about 40%), but not very important for the others signals (10% for Spo2 and 5% for Pmax). The detection delay associated with the temporal episode based alarm system is rather short for the three signal analysed (about a few seconds, 79s in the worst case). Of course, these figures (percentage of short alarms filtered, delay of detection) depend on the parameters settings of the temporal episode based method. The results presented in the previous section are obtained with the same set of tuning values for all the recordings. They correspond to the tuning values proposed in Charbonnier (2003). If parameter th2 that tunes the segmentation was increased, the filtering effect of the segmentation would be increased with a consequent effect of increasing the percentage of alarm episodes filtered (Al_CS_NEPB) and of increasing the detection delay. For instance, if the value of parameter th2 is multiplied by 2, the number of Al_CS_NEPB increases to 24 for Pmax and the detection delay to 11s (80^{th} percentile : 21s).

Few Al_TEBS_NCS were found, which is not surprising considering the condition defined to raise an alarm. These alarms are found when the signal crosses the alarm threshold for a very short time. However, they all correspond to either a change in the patient's state (Spo2 decreases from a high value to just below 90%, for example), or to large magnitude variations, which correspond to an unsteady state, which are situations interesting to report.

The real improvements of the temporal episode based alarm system are its ability to detect periods of time when the signal is very near the limit alarm threshold for a long time but does not cross it and its ability to recognize specific events, such as disconnections. During the 36 hours of analysed recording, 25 "near the thresholds" periods were detected, during which no alarm was raised by the classical system (median duration of these periods 252 sec). Four of them last more than 540s. The detection of these moments is interesting and may improve patient care. The system detected 54 alarm periods associated with a discontinuity. Among the 54 alarms, 24 were due to a Spo2 probe disconnection that was confirmed by the bed side observer and by visual analysis. All the disconnections annotated by the bed side observer were recognized by the system. None were missed. 8 of the discontinuities were interpreted as a ventilator disconnection. Only one ventilator disconnection reported by the bed-side observer was not recognized as such by the alarm system, though an alarm was raised.

To conclude, among the 229 alarm periods raised by the classical system, 39 would have been filtered by the temporal episode based system and 54 would have been interpreted as a specific clinical event. Among the 54 interpreted, 37 would have been muted because recognized as either a Spo2 probe disconnection or a patient's cough. The total is then 76 alarms out of 229 filtered by the system, ie 33%, without any important (clinically relevant) alarm missed.

5. CONCLUSION

In this paper, an alarm system based on temporal episodes is presented and the alarm periods obtained are compared to alarm periods raised by a classical alarm system. The results show that the temporal episode based alarm system is performing similarly to a classical limit alarm system with the advantage that 33% of false alarms are rejected. It does not miss any clinically relevant alarms and is able to recognize specific situations on the patient. The system was developed for ICU high frequency data monitoring. Yet it has potential industrial applications, such as chemical process monitoring. This study is pursued to increase filtered alarms by an expert automatic multi-signal interpretation.

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