Attentional overload as a fundamental cause of human error in monitoring

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Abstract

Objective -To study the intraoperative behaviour of anaesthetists in order to characterise clinical monitoring behaviour under real-time conditions.

Methods - Non-participatory observation and retrospective subject interview carried out at cardiac operating theatres at 2 UK teaching hospitals. 12 anaesthetists were observed, of which 7 were consultants and 5 were senior registrars in training. Clinical behaviour whilst administering anaesthesia during cardiac surgery was captured on video, and annotated by voice commentary provided by a shadow anaesthetist not participating in patient care. Other data recorded included all real-time patient signals accessible to subjects through patient monitoring devices. Subjects were interviewed pre and post-operatively, and approximately one week later, when selected events were reviewed.

Results - Analysis of the data suggests a hypothesis that cognitive loading may swamp attentional resource and result in perceptual errors whilst monitoring. Attention may be swamped by cognitively demanding tasks like plan reformulation, multi-parameter estimation, or excess data. Such data overloading was however not observed in the study. Possible mechanisms by which attentional loading affected clinical performance included failure to interpret the meaning of signals, perceptual narrowing, and task fixation.

Conclusions - Whilst perceptual errors are traditionally ascribed to data-overload, attentional overload should provide a more general explanation. Data-overload can be seen as a specific example of attentional overload. Since reasoning tasks seem to cause attention loading during clinical monitoring, proposals for monitoring displays that abstract data or group data according to physiological system seem ill-advised. Displays that unload clinicians by supporting specific complex tasks may be more appropriate.

Key words: anaesthesia, computer, medical informatics, cognitive psychology, medical decision making, data overload, ethnography.

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1 Introduction

Human error while using monitoring equipment contributes to poor clinical outcome [1][2]. However relatively little is known about the cognitive processes that underlie these errors. Recent work has begun to make significant progress in developing rich models of some of these processes and the manner in which they might affect monitoring behaviour [3]. In particular, the importance of situational awareness and the role of attention have begun to be highlighted [4] [5].

In the past, analyses of anaesthesia practice have focused directly on the causes of error. An alternate strategy is to examine routine behaviours, which constitute the bulk of clinical practice [6]. This has two advantages. Firstly, major errors usually arise in the context of a sequence of minor errors [7][1]. By analysing the dynamic context within which minor errors occur, we may obtain a clearer idea of how to prevent them. An important consequence may be that potentially critical errors can be prevented by optimising "normal" clinical practice. Secondly, by focusing on the elements of normal behaviour that are responsible for sub-optimal performance, we may be able to optimise common behaviours as well as support critical but rare failures.

This paper reports on a study of anaesthetic monitoring practice. The study aimed to develop an understanding of the cognitive factors that contributed to errors whilst monitoring [8]. The study resulted in the development of a simple descriptive language for annotating clinical behaviour during monitoring. Further, detailed analysis of monitoring behaviours resulted in a model of cognitive loading that explained the events observed. In particular, we hypothesise that data overloading is not a primary cause of monitoring error. Rather, it seems to be one example of a more general phenomenon of attentional loading. This attentional loading hypothesis supports the importance of situational awareness in monitoring situations. It also has significant implications for both the design of monitoring equipment, and the evolution of improved clinical monitoring practices.

2 Methods

In the absence of strong hypotheses about the nature of real-time decision processes, this study employed non-participatory observation. This is sufficiently formal to allow robust statements to be made, and has the advantage of being grounded in the clinical workplace. An ethnographic approach was adopted [9]. Here one tries to understand the actions of individuals through detailed observations of them carrying out their routine tasks.

Observations of anaesthetists at work with follow-up interviews post-operatively were undertaken. These were enhanced by commentary on clinical performance obtained at the time of surgery provided by an expert observer. The commentary provided a link between the observation and interview components of the study.

The data and interpretations collected in the first stage acted as control on each subject's verbal reports during interview. The rich data record validated subject recollections, and their reports on decision processes were checked against our expert clinician's assessment. In the absence of clear recall, the richness of the recorded data allowed subjects to reconstruct a hypothetical analogue of events [10]. In this situation we were likely to get reports which contained clinicians' *a priori* theories about their likely responses as well as partial recall of their actual responses [11] [12].

2.1 Stage 1 - Observation

Two UK sites were used for the study. Six participating clinicians with cardiac anaesthetic experience were selected from each site. Of these twelve, five were senior registrars in anaesthesia, who were able to take entire responsibility for the delivery of the anaesthetic, and seven were consultant anaesthetists. Each subject was observed for one entire cardiac anaesthetic, giving a cohort of 12 patients in total. All patient data were collected under confidentiality agreements, and no data that would identify individual patients was retained.

The observation technique consisted of passive recording of intraoperative behaviour, with no questioning of subjects. The subject anaesthetist was the one primarily responsible for delivery of the anaesthetic. Subjects were informed that the purpose of the data collection was to assist in the design of monitoring equipment. During each operation, two observers were present, one being an expert anaesthetist. The second observer was drawn from a pool of three with no specific anaesthetics expertise.

All monitored signals available to the subject were recorded by a secondary monitoring device. Other data included a record of drugs given by the subject, as well as video and audio recordings of the subject during the operation. The visual field of view for the video centred on the subject and the monitor, but also included the anaesthetic machine, ventilator, drip stands, bypass pump, and the surgeon. The field of view did not include the patient. Commentary from the observing anaesthetist recorded anaesthetic events, surgical phase, etc. The commentary was made via a close-range pick up radio microphone so that comments could be made *sotto voce*. Such commentary, while providing essential context to the primary data, is a potential source of bias. We sought to control for this at the analysis stage by corroborating the expert and subject interpretations with the primary data set.

2.2 Stage 2 - Expert review

Because a typical cardiac bypass operation takes several hours to complete, it would not have been practical to review the whole operation with each subject in the follow-up interviews. Instead, two to three event periods were selected. 26 such events were culled from the data, typically being 15-30 minutes long. The observers selected events containing either potentially suboptimal clinical performance or clinically significant changes to patient state. Event selection in such a phenomonologic study is another potential source of bias.

No major errors resulting in significant morbidity were observed. 16 of the 26 events demonstrated suboptimal performance, defined as a patient parameter moving to clinically unacceptable levels for periods of several minutes or more (Table 1).

2.3 Stage 3 - Subject review

Post-observation interviews with subjects were arranged for the week following the observation and lasted about one and a half hours. To cue a subject' s recall, access to the data set including the audio-visual record was allowed, but excluding the observing clinician's commentary and event interpretation.

Subjects was asked about the selected events. The emphasis was on building an understanding of the subject's decision making and they were specifically questioned about what information was used and what role the information played in the decision. They were questioned about their goals during the selected events, and the rationale for particular decisions.

3 Results

Nine of the 26 events contained an episode in which the subject failed to detect a potentially significant change in monitored data (Table 2). For each of these event periods, all clinical actions were examined, not simply those directly relating to the monitoring behaviour. Wherever possible, sequences of related actions were assembled.

The objective of this analysis was to characterise the clinical monitoring behaviour and the circumstances surrounding it. For each action, and sequence of actions, an attempt was made to identify what information was available to the clinician, what information could be positively identified as having been used, and what information could have been used. Analysis involved the detailed study of the observing clinician's commentary, the electronic data and the transcript of the interviews. The audio-visual records were used to resolve any ambiguities or contradictions appearing in the transcripts.

3.1 Characterising behaviours - the event language

We evolved a language for classifying clinical actions, and this was used to dissect the events. This is a permutation of a qualitative research technique known as 'Grounded Theory' ([13], [14]) which emphasises the emergence of concepts from the data rather than the imposition of an *a priori* theory by the researcher.

Each clinical action was labelled against two axes - the type of task being undertaken, and the clinician's intent. Four main task types were identified - *monitoring*, *diagnosis*, *control and planning*. Control describes the institution of a therapeutic loop, from administration of a therapy to the modification of subsequent doses based upon observed patient response. Diagnosis is a directed action to isolate the cause of unexplained observations. Planning was associated with composing strategies to handle new events, or tracking progress with existing plans. Anaesthetists also engage in *administrative* tasks, which include record keeping, manipulation or setting up equipment, and drawing up drugs. Table 3 summarises the distribution of clinical tasks observed in the events selected for the study.

Further, clinical events can be thought of as *intended* or *unintended*. Intended events are part of a predefined strategy, and unintended ones are unheralded and demand an unplanned reaction. Consequently we labelled clinical behaviours as *strategic* or *reactive*. Strategic behaviours are responsible for selecting and implementing treatment plans, while reactive behaviours cope with unexpected events.

The notion of intent and task type can be used to categorise individual actions in the observed behaviour of clinicians. Eight possible combinations arise:

	strategic	reactive
diagnosis	SD	RD
monitoring	SM	RM
control	SC	RC
planning	SP	RP

Using these labels, sequences of actions were identified to produce a chronological map of clinical behaviour for each event period. Each map was interpreted in relation to the inferred goals and reasoning of the subject.

3.2 An Example Event - Missed Hypoxia

A summary of one of the events (number 5 in Table 2), and its analysis follows. Each of the events in the study was examined and analysed in similar detail (Figures 4 to 11).

The clinician: A consultant anaesthetist with substantial experience of cardiovascular surgery.

The patient: A 47 year old male was admitted for excision of a left ventricular aneurism resulting from a large myocardial infarct several months previously. Prior to surgery, the subject anaesthetist noted a history of recurrent bouts of ventricular failure with episodes of pulmonary oedema. The subject suggested that because of the patient's relatively poor left ventricular contractility, the patient could require intensive haemodynamic support post bypass.

The event: The event demonstrates a gradually declining SaO_2 level post bypass, probably caused by pulmonary oedema (Figure 1.). The downward trend started with an SaO_2 of 100 immediately after bypass, and dropped to 87. The clinician did not detect the trend until he took a routine blood gas sample 30 minutes after the drop had commenced. The alarm capabilities of the monitoring device had been suspended. Consequently, no alarm sounded. However the downward trend would have been visible for quite some time before the SaO_2 dropped into the alarm region.

Chronology of clinical actions: The subject's patients normally came off bypass with an infusion of an inotropic agent to support cardiac function. In this case, the surgeon preferred to have the patient on an infusion of glyceryl trinitrate (GTN), and so an intravenous infusion of GTN was running at the end of bypass.

The subsequent post-bypass events were labelled in the following sequence, based upon evidence in the interview transcripts, the expert commentary, and the primary data (Figure 2.):

RC -> SC -> RC -> RM -> SM -> RC

Concerned about the patient's cardiac performance, and in the absence of his preferred strategy, the subject gave the patient repeated doses of Calcium Chloride for its inotropic action - the first RC action. After several alterations to the GTN (SC) the patient's pressures failed to make the expected post-bypass recovery. The subject then felt justified in departing from the surgeon's practice. Thus adrenaline was administered at 15:56 (RC). The subject spent much of the next 15 minutes closely tracking cardiac performance, culminating in a very active period between 16:05 and 16:10 in which he repeatedly measured left atrial pressure (Figure 3.) (RM).

At 16:12, he took a routine blood gas (SM). In so doing he noted the low SaO_2 value, and immediately increased the patient's inspired oxygen (FiO_2) (RC). He commenced hand ventilation, and increased the end-expiratory pressure on the ventilator (PEEP). The routine blood gas value taken at 16:12 showed an arterial PO_2 of 7.2.

An analysis: There were several possible explanations for the prolonged drop in saturation. Firstly, the lungs may have been partially collapsed after bypass. In view of the patient's previous history, and the high filling pressures, pulmonary oedema was a more likely explanation. The addition of PEEP and increase in FiO2 were commenced in response to this possibility.

Much of the clinical activity throughout the drop in saturation was seen to be reactive (Figure 2.). The subject was forced to deal with a combination of events for which he had not developed a preplanned response, having adopted the plan favoured by the surgeon. In particular, he was faced with a poorly performing heart, and pulmonary oedema.

It appears that this combination of circumstances led to a period of intense preoccupation with the management of the patient's cardiovascular performance. One consequence of this may have been that, despite looking repeatedly at the monitor, the subject did not detect the saturation trend.

The video and physiological data provide evidence to substantiate this hypothesis. He switches the CVP transducer to measure LA pressure repeatedly during the period between 16:05 and 16:10 (Figure 3.). The intraoperative video demonstrates the subject spending long periods in front of the monitor, dispelling any doubts that the SaO2 value was missed because there had been any failure to use the monitoring equipment.

4 Analysis

The goal of this study was to develop an understanding of the cognitive issues contributing to human error in a clinical monitoring environment. In particular, the sequence of events leading up to an error was of interest. To achieve this, the event maps from all events were pooled in an attempt to abstract commonalities.

It is clear from the example in the preceding section that it does not even necessarily make sense to speak of a chain of events leading to an error. In this example, the error occurred because one task dominated the subject's attention so completely that routine monitoring of other data did not occur. In general, this task dominance was typical of most of the 9 events in which the subject failed to notice monitored data.

The next stage in the analysis was to attempt to develop a psychologically valid model that explained the pooled findings. With such a small and unrandomised sample, the model developed must act as an hypothesis, and further study will be needed to specifically validate it.

4.1 Data overload

It is often suggested that clinicians in monitoring situations are prone to data overload. Data overload arises when more data are physically displayed than can reasonably be comprehended by an individual [15]. A nuclear power plant supervisor for example, may have up to 3000 controls and displays to deal with [16]. Typically, clinicians in our study had on the order of 40 parameters available, and chose to display about a quarter of these. Current understanding of human sampling behaviour suggests that in principle, anaesthetists should be able to handle this amount of data reasonably well [17] [18].

However, several subjects performed suboptimally because they failed to detect significant data events, *despite the fact that they apparently were looking directly at the monitor* for extended periods. Were they subject to genuine data overload conditions, one might explain this by suggesting a fundamental perceptual limit had been reached. For example, it may not have been physically possible to examine all the relevant parameters within a given time. However, no such physical limits were apparent during the study.

4.2 Attentional load

A more likely explanation is the notion of attentional loading, where attention is equated with the amount of cognitive resource available to carry out a particular task [19]. Simply put, one can model attention as a finite resource. A variety of cognitive activities compete for that resource [5]. Several models have now been proposed, detailing these specific process in some detail [3] , for example Rassmussen's well known skills, rules and knowledge framework [20]. In the present context, the details of the cognitive processes that compete for resources are less significant than the effects of the competition itself. Specifically, perception of data competes with higher level cognitive tasks that involve reasoning. Allocating attention to one means that less is available for the other.

One can conjecture that some of the subjects in this study exhibited cognitive loading with reasoning tasks. This resulted in reduced attention being available for monitoring tasks. Several reasoning tasks in particular seemed to load subject attention:

Plan reformulation - Having to change an existing plan to accommodate new circumstances or changed goals may consume large amounts of attention.

Multiple signal integration for control tasks - When direct data are not available, several parameters are used to estimate unobservable variables e.g. left ventricular performance. One could say that under these circumstances, clinicians might be data underloaded and processing overloaded.

In the case study presented above, the subject was probably overloaded both by plan reformulation and variable estimation from multiple parameters.

One might expect other tasks to also swamp attention, although these were not observed:

Diagnosis - At least in anaesthesia, control rather than diagnosis seems to be the more frequent task. This may be because the set of useful diagnoses routinely employed by anaesthetists is small.

Monitoring data - In the classic data overload situation, so many signals are competing for attention that some do not get interpreted successfully. There was no evidence that this is a common cause of attentional loading for current anaesthetic practice, based on the amount of data displayed and the study events.

4.3 Possible effects of attentional loading on monitoring behaviour

There are at least three possible mechanisms by which attentional loading could affect monitoring behaviour.

Firstly, individuals may look at displayed information, but fail to fully interpret it. There are several steps that need to occur before the meaning of a signal is determined, and with inadequate attention, this process may have been disrupted. For example, the numeric display of BP is first detected by its physical characteristics e.g its lines and colour. Next it is identified as a number, and then as *being* the BP. Finally a meaning is attached to its value. So, even if a numeric is glanced at on a monitor, changes in its value under loading conditions may not be fully interpreted. Interestingly a physical change in the properties of the numeric value, such as its colour, may still come to an individual's attention in such circumstances.

Secondly, as an individual scans a set of signals, each signal is filtered based upon its perceived relevance. Individuals only look at those things that are regarded as interesting. When they are loaded by other tasks, such data filtering may be particularly savage. This may result in pruning away all but those signals directly relevant to the task at hand. This may manifest as attentional fixation on a subset of displayed data, resulting in perceptual narrowing. The result of loading in this study did seem to suggest that some subjects focused exclusively on a few displayed parameters, and ignored others.

Attentional loading may also cause fixation to a data subset by a third mechanism. A complex task may prevent swapping from that task to another. This may be because individuals are reluctant to abandon the mental models they have constructed for the dominating task. They may for example, be estimating an unobservable variable such as depth of anaesthesia and carrying on a number of mental computations that cannot be easily committed to memory. Rather than be distracted by another task that is due and risk losing the model, they remain with the current task. Thus the high cost of setting up a model to deal with one task may make it difficult for that task to be temporarily suspended, since the clinician will "lose" intermediate calculations.

5 Discussion

We have presented a model of attentional resource allocation, and hypothesise that it provides a good model for describing a class of monitoring errors in real-time clinical situations. While further experiments will be needed to test out the utility of this hypothesis, its implications are significant.

Firstly, there are clear implication for the manner in which individuals are trained to use monitoring equipment [3]. As the specific causes of attentional loading in situations like the delivery of anaesthesia are confirmed, methods can be developed to enhance situational awareness through reduced cognitive load.

Secondly, there are several implications from the present results for the design of monitoring displays. At present, monitoring systems present patient data in a relatively unstructured way. Many decision support system proposals suggest that combining data into a smaller set of abstract parameters would be beneficial. This is based upon the belief that data overload is a significant cause of clinical error, and that by reducing the amount of data, clinical performance should be improved. According to the attentional loading model however, data overload is only one of many possible causes of reduced attentional resource, and may be an infrequent one in current clinical environments. In situations in which the clinician requires detailed data to institute changes to patient control, hiding data may worsen the situation. The effects of such a loss of immediate information or *out of the loop unfamiliarity* are well documented with autopilot and closed loop control systems [16].

Some or all of the proposed effects of attentional loading may be significant causes of error in clinical monitoring situations. Monitoring displays and clinical decision support systems can be designed to specifically unload the attentional burden on clinicians, and such designs will depend on the underlying mechanism leading to perceptual error.

If signals are not being filtered, but failing to be interpreted, then simple solutions like changing the physical properties of signals may be appropriate. When signals change value significantly, physical changes to the signal display may draw them to the clinician's attention. For example, on crossing an alarm threshold, the colour of a numeric could change or flash. This is already a commonly used mechanism, but is at present hampered by the high rate of false alarms that some monitoring systems generate.

If signal selection and filtering is a cause of attentional load, then one could group monitor data. The displayed data would need to be grouped in a way that supported individual tasks. This may increase the likelihood that all the data within a specific task group is examined. Grouping data in this way has several consequences. For example, grouping data by physiological system may initially seem appealing. However many anaesthetic tasks cut across physiological groupings. For example, maintaining blood pressure requires inferences about the state of analgesia, volume loading, vasoactivity and myocardial contractility. Grouping data by physiological system in this case would require a clinician to look at several different systems. Some tasks such as maintaining oxygenation might be satisfied by a single set of data grouped around the respiratory system. Thus it is not that physiological systems are never an appropriate view of clinical data, but rather that they are appropriate when they coincide with a given clinical task.

If task switching is an issue, then means by which clinicians can unload and reload mental computations or reduce the complexity of such computations would help. Displays which gather task specific information would again assist. Further if such task related data were grouped so that clinicians could more easily make the necessary inferences from them, then this would assist further.

Our main concern has been to improve the design of monitoring systems [4], but the attentional load model also has implications for anaesthetic training and practice. Firstly, the habit in some institutions of disabling alarms on monitoring systems to reduce the interruptions caused by false alarms may now seem even more imprudent. Alarms may be the only way to grab a clinician's attention in some circumstances. Further, understanding that simple tasks like the routine checking of monitor displays can be overloaded by other tasks, clinicians may wish to modify the way they routinely scan monitors. The issue of task fixation has significant implication in general for the way clinicians plan and execute their actions.

6 Conclusion

The study of clinical decision making processes has fundamental implications for the way in which clinicians approach clinical practice, for clinical training, and for the design of computer based decisions support systems. While the results of the present study have generated an attentional loading hypothesis to explain a class of perceptual errors whilst monitoring, significant work needs to be done in validating and expanding it. In particular, it remains to be determined whether attentional loading is a significant cause of monitoring error and which of the several possible proposed mechanisms actually affect current practice.

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Tables

Table 1: Primary abnormality in monitored parameter that characterised selected events (N=26)

	ABP	SaO2	ETCO2	Temperature	Cardiac Rhythm
Senior Registrar	7	1		1	1
Consultant	13	2	1		
Total	20	3	1	1	1

Table 2: Brief description of events containing episodes in which subjects failed to notice monitored data

Event	Brief description of monitoring error
1	2 min. sharp rise in ABP systolic 100->140 mmHg at beginning of surgery.
2	3 min. period of drop in ABP systolic 100->65 mmHg.
3	Missed 4 min. period rise in ABP systolic 95 -> 140 mmHg
4	Missed repeated episodes of asystole due to intermittently faulty pacing wire. Detected by surgeon.
5	Missed 30+ min. period of drop in SaO2 100 -> 87
6	On bypass, missed 30 s period of drop in mean ABP 68-> 11 mmHg
7	Missed 15 min. period rise in ABP systolic 100 -> 140 mmHg. Left room for 10 minutes.
8	Missed 25 min. period of drop in SaO2 100 -> 88. Subject relying on capnogram for ventilation data, and did not use SaO2
9	Missed 8 min. rise in CO2 1 -> 9 torr. Followed by 2 similar episodes.

Table 3: Primary clinical task that characterised selected events (N= 26). Some events were characterised by multiple tasks.

	Monitor	Diagnosis	Control	Planning	Total Events
Senior Registrar	4	0	3	3	9
Consultant	5	0	8	6	17
Totals	9	0	11	9	26

Figures

Figure legends

Figure 1

Event 5 - A decline in patient's SaO2 level in the immediate post-bypass phase remained undetected for over 30 minutes, despite the clinician repeatedly examining the patient monitor screen.

Figure 2

Clinical actions observed during event 5. Strategic(S) and Reactive (R) monitoring and control actions taken during the period of evolving hypoxia

Figure 3

Time line for observed clinical tasks during event 5. Blood pressure changes during the dropping SaO_2 trend revealed relatively poor cardiac performance immediately post-bypass. By 16:00 the ABP systolic value is below 80 mmHG. The lower curve in the blood pressure set shows central venous pressure (CVP). For the middle third of this curve, the clinician uses the CVP transducer to measure left atrial pressure (LAP), and towards the end of this middle third, he switches repeatedly between the two (as evidenced by the spikes in the trace). The switching behaviour indicates a period of intense concentration on these values

Figure 4

Time line for observed clinical tasks during event 1 - A 2 min. sharp rise in ABP systolic 100->140 mmHg at the beginning of surgery, due to inadequate anaesthesia. The event is bounded by skin incision and sternotomy. The rise was probably caused by a failure to observe the rise in ABP on skin incision, indicating that anaesthesia was inadequate, and the consequent delay in administering an intravenous does of anaesthetic agent until sternotomy (marked *) . (DOA - Depth of Anaesthesia)

Figure 5

Time line for observed clinical tasks during event 2 - A 3 min. period of drop in ABP systolic 100->65 mmHg, prior to going onto cardiac by-pass at 10:11. Depth of anaesthesia is controlled by modifing the percentage on inspired anaesthetic gas : Enflurane is increased in 2 turns from 0.4% to 1.5% at 9:55 am. This along with a probable hypovolaemia (as evidenced by the increasing heart rate between 9:50 and 10:00), led to the drop in pressure. The Enflurane was then completely turned off at 10:05, followed by 2 doses of the drug Aramine in response to the drop in blood pressure. Possibly the subject focussed exclusively on optimsing blood pressure prior to going onto bypass, and consequently failed to note the evolving hypovolaemia. (DOA - Depth of Anaesthesia)

Figure 6

Time line for observed clinical tasks during event 3 - A missed 4 min. period of rise in ABP systolic from 95 to 140 mmHg. The event is bounded by skin incision at 15:00 and sternotomy commencing at 15:34. The subject delays noticing that depth of anaesthesia is inadequate until well into the event, primarily because he is distracted setting up iv syringe pumps during this period. Some equipment was unexpectedly unavailable, and the subject had to rearrange his expected set-up. Monitor alarms were disabled by the subject. (RA = Reactive Administrative task)

Figure 7

Time line for observed clinical tasks during event 4 - Missed repeated episodes of asystole due to intermittently faulty pacing wire. The subject was intercurrently busy with several tasks during the period of faulty pacing, including administration of drugs to control BP (Isoprenaline, followed by two adjustments to the GTN infusion rate), reversal of heparinisation with Protamine, and completing the anaesthetic record. The intermittent nature of the problem made it less likely that it woudl be detected on a routine monitor scan by the subject.

Figure 8

Timeline for event 6 - On cardiac bypass, a missed 30 s period of drop in mean ABP 68 -> 11 mmHg. The cause was probably a kink in the venous return tubing to the bypass machine. The subject was in the operating theatre, and had a relatively inactive role during the bypass phase. Nevertheless, she did not detect the short event, and was surprised to see it during the post-operative interviews. Had it persisted, it would have required rapid action on the part of the subject to protect the patient.

Figure 9

Timeline for event 7 - Missed 15 min. period rise in ABP systolic 100 -> 140 mmHg. Skin incision (14:07) and sternotomy (14:14) do not produce a rise in the patient's blood pressure, and the pressure is controlled by adjsutments to the percentage of inspired anaesthetic gas Isoflurane until 14:42, when it is turned down to 1%. At this point the subject left the operating room for until 14:55. The event is corrected by increasing the Isofluorane to 1.5% at 15:02, 7 minutes later.The subject suggests later that the pressure may have seemed within the limits expected for that stage of the operation, and only after seeing a trend for a few minutes did it become apparent that intervention was necessary. A concomitant rise in ETCO2 over thsi period was also not detected by the subject.

Figure 10

Timeline for event 8 - Missed 25 min. period of drop in SaO2 100 -> 88. The subject relied on the capnogram for ventilation data, and did not have SaO2 displayed. The short dip in SaO2 at 12:30 is artefactual, caused by tilting the operating table, from head down to level and accidentally moving the transducer. The extended drop in SaO2 was probably due either to basal atelectasis following bypass (collapse of part of the patient's lungs) or pulmonary oedema. The head down table tilt may have contributed to the pulmonary oedema. A routine blood gas is taken at 12:39, and the result arrives at 12:45, causing the subject to adjust the ventilator parameters (I:E ration changed from 1:2 to 1:1).

Figure 11

Timeline for event 9 - Missed 8 min. rise in CO_2 1 -> 9 torr. The rise in CO_2 is due to the sodalime absorber in the ventilation circuit requiring replacement. The subject notes the CO_2 trend around 14:19, and in response increases the fresh gas flow. An arterial blood gas sample is then immediately taken at 14:20.

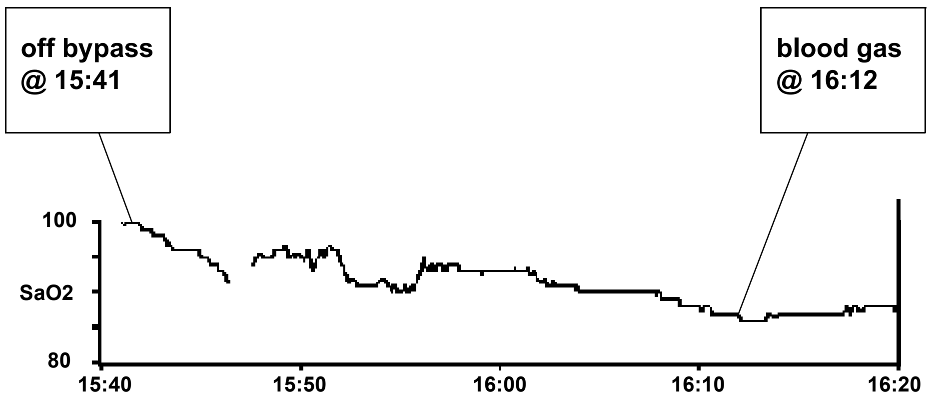


Figure 1. Event 5 - A decline in patient's SaO2 level in the immediate post-bypass phase remained undetected for over 30 minutes, despite the clinician repeatedly examining the patient monitor screen.

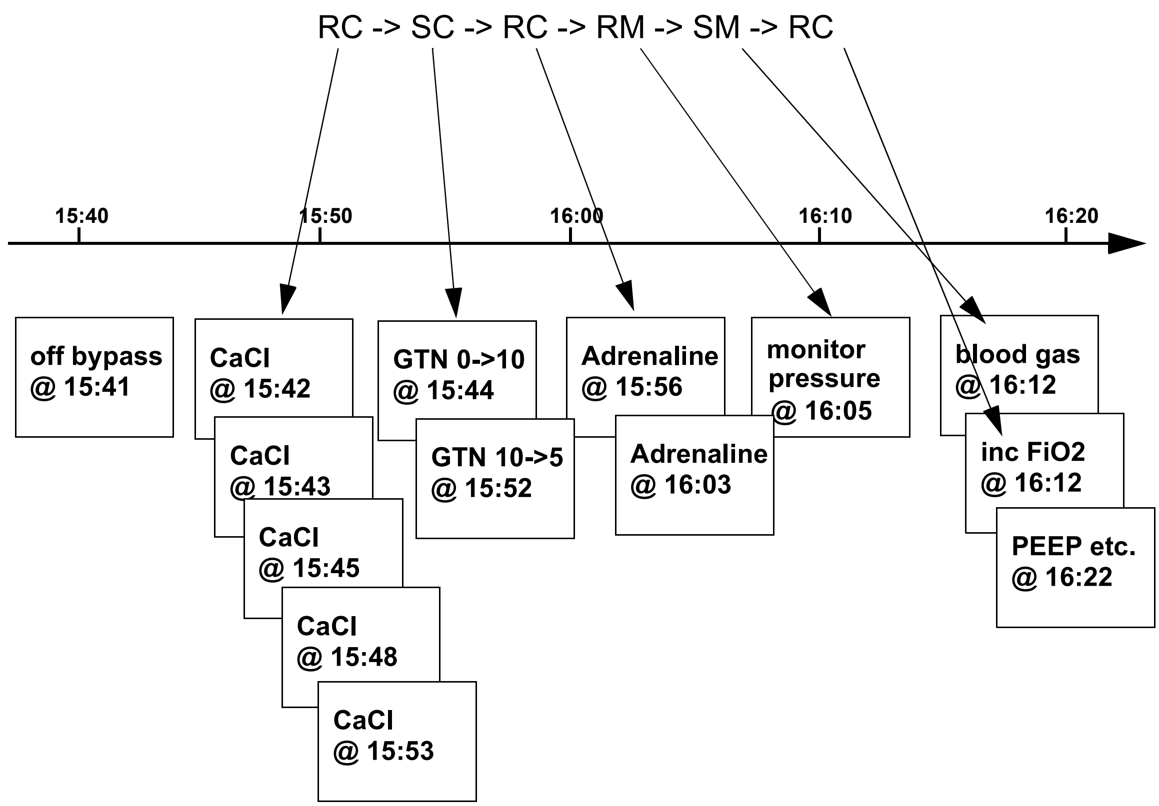


Figure 2. Clinical actions observed during event 5. Strategic(S) and Reactive (R) monitoring and control actions taken during the period of evolving hypoxia

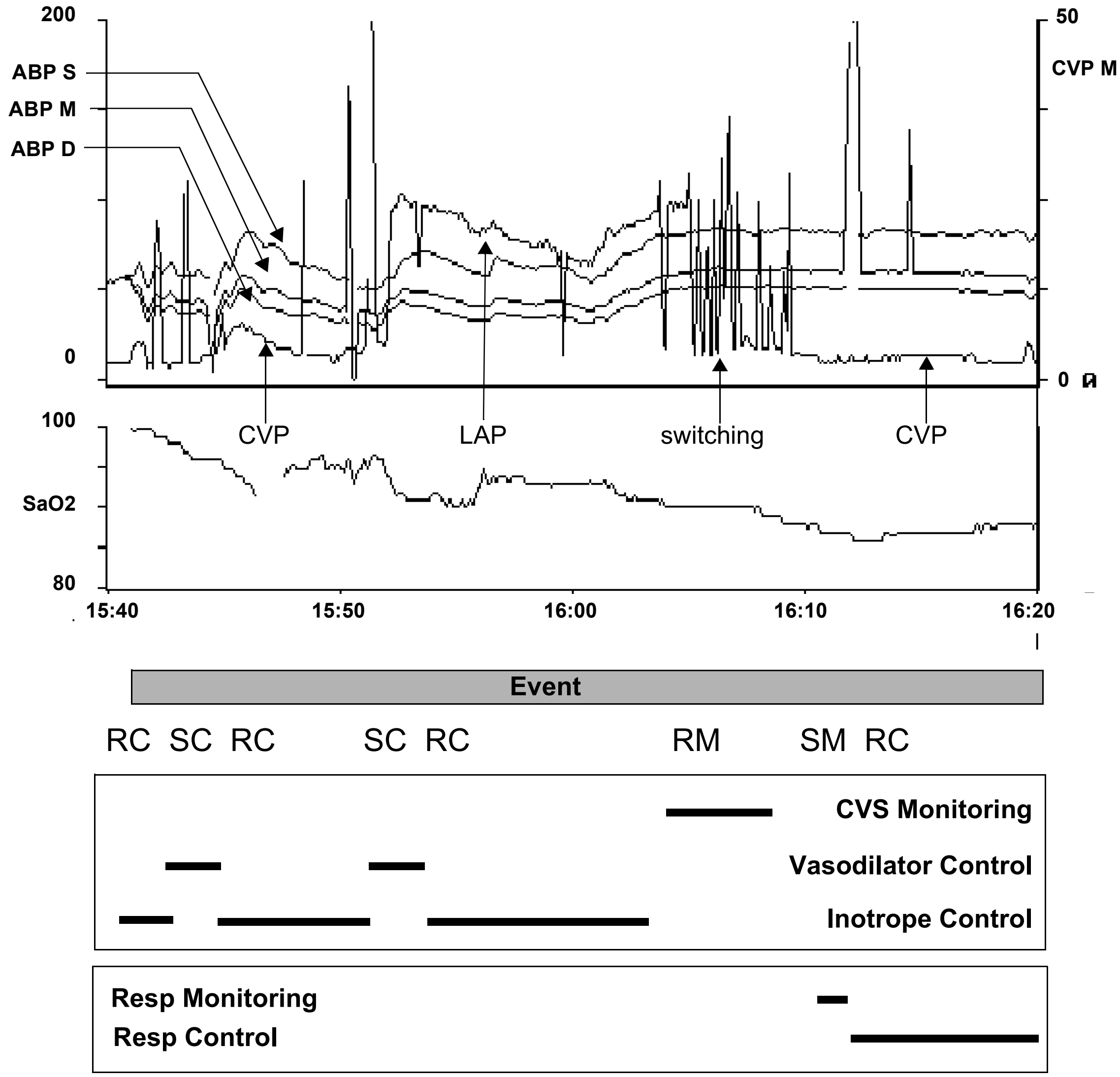


Figure 3. Time line for observed clinical tasks during event 5. Monitored data for event 5. Blood pressure changes during the dropping SaO_2 trend revealed relatively poor cardiac performance immediately post-bypass. By 16:00 the ABP systolic value is below 80 mmHG. The lower curve in the blood pressure set shows central venous pressure (CVP). For the middle third of this curve, the clinician uses the CVP transducer to measure left atrial pressure (LAP), and towards the end of this middle third, he switches repeatedly between the two (as evidenced by the spikes in the trace). The switching behaviour indicates a period of intense concentration on these values.

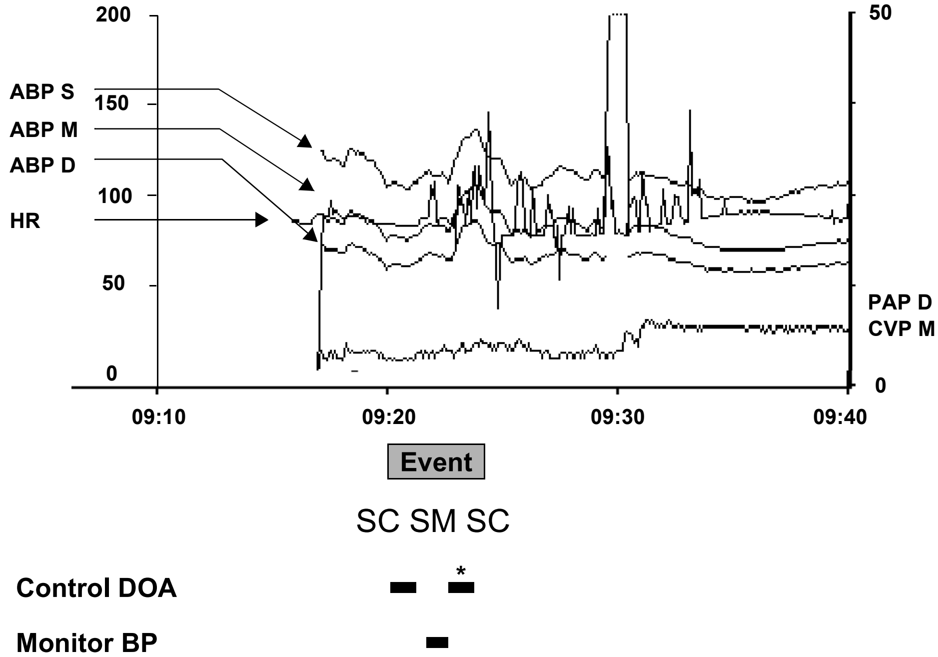


Figure 4. Time line for observed clinical tasks during event 1 - A 2 min. sharp rise in ABP systolic 100->140 mmHg at the beginning of surgery, due to inadequate anaesthesia. The event is bounded by skin incision and sternotomy. The rise was probably caused by a failure to observe the rise in ABP on skin incision, indicating that anaesthesia was inadequate, and the consequent delay in administering an intravenous does of anaesthetic agent (marked *) until sternotomy . (DOA - Depth of Anaesthesia)

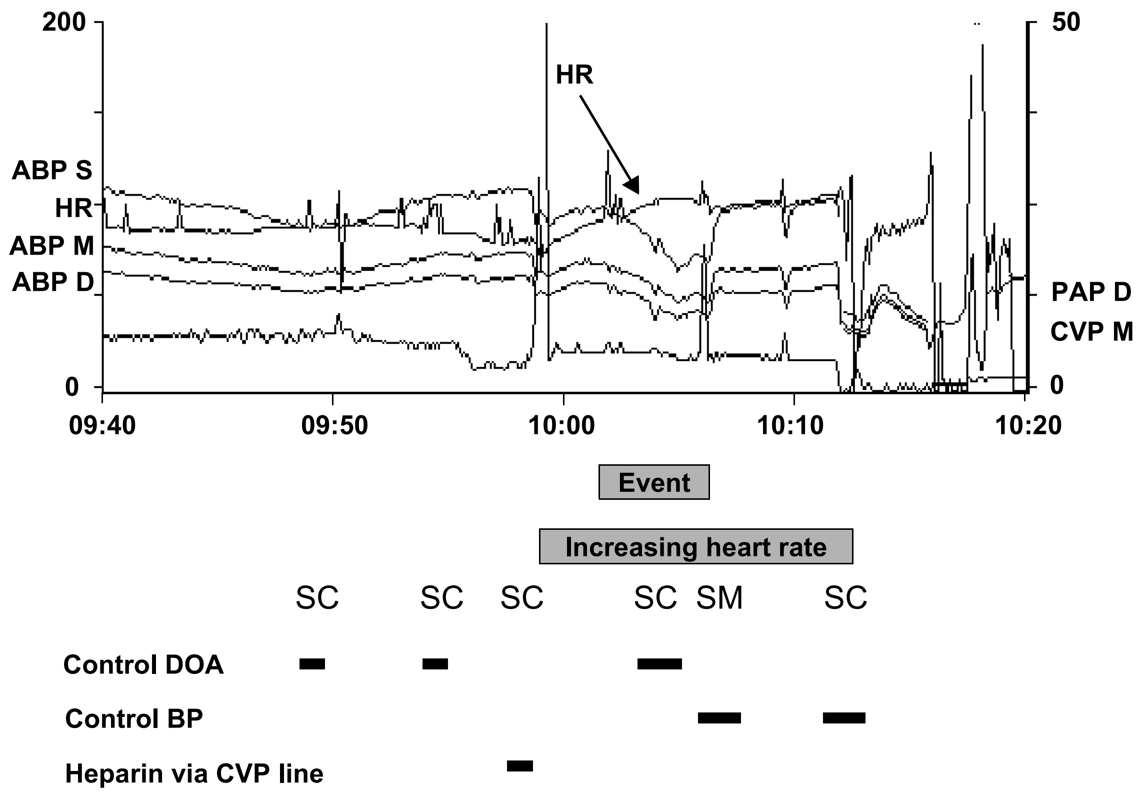


Figure 5. Time line for observed clinical tasks during event 2 - A 3 min. period of drop in ABP systolic 100->65 mmHg, prior to going onto cardiac by-pass at 10:11. Depth of anaesthesia is controlled by modifing the percentage on inspired anaesthetic gas : Enflurane is increased in 2 turns from 0.4% to 1.5% at 9:55 am. This along with a probable hypovolaemia (as evidenced by the increasing heart rate between 9:58 and 10:05), led to the drop in pressure. The Enflurane was then completely turned off at 10:05, followed by 2 doses of the drug Aramine in response to the drop in blood pressure. Possibly the subject focussed exclusively on optimsing blood pressure prior to going onto bypass, and consequently failed to note the evolving hypovolaemia. (DOA - Depth of Anaesthesia).

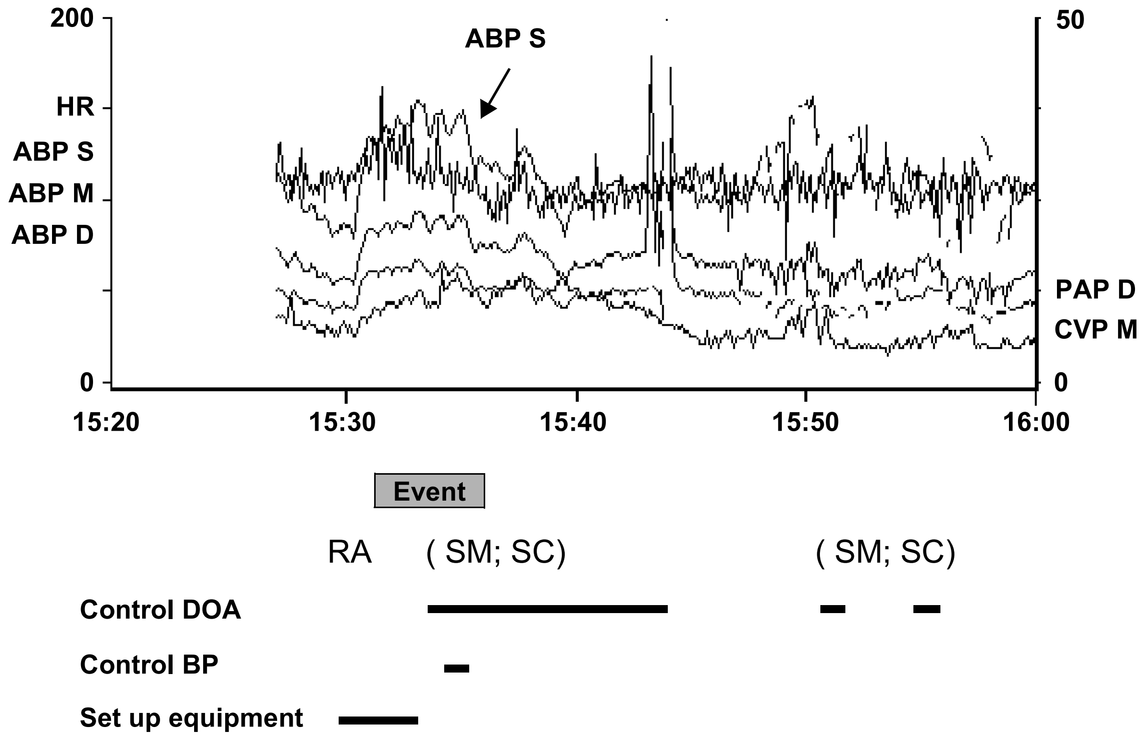


Figure 6. Time line for observed clinical tasks during event 3 - A missed 4 min. period of rise in ABP systolic from 95 to 140 mmHg. The event is bounded by skin incision at 15:00 and sternotomy commencing at 15:34. The subject delays noticing that depth of anaesthesia is inadequate until well into the event, primarily because he is distracted setting up iv syringe pumps during this period. Some equipment was unexpectedly unavailable, and the subject had to rearrange his expected set-up. Monitor alarms were disabled by the subject. (RA = Reactive Administrative task)

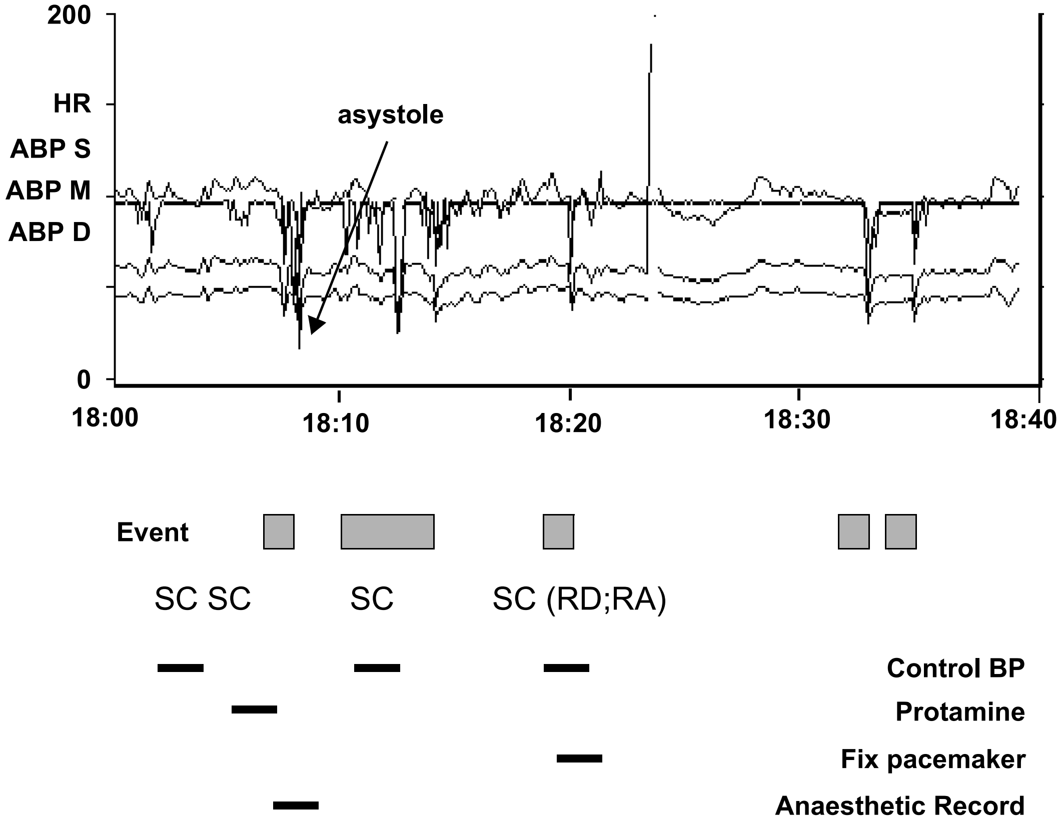


Figure 7. Time line for observed clinical tasks during event 4 - Missed repeated episodes of asystole due to intermittently faulty pacing wire. The subject was intercurrently busy with several tasks during the period of faulty pacing, including administration of drugs to control BP (Isoprenaline, followed by two adjustments to the GTN infusion rate), reversal of heparinisation with Protamine, and completing the anaesthetic record. The intermittent nature of the problem made it less likely that it woudl be detected on a routine monitor scan by the subject.

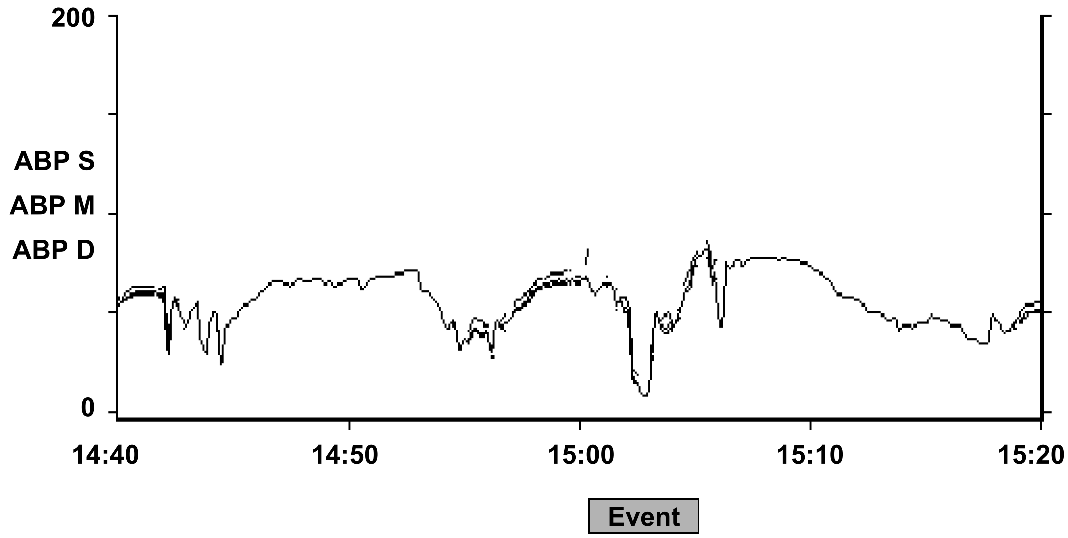
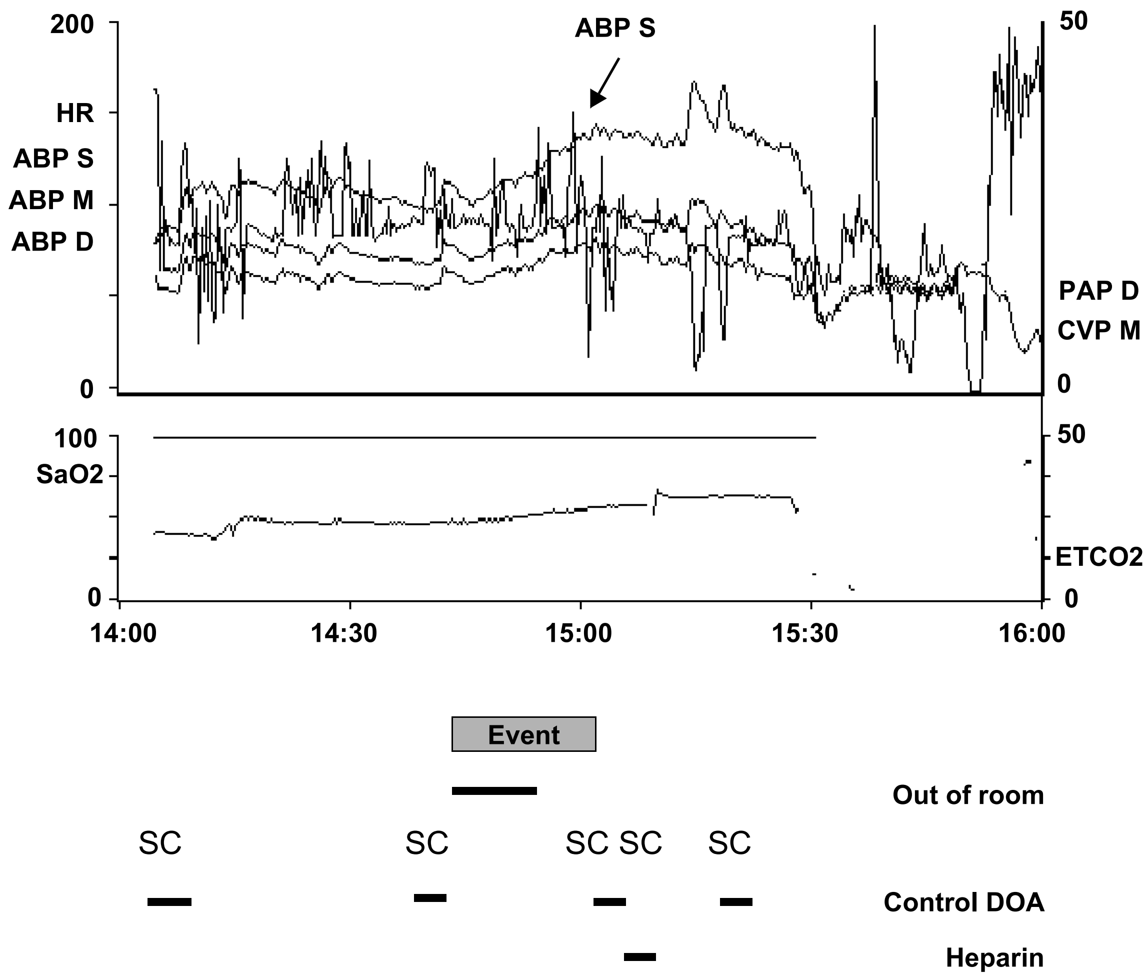


Figure 8. Timeline for event 6 - On cardiac bypass, a missed 30 s period of drop in mean ABP 68 -> 11 mmHg. The cause was probably a kink in the venous return tubing to the bypass machine. The subject was in the operating theatre, and had a relatively inactive role during the bypass phase. Nevertheless, she did not detect the short event, and was surprised to see it during the post-operative interviews. Had it persisted, it would have required rapid action on the part of the subject to protect the patient.



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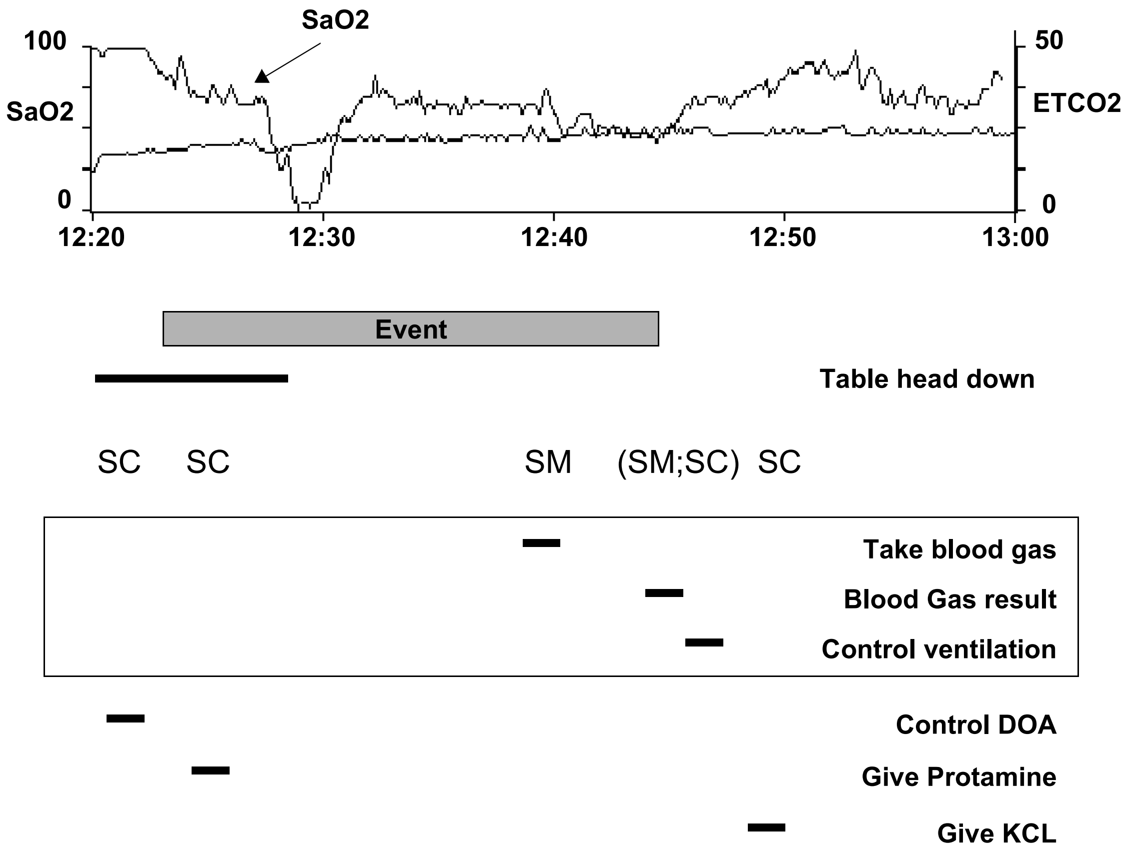

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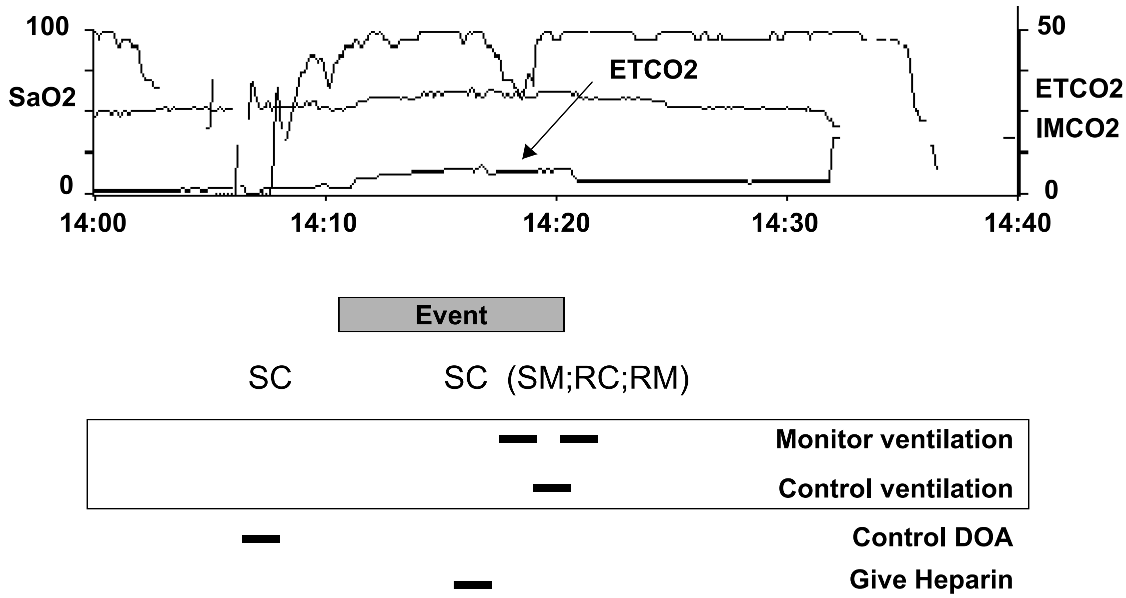

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