Expanding the Role of Mobile Devices in the Operating Room: Direct Wireless Connection to the Anesthesia Monitor

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MOST MODERN ANESTHESIA monitors provide an open-source communication interface to the monitored data. These interfaces are included in order to permit the hard-wired connection of the monitor to a separate recording system and to allow the integration of the monitor's data with that generated by other medical devices.

If the monitors are connected to a server-based patient information system, it is possible (but expensive) to transmit a subset of the monitored data to a mobile device ("the device") with a significant delay.[1,2] However, with the advent of wireless RS232 serial adapters, a direct connection between the device and the monitor (using either 'Bluetooth' or 'Wi-Fi' technologies) can be implemented and the complete monitored dataset then made available in near real time to the device user.

The processing power, display resolution, storage capacity, and connectivity of these devices is now so great that they can easily manage such connections. Furthermore, they can be "paired" simultaneously with other devices (such as "smart glasses" or "smart watches"), which then can process subsets of the monitored data in novel ways.

In this technical communication, a method for implementing real-time, wireless data transfer from an anesthesia monitor to a mobile device is described, and the feasibility of the technique is demonstrated using a simple data display and recording application. The potential applications of this technology are outlined, and, finally, the problems posed by direct wireless data transfer are mentioned.

IMPLEMENTATION

The requisite hardware and the programming techniques used in this implementation are described in greater detail in the Supplemental Digital Content. The technique required to implement the direct, wireless connection of a mobile device to an anesthesia monitor is illustrated here by reference to a version that runs on an Android® tablet or smartphone. The device acquires data wirelessly from a transmitter (Fig 1) attached to the monitor (GE Datex Ohmeda S5 Anaesthesia Monitor) and displays it in real-time as a series of user-selectable wave forms and numeric data fields (Fig 2). The user also is able to record the data on the device itself or to a web-based location.

Data Acquisition

Data are acquired using a Bluetooth adapter connected to the serial port (USB or RS232) of the monitor. The device is paired with the adapter and requests the monitor to transmit a stream of Datex-Ohmeda Records, which comprise continuous waveform data together with instantaneous values (such as heart rate or oxygen saturation).[3] The effective wireless range of the connection is 10 to 15 meters and the latency of signal display less than 1.5 seconds. If used with a Wi-Fi RS232 adapter, this effective range can be greatly increased.

Data Display

A single graphical waveform is displayed on the user interface (UI) of the device, but the user is able to view any other waveform variable by simply swiping the graphical display to the right or left. Five instantaneous values (such as heart rate, F_IO_2, SaO_2, $ETCO_2$, and respiratory rate) are displayed in numeric format at the bottom of the UI. These displayed values are also user-selectable. The waveform data are updated at 50 Hz and the instantaneous data at 0.2 Hz. Many mobile devices now incorporate Miracast® technology in which case the display can be mirrored onto a full high-definition television (HDTV) up to 10 meters away.

Data Recording

Data can be recorded on the device as fixed-length Datex-Ohmeda Records that accrue at a rate of about 6.5 MB/h. Used in this way, a 64-GB Micro SD card of the kind used by the device can hold about 10,000 hours of complete anesthetic data. If connected to the internet, the user also has the opportunity to upload the data to a remote storage site. In this way, the complete anesthetic record of a patient undergoing, for example, cardiac surgery, can be transferred to a remote site within a few seconds.

POTENTIAL APPLICATIONS OF THE TECHNOLOGY

Jorm and O'Sullivan[4] recently have drawn attention to the pervasive presence of personal mobile computing devices in the operating room and have remarked that although these devices can be used "to find out essential information for care of the current patient …this appears to be a rare occurrence."

However, it seems likely to the author that if the user has immediate, direct access to the monitor's complete dataset on their device, then its role in the operating room could be

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Fig 1. A Bluetooth RS232 serial adapter. Numerous such devices are available. The adapter enables the anesthesia monitor to appear as a pairable Bluetooth device on the user's mobile device. The adapters are typically Class 1 devices and have a range of about 100 meters. However, most mobile devices are Class 2 devices and have a range of only 10 to 15 meters.

significantly expanded. An enumeration of its potential roles might then include use as a secondary display, pairing with additional displays, data recording, the development of smart alarms, the integration of anesthetic data with data generated by other medical devices, retrospective data analysis, presentation of data in a novel fashion, development of novel performance indicators, and conduct of real-time randomization studies.

Use as a Secondary Display

In Figure 3, a Nexus 7 tablet is shown positioned just above the blood pressure transducers. It is being used as a secondary display and is able to present data that are not displayed currently on the primary monitor.

Pairing with Additional Displays

The author is experimenting with the simultaneous tethering of the mobile device to a pair of smart glasses (Fig 4). In this application, a dynamic, iconic representation of the current physiologic state is displayed at a constant position in the user's visual field (Video clips 1 and 2). The icon presents the patient's systolic blood pressure, pulse rate, saturation, and respiratory activity in an entirely graphical manner and is updated at 25 Hz (Fig 5). In designing the icon, the author has attempted to depict many of the important variables that are tracked during cardiac anesthesia and to present them in a manner that can be assimilated rapidly and in which deviation from normality can be readily detected. The author also has attempted to comply with the principles of graphical data display described by Drews and Westenskow.[5] The geometry of the display is such that if an adult is under stable anesthesia, the icons will be green, and the values they represent will be positioned in the central area of the reticule. This will symbolize a state in which the SaO_2 is greater than 95%, the systolic blood pressure is between 100 and 150 mmHg, the Bispectral index (BIS) between 40 and 60, and the end-tidal CO_2 between 30 and 45 mmHg. The current heart rate is indicated by the blink rate of the triangular icons and the respiratory rate by the rise and fall of the vertical bar icon. The efficacy of this display has not been formally evaluated. However, Liu et al[6] examined the utility of an (early) head-mounted display in the operating room and concluded that it "could help anesthesiologists free their attention from the patient monitor and focus on monitoring the patient's clinical signs and the surgical field."

Data Recording

Mobile devices are optimized for efficient internet activity and are well suited for contributing to internet-accessible registries of anesthetic monitoring data. Several uses for such registries have been described including pharmacodynamic

Fig 2. The user interface of the mobile device application. In this case, the application is being used to play back the anesthetic data of a patient shortly before weaning from cardiopulmonary bypass. Swiping the graphical display allows the user to switch between the available waveform variables. The Galaxy S4 display resolution is the same as that of an HDTV (1920 * 1080 pixels). The green triangular buttons to the left of the Y axis allow the signal gain to be varied. This image was acquired using the screenshot facility of a Galaxy S4.

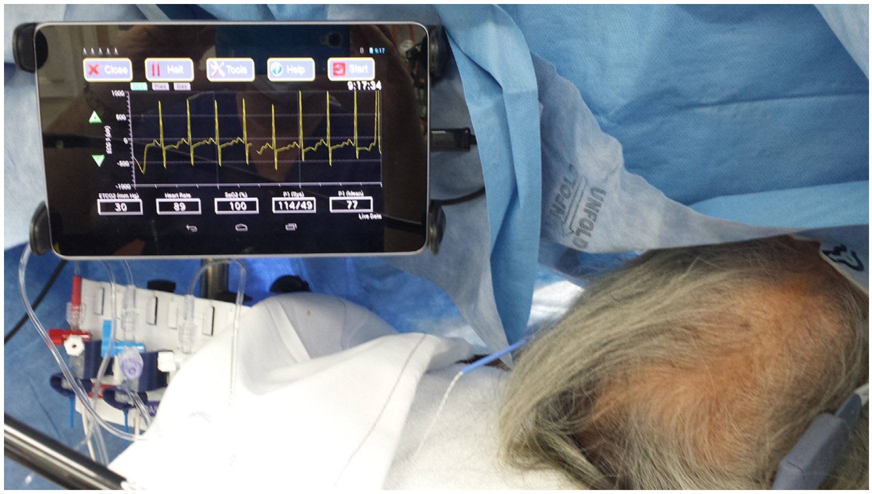

Fig 3. A Nexus 7 tablet is shown in use as a secondary monitor. It has been clamped to the drip pole just above the blood pressure transducer manifold. The patient's head can be seen to the right of the image. Owing to the highly reflective nature of Gorilla glass, a reflection of the photographer can also be discerned on the tablet display.

and simulation model validation and the development of diagnostic or predictive algorithms.[7–9] This application stores the data in a temporal database (flat file) of raw Datex-Ohmeda records. Temporal databases are designed for the high-speed storage and retrieval of data and can typically process millions of transactions per second. As a result, the data can easily be played back (ie, read from a data file and displayed) at the same rate as the data were recorded. This feature is particularly important if the data are used for the development or evaluation of real-time expert systems or smart alarms.

For comparison, Sessler recently has reviewed the emerging role of high-density data registries (Big Data) in the practice of perioperative medicine.[10] These registries generally are relational databases and, as a result, suffer from the problem of data granularity. (For example, blood pressure may be recorded once per minute rather than at the raw signal frequency of, for example, 100 Hz). Furthermore, relational databases are optimized for analyzing complex relationships between data and are not as well suited to real-time data analysis.

Development of Smart Alarms

Accessible data registries may facilitate the development of real-time decision support tools in the form of smart (context-sensitive) anesthetic alarms.[11] Sessler[10] has described such a system that is intended to assist in the maintenance of normothermia in patients undergoing surgery. The author is working on a similar system that analyzes four domains of the monitored dataset (circulation, oxygenation, ventilation and anesthesia). In this case, the expert system is being tested on the incoming data in real time and delivers its output in iconic format to the smart glasses (Fig 6).

By displaying the alarm state at a constant position in the anesthesiologist's visual field, it is possible that the need for auditory signaling of alarm conditions may be greatly reduced. In this regard, Edworthy[12,13] recently has reviewed the current status of audio alarms and has described the problem of high false-alarm rates as "the most significant current issue concerning (audio) alarms."

The Integration of Anesthetic Data With Data Generated by Other Medical Devices

It is quite easy to create interfaces to, for example, a heart-lung machine and an in-line blood gas analyzer and to combine the data from these devices with that provided by the anesthetic monitor. In this way, a single, coherent data stream (of Datex-Ohmeda records) can be created for a patient undergoing

Fig 4. The Optinvent ORA-S head-mounted display. The device can be used to display information in the periphery of the wearer's visual field and is paired with the user's mobile device using a wireless connection. The device also can incorporate an audio system. The loudspeaker can be used for the sonification of physiologic data signals and the microphone for interacting with an expert system.

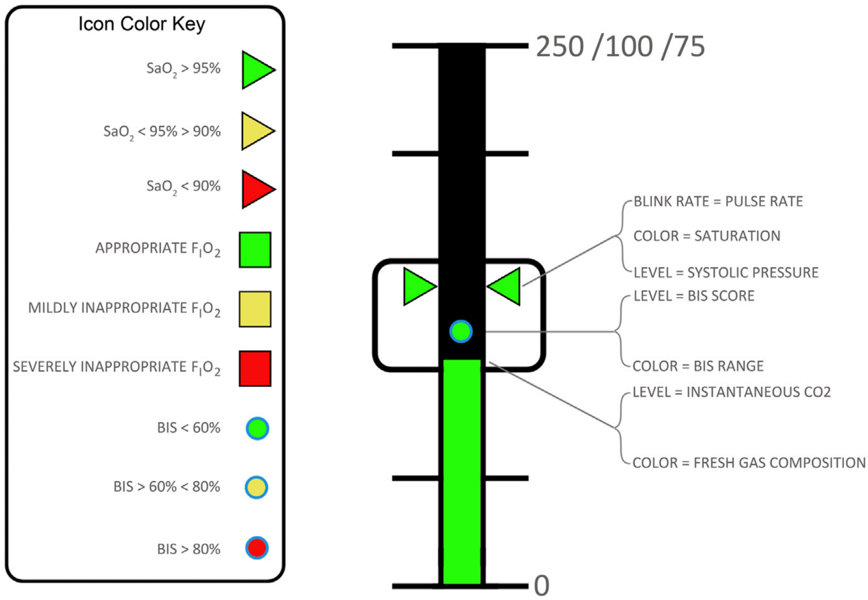

Fig 5. The status icon. The 2 triangular pulse indicators rise and fall according to the systolic pressure (in the range 0-250 mmHg). The indicators blink at the pulse rate and change color according to the current saturation. The circular BIS indicator rises and falls according to the bispectral index (in the range 0-100). If the index is greater than 80%, it is red. If the index is in the range 60% to 80%, it is orange. If it is less than 60%, it is green. The respiratory activity indicator rises and falls with the capnograph signal (in the range 0-75 mmHg). This indicator is green if the saturation is greater than 95%. If the saturation is in the range 90% to 95% and the F_IO_2 is less than 1.0, it is orange. If the saturation is in the range less than 90% and the F_IO_2 is less than 1.0, it is red. So as to reduce clutter, numeric values are intentionally not shown in the icon that appears in the visual field.

cardiac surgery. Similarly, data acquired from other anesthetic monitoring systems also can be transformed into Datex-Ohmeda records and thereafter stored, analyzed, and manipulated in exactly the same manner as raw Datex-Ohmeda data.

Retrospective Data Analysis

The granularity of the data stream is much finer than that acquired by manual or semi-automatic anesthetic charting. For comparison, in a personal audit of the author's handwritten charts, data were charted at 25 to 100 values per hour. The monitor itself recorded data at 500 to 1,000 values per hour, whereas the exemplar application recorded about 3 million values per hour. Clearly, much more detailed retrospective analysis of critical events is possible at this level of data granularity. Support for this view comes from Kadry et al[14] who recently stated, "The more critical the condition, the

Fig 6. A simulation of the `Smart Alarm' projected onto the user's visual field. The four components of the alarm represent the current status of the Circulation, Oxygenation, Ventilation and the depth of Anesthesia and are updated every five seconds. The evolution of an alarm state is shown in the figure. In the absence of any alarm condition, four green lights are shown (1). If the expert system detects an abnormality in any of the monitored domains, the appropriate light changes to orange (2) or red (3) according to the magnitude of the detected abnormality. In this case, the oxygenation alarm has been triggered. The complexity of the monitored environment is also well seen in this photograph.

more important it is to have a higher sampling frequency of meaningful data such as vital signs." In this regard, the ability to play back the complete anesthetic record (including waveforms) is particularly useful for presentations made at morbidity review meetings.

Presentation of Data in a Novel Fashion

Watson and Sanderson[15] have described the presentation of respiratory state data as an audio stream (sonification). If the device has been paired to smart glasses, some form of sonification can be implemented using the audio system of the glasses. If the device has been paired to a smart watch, the vibration function of the watch can be used to signal an alarm state to the wearer. Both presentation tasks can accomplished be easily by a mobile device.

Development of Novel Performance Indicators

Once a complete dataset has been acquired, it can be analyzed retrospectively from a quality improvement perspective. This technique has been described in detail for the assessment of the conduct of cardiopulmonary bypass.[16] In patients undergoing anesthesia, Sessler et al[17] identified a Triple Low State (low mean arterial pressure, low bispectral index, low minimum alveolar concentration) which, when present for more than 60 minutes, was associated with a quadrupling of 30-day mortality (in comparison with those in whom the state was present for 15 minutes or less), and they were particularly concerned because "the average low values for each state were well within the range that many anesthesiologists tolerate routinely." However, a more recent study has failed to confirm this observation,[18] and the finding has been the subject of editorial analysis and discussion.[19] In any case, it is easy to imagine other metrics that may be indicative of the quality of anesthesia. For example, during one-lung anesthesia, clinicians might measure the time-weighted sum of saturations of less than 90% and then use this index as a measure of the effectiveness with which the technique has been undertaken.

Conduction of Real-Time Randomization Studies

Sessler[17] also has described a novel form of study in which a therapeutic intervention (for example, the response to hypotension) is determined by a decision-support system that continually scans the incoming data and then randomly allocates the patient to receive a particular form of therapy. The efficacy of the chosen intervention then is assessed by measuring the response during the post-intervention period. This type of study performs best if the data are of fine granularity and immediately accessible, and the study is clearly possible using an application of this kind.

CONCLUSIONS

There are no technologic barriers to the implementation of the techniques that have been outlined above. A Bluetooth adapter, together with a suitable mobile device, can be purchased for less than $US300 (€200), and, because of advances in both hardware and programming systems, it is now possible for individuals to create any of the applications that have been described. Others also have commented on the ease and rapidity with which such mobile applications can be developed.[1]

However, significant problems remain. In particular, issues such as regulatory approval, the security and privilege status of recorded data and the problem of user distraction (by the device itself) remain largely unaddressed and unresolved. It is possible that solutions to these problems may transform this cheap and effective form of technology into a much more expensive medical technique.

Finally, it should be noted that the Datex-Ohmeda Record is a well-documented, open-source data structure that is very compact and permits extension to include patient or drug-administration data, calculated pharmacodynamic variables, or readings from other medical equipment. Furthermore, the records can be converted easily to other formats for the purposes of statistical or graphical analysis. It is for these reasons that the author believes that the Datex-Ohmeda record should be adopted as the standard data format for use by internet-accessible, temporal, anesthetic databases.[20]

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APPENDIX A. SUPPORTING INFORMATION

Supplementary material cited in this article is available online at doi:10.1053/j.jvca.2014.10.009.

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