Wireless On-Demand and Networking of Puritan Bennett 840 Ventilators for Direct Data Capture

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Manual transcription inaccuracies have been reported to be a frequent occurrence in clinical practice, which has been confirmed in my institution. I explored alternative methods of obtaining data directly from the Puritan Bennett ventilator. The aim of this project was to record all of the ventilator settings and monitored data with wireless technology. I evaluated 2 data-capture methods: on-demand data capture into a personal digital assistant, and continuous ventilator networking with a stand-alone computer. I was successful in both the intensive care unit and laboratory environment in transferring ventilator data, for up to several days, and with a data-capture interval as short as 60 seconds. *Key words: ventilator, data capture*. [Respir Care 2007;52(11):1530–1541. © 2007 Daedalus Enterprises]

Introduction

Accurate critical care data are a paramount foundation for making and implementing reasonable clinical decisions. Considerable variability of respiratory therapist (RT) documentation is reported, though with low compliance to the American Association for Respiratory Care clinical practice guidelines for patient-ventilator system checks.[1] Manual transcription charting errors are a frequent contributory factor in documentation flaws (13%).[2–4] There appear to be indicators that electronic charting offers an improvement over manual entry methods.[5]

There have been no reports of wide-scale adoption of electronic charting,[6,7] yet it is considered reasonable to avoid manual documentation where possible. Enlisting technology for data recording indicates a decline in error rates by as much as 50%.[8]

In the respiratory care profession, data recorded for mechanically ventilated patients, in most institutions, has been accomplished by manually transcribing information onto paper flow sheets by RTs and nurses at intervals that vary but are typically every 2–4 hours. Intermittent recording has been the common practice, but this standard may miss opportunities of detecting events that occur after these recording intervals.[9] The Joint Commission (formerly the Joint Commission on Accreditation of Healthcare Organizations) reviews reports of deaths or injuries related to long-term ventilation. A risk-reduction strategy of identifying causes, trends, settings, and outcomes of sentinel events is a priority for reducing injury. Current clinical alarm systems have been reported as a contributing factor, which suggests that outcomes should improve as additional information is recorded and analyzed.[10,11]

Furthermore, it is my experience in an academic medical center setting that ventilator adjustments are made on occasion by overly zealous and unauthorized non-respiratory-care staff. Ventilator changes may be accidental or "unclaimed" by an individual unwilling to assume responsibility. The effects that erroneous changes have are either no measurable impact on the patient or clinical compromise of their condition. In any event, these unauthorized changes are not coupled with concurrent adjustment of appropriate and institution-accepted alarm settings. When added to malfunctions—real or perceived—these are further reasons for heightening awareness by surveillance to improve the recording of ventilator settings and measured variables.

I considered the possible advantages of direct data transfer from the ventilator that would include a higher level of detail, the option for more frequent and unattended data

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Fig. 1. Puritan Bennett 840 ventilator RS232 data port.

capture, a high degree of accuracy when compared to manually recorded data transcription, and the detection of events not usually captured with every-2–4-hour recordings. The aim of this project was to successfully record all of the ventilator settings and monitored data from ventilators (840, Puritan Bennett, Pleasanton, California) with wireless technology.

Methods

A series of tests were performed to obtain data from Puritan Bennett 840 ventilators. Several tests were designed to confirm equipment functionality testing in the intensive care unit (ICU), with long-term data capture established in a laboratory setting. Testing included on-demand data transfer from the Puritan Bennett 840 to a personal digital assistant (PDA). Additionally, a stand-alone computer was used to create 2 types of networks, with 4 simultaneously operating Puritan Bennett 840 ventilators. The Puritan Bennett 840 ventilator communication port 1 was configured as follows: device control interface (DCI) output, baud rate 9,600, data bits 8, parity none.

Components and Software for Data Acquisition

PDA Data Capture. Bluetooth wireless technology was selected to transfer data from the ventilator into a PDA. A BluePort Bluetooth serial transceiver (model GC-BT-BluePort-Pair-DTE, Grid Connect, Naperville, Illinois) was attached to the RS232 data port (Fig. 1) on the ventilator. Serial data-collection software (TriConnect, Tridone, Bucharest, Romania) was installed in a PDA (Tungsten E2, Palm, Sunnyvale, California). The command SNDA was typed into the TriConnect software, followed by a carriage return. This required signal for initiating data transfer from the ventilator was programmed to be transmitted wirelessly via the BluePort transceiver for each series of data. The TriConnect software was also programmed to automate the transmission of the SNDA command every 60 seconds.

Computer-Based Network. Two types of networks were evaluated in laboratory and ICU settings. One network was established with Bluetooth, and the second with wireless fidelity (wi-fi) 802.11g network technologies.[12,13]

The Bluetooth network was established between 4 Puritan Bennett 840 ventilators and a laptop computer (Windows Vista operating system, Microsoft, Redmond, Washington) installed with BlueSoleil software (IVT Corporation, HaiDian District, Beijing, China). The hardware components included the single BluePort Bluetooth serial transceiver described above, connected to the RS232 data port of each Puritan Bennett 840 ventilator, and a Bluetooth USB dongle (BlueSoleil, IV_T Corporation, HaiDian District, Beijing, China). The SNDA command to and the data transfer from the ventilator were programmed to communicate wirelessly between the Bluetooth USB dongle and the BluePort transceiver. In the ICU setting, after establishing individual identity on the network, data were instructed to transfer every minute for 1 hour from the ventilators to the laptop computer via data-logging software (Advanced Serial Data Logger, AGG Software, Vladimir region, Kolchugino, Russia).

Following the Bluetooth tests, a wi-fi ad hoc (peer-to-peer network) was created. This separate network was created with the laptop's built-in wi-fi feature. The network adapter card was programmed with a unique Internet-protocol address and wirelessly networked with AirborneDirect Serial Bridge servers (DPAC Technologies, Garden Grove, California) (Fig. 2), installed on the RS232 serial port of each Puritan Bennett 840 ventilator. Each server was also configured with a unique Internet-protocol address.

In the laboratory setting, this software was programmed to control data transfer from the Puritan Bennett 840 ventilators every 60 seconds until intentional interruption after several days of operation. In the ICU setting, after establishing individual identity on the network, data were instructed to transfer every minute for 1 hour from the ventilators to the laptop computer. The ventilator data were instructed to transfer to the computer every minute via the data-logging software. Data transfer was directed to the computer's USB installed flash drive. Data were signaled

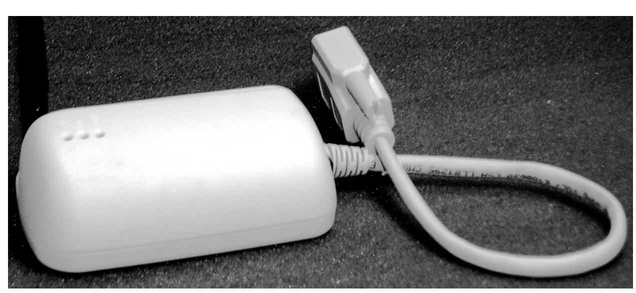

Fig. 2. AirborneDirect Serial Bridge.

to commence with the software programmed instruction SNDA, followed by a keyboard carriage return.

Results

Personal Digital Assistant Data Capture

In the laboratory setting the capacity of the PDA Notepad of 4 kilobytes for each "note" translated into a maximum of 44 transfer events of data transfer from the ventilator. In the ICU, 10 separate on-demand and 10 automated 60-second requests from the ventilator successfully transferred a total of 20 data streams. Each SNDA signal transmitted from the PDA resulted in data transfer from the Puritan Bennett 840, which was stored in the PDA Notepad.

Computer-Based Network

Individual ventilator server identity on the network was automatic as software was activated on the computer and as each Puritan Bennett 840 was cycled. In the laboratory setting, using Bluetooth technology, data were transferred from a single Puritan Bennett 840 ventilator every minute for 6.5 days, before intentional interruption, which represented 156 hours and 9,360 recorded events. In the ICU test, the SNDA signal transmitted every minute for 1 hour to 4 Puritan Bennett 840 ventilators. Sixty data-stream events were recorded from each of the 4 Puritan Bennett 840 ventilators to the laptop computer. All ventilator settings and measured variables were recorded in a text file on the flash drive.

In the laboratory setting, data log testing with the wi-fi network continued for 114 hours before intentional interruption, which resulted in the successful capture and text-file storage of 6,840 records. In the ICU wi-fi test, the data stream transferred for 1 hour, at 60-second intervals, from each of the 4 Puritan Bennett 840 ventilators to the laptop computer. The SNDA signal initiated and resulted in 60 events of data transferred and recorded from each ventilator.

Data Flow

Ventilator data were transferred on demand as a continuous stream of information. For the PDA evaluation these data were stored in the Palm Notepad as a text file. After synchronization to a Windows-operating-system computer, the file was imported into database software (Access, Microsoft, Redmond, Washington).

The computer-to-ventilator network data path also formed a text file. Microsoft Access linked that text file to the database table and updated it every minute as the data transferred from the ventilator.

Table 1. Data From a Single SNDA-Command-Initiated Ventilator Check Transfer*

,840 3510030304 , ,DEC 11 2006 ,CMV ,10.0 ,0.60 ,74 ,21 ,0.0
,3.0 ,0.0 , , , , ,20 ,0.36 ,10.0 ,22 ,100 ,0 ,RAMP , ,
,OFF , , , ,10 ,0.55 ,5.51 ,0.0 ,34.0 ,7.4 ,34.0 ,5.80 ,40 , ,
,0.26 ,2.5 ,100000,NORMAL , ,
,NORMAL,NORMAL,NORMAL,NORMAL,NORMAL,NORMAL,
NORMA
L, , ,11:34 , ,DEC 11 2006, , , , , , , ,4 ,3 ,
, , , , , , , , , , ,NOOP C,34.00 ,0 ,0.00 ,20
,0 ,10.0 ,0.00 ,100 ,40 ,OFF ,NORMAL,NORMAL,0.00 ,0.00 ,0.00
,0.00 , ,1:5.80,

*The data in this format requires delimiting and field assignment to be understood.

Delimiting the Data

The transmitted data from the Puritan Bennett 840 was stored in a text file. The file stored a continuous stream of data in which the individual fields were separated by commas (Table 1). The process that transferred the data from the text file was an import function into a Microsoft Access table. This transfer included a delimiter function of the data that removed the comma separators and placed the data into specific corresponding labeled fields described in the Puritan Bennett 840 operator's manual (Table 2).[14] Data stored in the tables was the basis from which the database queries and reports described below were created.

Discussion

Inaccurate data have been reported to be problematic.[1,2,4] At my facility we attempt to comply with American Association for Respiratory Care clinical practice guidelines for patient-ventilator system check.[9] We expect specific information to be recorded, as basic patient surveillance, to include alarm settings and ventilator measurements.[15,16] As examples of these expectations, ventilator records are to include the documentation of set alarms for circuit disconnect, high circuit pressure, low tidal volume (V_T), low positive end-expiratory pressure (PEEP), and high respiratory rate.

Inspection of 2,024,472 events of my institution's clinical data documentation between the years 2003 through 2006 revealed 136,400 transcription errors (a 6.7% error rate).[15]

Reviewed transcription events included illogical documentation of alarm or mode settings. These all indicate recording errors, which are described below.

- Disconnect alarm: if ventilator mode was assist-control (AC) or synchronized intermittent mandatory ventilation

Table 2. Data Fields for the Puritan Bennett 840 Ventilator Settings and Monitored Data

Component	Description of Data Sent From Ventilator
MISCA	Response to SNDA command
706	The number of bytes between Field <STX> and <ETX>
97	The number of Fields between Field <STX> and <ETX>
<STX>	Start of transmission character (02 hex)
Field 1	Ventilator time (HH:MM)
Field 2	Not used
Field 3	Not used
Field 4	Date (MMMDDYYYY)
Field 5	Mode (CMV, SIMV, or CPAP) (CMV = A/C, CPAP = SPONT) setting
Field 6	RR setting (breaths/min)
Field 7	V_T setting (L)
Field 8	PFR setting (L/min)
Field 9	O_2% setting
Field 10	Pressure sensitivity setting (cm H_2O
Field 11	PEEP setting (cm H_2O)
Field 12	Plateau time (s)
Field 13 to Field 16	Not used
Field 17	Apnea interval (s)
Field 18	Apnea V_T setting (L)
Field 19	Apnea RR setting (breaths/min)
Field 20	Apnea PFR setting (L/min)
Field 21	Apnea O2% setting
Field 22	Pressure support setting (cm H_2O)
Field 23	Flow pattern setting (square or ramp)
Field 24 and Field 25	Not used
Field 26	100% O_2 state (on or off)
Field 27 to Field 29	Not used
Field 30	Total RR (breaths/min)
Field 31	Exhaled V_T (L)
Field 32	Exhaled minute volume (L)
Field 33	Spontaneous minute volume (L)
Field 34	Maximum circuit pressure (cm H_2O)
Field 35	Mean airway pressure (cm H_2O)
Field 36	End inspiratory pressure (cm H_2O)
Field 37	Expiratory component of monitored value of I:E ratio, assuming inspiratory component of 1
Field 38	High circuit pressure limit (cm H_2O)
Field 39 and Field 40	Not used
Field 41	Low exhaled V_T limit (L)
Field 42	Low exhaled minute volume limit (L)
Field 43	High RR limit (breaths/min)
Field 44	High circuit pressure alarm status (normal, alarm, or reset)
Field 45 and Field 46	Not used
Field 47	Low exhaled V_T (mandatory or spontaneous) alarm status (normal, alarm, or reset)
Field 48	Low exhaled minute volume alarm status (normal, alarm, or reset)
Field 49	High RR alarm status (normal, alarm, or reset)
Field 50	No O_2 supply alarm status (normal, alarm, or reset)
Field 51	No air supply alarm status (normal, alarm, or reset)
Field 52	Not used
Field 53	Apnea alarm status (normal, alarm, or reset)
Field 54 and Field 55	Not used
Field 56	Ventilator time (HH:MM)
Field 57	Not used
Field 58	Date (MMMDDYYYY)
Field 59 to Field 65	Not used
Field 66	Ventilator-set base flow (L/min)

(Continued on next page)

Table 2. (Continued)

Component	Description of Data Sent From Ventilator
Field 67	Flow sensitivity setting (L/min)
Field 68 to Field 79	Not used
Field 80	End inspiratory pressure (cm H_2O)
Field 81	Inspiratory pressure setting (cm H_2O)
Field 82	Inspiratory time setting (s)
Field 83	Apnea interval setting (s)
Field 84	Apnea inspiratory pressure setting (cm H_2O)
Field 85	Apnea RR setting (breaths/min)
Field 86	Apnea inspiratory time setting (s)
Field 87	Apnea O2% setting
Field 88	High circuit pressure limit (cm H_2O
Field 89	Alarm silence state (on or off)
Field 90	Apnea alarm status (normal or alarm)
Field 91	Disconnect alarm status (normal or alarm)
Field 92	Inspiratory component of I:E ratio setting
Field 93	Expiratory component of I:E ratio setting
Field 94	Inspiratory component of apnea I:E ratio setting
Field 95	Expiratory component of apnea I:E ratio setting
Field 96	Constant during rate setting change for pressure control mandatory breaths (inspiratory time or I:E)
Field 97	Monitored value of I:E ratio
<EXT>	End of transmission
<CR>	Terminating carriage return

CMV = continuous mechanical ventilation
SIMV = synchronized intermittent mandatory ventilation
CPAP = continuous positive airway pressure
A/C = assist control
SPONT = spontaneous
RR = respiratory rate
breaths/min = breaths per minute
V_T = tidal volume
PFR = peak flow rate
PEEP = positive end-expiratory pressure
I:E = inspiratory-expiratory ratio

(SIMV) and set low-inspiratory-pressure alarm was recorded to be higher than measured peak airway pressure

- High pressure alarm: if ventilator mode was AC or SIMV and high-peak-airway-pressure alarm setting was recorded to be less than measured peak airway pressure
- Low V_T alarm: if ventilator mode was AC or SIMV and low-exhaled-V_T alarm greater than set V_T
- Low PEEP alarm was recorded to be higher than set PEEP
- If ventilator mode was AC, SIMV, or CPAP and the high-respiratory-rate alarm was recorded to be less than the measured total respiratory rate
- TotRRErr: if ventilator mode was AC or SIMV and set respiratory rate = 0
- Mode: if mode was SIMV or AC and exhaled V_T = 0
- Total breath time in time-cycled mode: If total of documented inspiratory time plus expiratory time was not equal to the calculation of the mandatory breath time or (60 s/breath/rate).
- Missing entries for total respiratory rate where ventilator mode was SIMV, CPAP, or AC

Considering the degree of transcription errors, it was considered a reasonable course to explore options for obtaining the data more accurately. With automated or on-demand electronic recording, errors in transcribing can be eliminated.

Data-logging recorders are not necessarily new technology; this tool is in widespread use for numerous applications. AntiLog RS232 (Anticyclone Systems, Hampshire, United Kingdom) and DataBridge SDR-CF (serial data recorder with compact flash data card, Acumen Instruments, Ames, Iowa) are examples of commercial data loggers. They are stand-alone recorders that read various types of electrical signals and store the data internally or on removable digital media. Widely available inexpensive data storage media are used of the type typically found in dig-

ICU-Rm: MICU - AM Shift

Tufts-New England Medical Center
Respiratory Care Programs

Therapist's

Vent SER NO: 840 3510040149

Date	11/29/2006				
	23:00	19:00	17:00	16:00	14:00
Mode	SIMV	SIMV	SIMV	SIMV	SIMV
VT	0.33	0.33	0.33	0.33	0.33
Rate	18	18	18	18	18
FIO2	40	40	40	40	40
PEEP	5	5	5	5	5
Trig Sens l/m	3	3	3	3	3
FlowPattern	RAMI	RAMI	RAMI	RAMI	RAMI
PFR	22	22	22	22	22
PSV	0	0	0	0	0
ESens%					
BiLev-PEEPH					
BiLev-PEEPL					
VTexhaled	0.28	0.28	0.08	0.08	0.07
VEspon	0	0	0	0	0
f Tot					
Mean AWP	27	27	10	10	10
Pawo	65	65	16	16	16
Min Vol l/m	5.04	5.01	1.44	1.35	1.35
I:E or 1:x.x	0	0	0	0	0
TimeHi					
TimeLo	1.00	1.00	1.00	1.00	1.00
DiscAlarm	NORMAL	NORMAL	NORMAL	NORMAL	NORMAL
Low Insp Pres					
Low Exh Vt	-1	-1	0.15	0.15	0.15
Low Exh VE	1.3	1.3	1.3	1.3	1.3
High RR	40	40	40	40	40
APNA O2%:	100	100	100	100	100

<<< Settings Measurements>>>

Fig. 3. Example report.

ital cameras. They are available in a range of capacities that allow data storage for periods of up to several days.

My decision to network ventilators was an attempt to channel multiple devices into a central storage device or laptop computer. This avoided manipulation of several pieces of portable digital media to and from a data log recorder, a laptop computer, and a desktop computer where final storage was compiled, plus the additional time required to play back or download the data. However, this method of capturing ventilator data in a stand-alone fashion is a reasonable alternative for single ICU facilities.

Reporting of Data

There is a large amount of information recorded with electronic data logging, which creates a challenge of organizing it for a meaningful display. In my network tests, each ventilator transferred data at 60-second intervals, which created 1,440 records daily from each ventilator. These data can quickly become unmanageable unless organized. This task was accomplished with Microsoft Access.

The data were stored in Microsoft Access tables, but it was the queries and finally the report feature that allowed designs for presentation. The reports can be as detailed or as compact as desired. Figure 3 shows a standard report form that we currently use, which demonstrates an end-of-shift document in which wirelessly transmitted data from the ventilator is displayed at 2-hour intervals. This is my department's standard interval for manual recording.

Reporting in Microsoft Access is flexible, and is dependent on individual needs for displaying data. For example, we desired an increase in patient surveillance, although there is no standard for recording the number of alarmed events, their duration, or the effect on other measured variables. In fact, we do not document these data currently, except in a narrative SOAP (subjective,

Status of Alarms

Date: November 2006

Date	SER NO	Time	Disconnect	Apnea	Alarm Silence	Hi Cir Press	Lo VT Exh	Lo Ve Exh	Hi RR	No O2 Supp	No Air Supp
	840 3510040149										
Summary for 'Date' = 11/29/2006 (530 detail records)											
		Alarm Event Violations:	16	0	530	1	184	95	11	253	0

Date: December 2006

Date	SER NO	Time	Disconnect	Apnea	Alarm Silence	Hi Cir Press	Lo VT Exh	Lo Ve Exh	Hi RR	No O2 Supp	No Air Supp
	840 3510030339										
Summary for 'Date' = 12/5/2006 (1 detail record)											
		Alarm Event Violations:	1	0	1	0	0	0	0	0	0

Date: February 2007

Date	SER NO	Time	Disconnect	Apnea	Alarm Silence	Hi Cir Press	Lo VT Exh	Lo Ve Exh	Hi RR	No O2 Supp	No Air Supp
	840 3510030307										
Summary for 'Date' = 2/5/2007 (232 detail records)											
		Alarm Event Violations:	4	0	232	229	229	229	16	0	0
		Grand Total - Alarm Event Violations:	23	0	763	230	413	324	27	253	0

Fig. 4. Example alarm events report.

Alarm violation effect:

SER NO 840 3510030307 Date by Month February 2007

Time by Month December 1899

Date	Time	MODE	RR	VT SET	O2%	PFR	PEEP	PSV	RR TOT	VT EXH	EXH VE	MV SPON	MAX CIR PRES	MAWP	END INSP PRES	EXP PART OF I:E MEAS	Disconect Alarm Status	Hi Pawp Alarm Status	Lo VTexh Alarm Status	Hi RR Alarm Status
2/5/2007	11:00:00 AM	CMV	16	0.38	21	22	5	0	16	0.33	5.26	0	30	15	30	1	NORMAL	NORMAL	NORMAL	NORMAL
2/5/2007	11:01:00 AM	CMV	16	0.38	21	22	5	0	16	0.33	5.25	0	30	15	30	1	NORMAL	NORMAL	NORMAL	NORMAL
2/5/2007	11:02:00 AM	CMV	16	0.38	21	22	5	0	16	0.33	5.25	0	30	15	30	1	NORMAL	NORMAL	NORMAL	NORMAL
2/5/2007	11:03:00 AM	CMV	16	0.38	21	22	5	0	16	0.33	5.26	0	30	15	30	1	NORMAL	NORMAL	NORMAL	NORMAL
2/5/2007	11:04:00 AM	CMV	16	0.38	21	22	5	0	16	0.33	5.24	0	30	15	30	1	NORMAL	NORMAL	NORMAL	NORMAL
2/5/2007	11:05:00 AM	CMV	16	0.38	21	22	5	0	16	0.33	5.25	0	30	15	30	1	NORMAL	NORMAL	NORMAL	NORMAL
2/5/2007	11:06:00 AM	CMV	16	0.38	21	22	5	0	16	0.33	5.24	0	30	15	30	1	NORMAL	NORMAL	NORMAL	NORMAL
2/5/2007	11:07:00 AM	CMV	16	0.38	21	22	5	0	16	0.06	0.93	0	18	5.8	18	11	NORMAL	ALARM	ALARM	NORMAL
2/5/2007	11:08:00 AM	CMV	16	0.38	21	22	5	0	16	0.04	0.78	0	18	5.8	18	12	NORMAL	ALARM	ALARM	NORMAL
2/5/2007	11:09:00 AM	CMV	16	0.38	21	22	5	0	16	0.05	0.77	0	18	5.8	18	11	NORMAL	ALARM	ALARM	NORMAL
2/5/2007	11:10:00 AM	CMV	16	0.38	21	22	5	0	16	0.04	0.75	0	18	5.8	18	11	NORMAL	ALARM	ALARM	NORMAL
2/5/2007	11:11:00 AM	CMV	16	0.38	21	22	5	0	16	0.32	1.27	0	29	6.9	29	1	NORMAL	RESET	RESET	NORMAL
2/5/2007	11:12:00 AM	CMV	16	0.38	21	22	5	0	16	0.33	5.25	0	30	15	30	1	NORMAL	RESET	RESET	NORMAL
2/5/2007	11:13:00 AM	CMV	16	0.38	21	22	5	0	16	0.33	5.25	0	30	15	30	1	NORMAL	RESET	RESET	NORMAL
2/5/2007	11:14:00 AM	CMV	16	0.38	21	22	5	0	16	0.33	5.25	0	30	15	30	1	NORMAL	RESET	RESET	NORMAL
2/5/2007	11:15:00 AM	CMV	16	0.38	21	22	5	0	16	0.33	5.25	0	30	15	30	1	NORMAL	RESET	RESET	NORMAL

Fig. 5. Example alarm violation effects report.

objective, assessment, plan) note for witnessed events. Figure 4, as an alternative to displaying large volumes of data, including alarm events, demonstrates the number of alarm violation occurrences in a single form of summarized data. While also assessing measured variables, the clinician can objectively determine cross-relationships between alarm events with clinical impact, as seen in Figure 5. Finally, trending of the data may be desirable, but it is not available on most ventilators, including the Puritan Bennett 840. Figure 6 demonstrates an export of the graphed data in Microsoft Excel.

Alternatives for Obtaining the Data

Table 3 shows several options for recording ventilator settings and measured variables from a ventilator, including manual transcription methods and digital technologies.

Manual Transcription

Paper Forms. RTs and other clinical staff routinely manually record ventilator settings and measured variables.

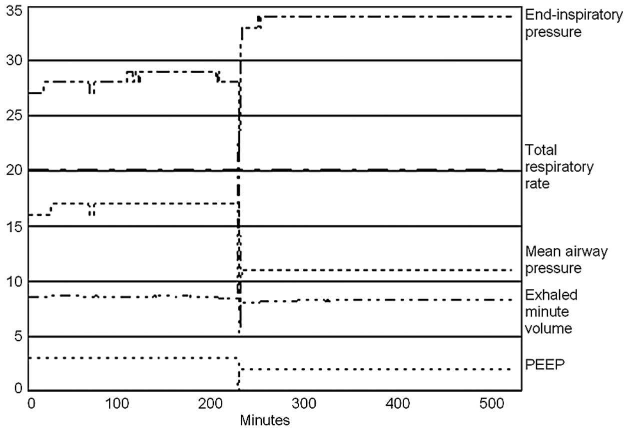

Fig. 6. Example of graphed data.

With the majority of patients who receive mechanical ventilation, manual transcription is by far the most performed method.[9]

Handheld Recording Device. PDAs have been used at my site for several years.[15,16] PDA use has been limited to intermittent recording of each ventilator setting and measurement, as a replacement to manual-entry paper forms.

Digital Recording of Individual Ventilator Checks Into a Handheld Computer

Using a PDA and TriConnect software for serial data collection, approximately 45 events can be logged into a single text file. The text files require synchronization to a computer, where they would then be uploaded into software such as Microsoft Access for delimiting, storage, analysis, and reporting.

Stand-Alone Unattended Data Logging

Commercial self-contained data loggers, such as the AntiLog RS232, are available to capture data for up to several days. Each ventilator would require a single unit and data transfer to and delimiting on a computer.

Although capable of performing a similar function as a self-contained data logger, PDAs have an important restriction for recording frequent events. The restriction is the limitation that the Palm operating system has for storing data. With the TriConnect PDA software noted above, data storage is routed to the PDA's Notepad. Palm Notepad is limited to a storage capacity of 4 kilobytes. This represents approximately 45 data events for each file from a critical care ventilator such as a Puritan Bennett 840. This capacity would allow ventilator checks every 4 hours to occur 6 times a day for about 2 days per note. It is reasonable if performing ventilator checks every 4 hours, but does not account for additional recordings attributed to ventilator adjustments more frequent than that. Also, this automated setup requires a single, externally powered PDA mounted on each ventilator.

Networking

The challenge in the present study was to acquire the data produced by the ventilator and electronically record it, with a goal of eliminating transcription errors by clinicians. These data are displayed by the ventilator but remain internal (or are purged when the memory limit is exceeded), unless very limited capital funds are obtained for external data-capture equipment and software. Commercial examples for networking ventilators include Clinivision, and Bernoulli Ventilator Management System (Cardiopulmonary Corporation, Milford, Connecticut).

Ventilator manufacturers (eg, Puritan Bennett, Viasys Healthcare, and VersaMed) locally log measured variables and alarm events and adjustments made by the clinician. Only by adding VentView software (Dräger, Telford, Pennsylvania) will their ventilators allow the clinician to acquire measured and set values and alarm messages.[17] These data can be tracked over periods of up to 10 days and can be exported to a spreadsheet or a database. However, a dedicated computer and spare RS232 data port is required for each ventilator.

The Puritan Bennett 840 internally logs setting changes and alarmed events, but, again, the data remain within the ventilator. Print drivers for hard-copy documentation or a means to download the data onto storage media are not available for current-generation ventilators. To obtain the data for analysis or download, the end-user is obliged to buy expensive third-party software.

Third-party manufacturers offer the feature of direct data transfer to recording devices, allowing the clinician access to the data for digital storage, analysis and reporting. However, without significant hardware and software expense, the majority of clinicians are limited to the localization of the data within individual ventilators. These systems represent a $250,000 to $600,000 expense for a facility the size of Tufts-New England Medical Center. Because of this expense, less than 2% of hospitals in the US have secured funding to make this transition to digital recording.[15] This expense was not considered financially feasible at our institution, so we developed methods to capture and store these data with an inexpensive alternative. The networking expense for a typical ICU was less than $2,700, and is itemized in Table 4.

Network Data Logging. With the attachment of wireless (Bluetooth or wi-fi) transceivers to the RS232 port of

Table 3. Options Available for the Recording Data From Patients Who Are Receiving Mechanical Ventilation

Data-Recording Option	Associated Expense	Advantages	Disadvantages
Manual transcription on paper forms	Art work Forms Long-term storage	Time-honored standard Easy to use	Time-honored standard May be illegible Expensive to store Difficult to analyze data from multiple records Intermittent data record: events between ventilator checks missed
Manual transcription into handheld recording device	Software Handheld recording device Bulk paper to print reports	Legible Easy to use Digital data allows convenience to analyze data	Intermittent data record: events between ventilator checks missed
Digital recording of individual ventilator checks into personal digital assistant	Software Handheld recording device Bulk paper to print reports	Legible Easy to use Avoids manual-transaction errors Faster recording process than manual entry	Intermittent data record: events between ventilator checks missed Limited to about 40 ventilator checks for each text file Numerous files are cumbersome to work with Requires upload into computer, with the delimiting of the data prior to finished report presentation
Stand-alone unattended data-logging with user defined frequency of recording	Data-logger device Software Bulk paper to print reports	Legible Detailed record of ventilator settings, measured variables and events Easy to use Avoids manual-transcription errors Eliminates need to manually enter data	Multiple units required: one for each ventilator Not networked to central computer Intermittent data record: events between ventilator checks missed Required upload of each device's data into computer Data-delimiting required to prepare finished report If not networked, data remain resident on the computer until data are retrieved
Networked data-logging with unattended data-logging	Stand-alone or network computer with wi-fi capability Wireless server for each ventilator Software	Unattended data recording as often as every minute Detail of ventilator settings and measurement changes that occur after previous patient and ventilator assessment	If not networked, data remain resident on the computer until data are retrieved
Trended memory data-capture: individual ventilator based	Not applicable with the Puritan Bennett 840 ventilator	None	Localized to individual ventilator: not networked Most manufacturers do not provide means to download data to storage media and do not allow data to be printed
Data-capture routed to third-party software	Vendor-specific software Annual maintenance	Unattended data recording as often as every minute Detail of ventilator settings and measurement changes that occur after previous patient and ventilator assessment	Very expensive

Table 4. Expenses of Networking Puritan Bennett 840 Ventilators in a 10-Bed ICU

Item	Cost/Unit ($)	Number of Components	Extended Expense ($)
Server	160	10	1,600
Computer with wireless networking and Microsoft Access installed	900	1	900
4-gigabyte USB flash drive	50	1	50
Advanced TCP/IP data-logger	65	1	65
Total	1,175	13	2,615

USB = universal serial bus
ICU = intensive care unit
TCP/IP = transmission control protocol/Internet protocol

an individual ventilator, data can be transferred to a computer at a predetermined interval, with a frequency as often as every minute. This frequency is more often than practical with manual entry. The amount of detail that can be captured by the date-and-time-stamped method is substantially greater than the amount captured by manual documentation methods.

Data from all ventilators within an ICU can be routed to a stand-alone desktop or laptop computer. Database software can receive these data directly into tables, from which queries and reports are designed.

The option for unattended automated recording was evaluated because clinical events that precede alarm conditions may increase our knowledge of the patient's status between attended and intermittent assessments. There is currently no standard to document when a ventilator alarm occurs or even to document how often it occurs. Capturing this information with frequent unattended recordings may be helpful in determining opportunities for intervention.

Ventilator errors, mishaps, or mistakes that result in sentinel events do occur.[16,18,19] These events affect patients, possibly preceded by clinical deterioration that may be pathological or equipment-related. RT-set alarms detect events once thresholds are violated. However, leading up to the alarm condition, additional surveillance may be valuable in determining which event(s) initiated the patient's deterioration.

The Technology

The testing in the present study included 2 methods of obtaining data output from Puritan Bennett 840 ventilators: PDA and desktop or laptop computer-based networking. The technology described in this paper includes components that wirelessly transfer data from a ventilator to a flash drive for short-term digital storage. Both the Bluetooth and the wi-fi methods were reliable, but each has advantages and disadvantages, as described in Table 5. Wireless technology was favored to avoid the expense and time in constructing a dedicated wired network.

The data stream obtained through the ventilator's RS232 port was considered as an opportunity for recording with higher accuracy and frequency, when compared to manual transcription.[1–4] In telecommunications, the RS232 port is a standard for serial binary data interconnection between a DTE (data terminal equipment) and a DCE (data circuit-terminating equipment). It is commonly used in computer serial ports.[20,21] While such interfaces as Ethernet, FireWire, and USB all send data as a serial stream, the term "serial port" usually identifies hardware compliant to the RS232 standard.

In computing, a serial port is a serial-communication physical interface through which information transfers in or out one bit at a time. Throughout most of the history of desktop and laptop computers, data transfer through serial ports has connected the computer to devices such as terminals and modems. Mice, keyboards, and other peripheral devices have also connected in this way.

Bluetooth is a short-range communications technology intended to replace cables for connecting portable and/or fixed devices while maintaining a high level of security. The key features of Bluetooth technology are powerful, low operating energy, and low cost. The Bluetooth structure supports a wide range of devices, including medical products, to connect and communicate with each other. Any Bluetooth-enabled device has the ability to connect to other Bluetooth-enabled devices in proximity. Bluetooth-enabled electronic devices connect and communicate wirelessly through short-range, ad hoc networks known as piconets.[22]

Each device can simultaneously communicate with up to 7 other devices within a single piconet. Each device can also belong to several piconets simultaneously. Piconets are established dynamically and automatically as Bluetooth-enabled devices enter and leave radio proximity. This enables opportunities for creative solutions, such as synchronizing PDA, laptop, and medical devices.

Bluetooth technology operates in the unlicensed industrial, scientific, and medical (ISM) band, at 2.4–2.485 GHz, and uses a spread-spectrum, frequency-hopping, full-du-

Table 5. Advantages and Disadvantages of the Electronic Methods for Recording Data From the Ventilator

	Bluetooth	PDA	Computer or Laptop-Based Wi-Fi 802.xxx
Advantages	Inexpensive Accurate Easy to establish wireless component connection	Inexpensive Accurate: ability to replace manual-transcription errors	Fairly inexpensive Centralizes data collection for multiple ventilators Capacity of storing many days worth of information Accurate Negates the need and expense for a wired dedicated network Continuous, automatic unattended flow of data Increased surveillance and ability to reconstruct unwitnessed clinical events Data storage is unlimited Range is dependent on building construction but is significantly superior to Bluetooth
Disadvantages and/or considerations	Range is limited to within 3–4 feet of the ventilator	Data require delimiting on a computer Limited to intermittent ventilator checks Software limited to approximately 40 ventilator-data-transfer events per Notepad note	Data require delimiting on a computer

PDA = personal digital assistant
Wi-Fi = wireless fidelity

plex signal at a nominal rate of 1,600 hops/s. The 2.4-GHz ISM band is available and unlicensed in most countries and is not in conflict with frequencies of other hospital-used wireless devices (pacemaker programmers, telemetry transmitters), Nextel phones, security walkie-talkies, or cell phones that operate in the 400–900 MHz range.

Bluetooth technology's adaptive frequency-hopping capability was designed to reduce interference between wireless technologies sharing the 2.4-GHz spectrum. Adaptive frequency-hopping works within the spectrum to take advantage of the available frequency. This is done by detecting other devices in the spectrum and avoiding the frequencies they are using. This adaptive hopping allows for more efficient transmission within the spectrum and provides users with greater performance, even if using other technologies along with Bluetooth technology. The signal hops among 79 frequencies, at 1-MHz intervals, to give a high degree of interference immunity.

The operating range depends on the device class. Class 3 radios have a range of up to 3 feet. Class 2 radios (which I used in this research) have a range of 30 feet. Class 1 radios (used primarily in industrial use cases) have a range of 300 feet. The most commonly used radio is Class 2, which uses 2.5 mW of power. Data transmission rates range from 1 megabyte/s, with version 1.2 and up, to 3 megabyte/s, with version 2.0.

The term wi-fi is used generically when referring to any type of 802.11 network. Wi-fi is a communications system that transmits computer data over short distances via radio waves.[13] A wi-fi network operates just like a wired network, in the unlicensed 2.4 GHz and 5 GHz radio bands, without the restrictions imposed by wires. All wi-fi systems follow a standard known as 802.11, which was created by the Institute of Electrical and Electronics Engineers (IEEE).

The IEEE published 3 specifications for wi-fi systems, 802.11a, 802.11b, and 802.11g, with performance similar to the basic 10BaseT wired Ethernet networks used in many offices. The data transmission rate ranges from 11 megabyte/s (802.11b) to 54 megabyte/s over a range of 100–1000 feet. A wi-fi network can be used to connect computers to each other, to the Internet, to medical devices, and to wired networks (which use IEEE 802.3 or Ethernet).

We developed an ad hoc network for this project.[13,22] In an ad hoc network, there is no fixed infrastructure such as base stations or mobile switching centers. Mobile nodes that are within each device's radio range communicate directly via wireless links, whereas those that are far apart rely on other nodes to relay messages as routers. Node mobility in an ad hoc network causes frequent changes of the network topology. When networked devices move out of radio range, the link is broken. However, the communication is still available for devices programmed for the specific network once within range.

Military tactical operations are still the main application of ad hoc networks today. For example, military units (eg, soldiers, tanks, or planes) equipped with wireless communication devices could form an ad hoc network when they roam in a battlefield. Ad hoc networks can also be used for emergency, law enforcement, and rescue missions. Since an ad hoc network can be deployed rapidly with relatively low cost, it becomes an attractive option for commercial uses.

Although wireless transmission is short-range, security must be addressed.[23–25] This private information needs to be communicated securely to its intended recipient, without interception. Wireless standards have various formats for dealing with the security issues that evolved from the Bluetooth Special Interest Group, which was made up of over 4,000 member manufacturers. This group includes Bluetooth security experts, made up of engineers from its member companies, who provide critical security information and feedback. The BlueSoleil software used in the present research offers 3 security levels:

- Low (security mode 1). No security procedure is needed for connections.
- Medium (security mode 2, service-level enforced security). Authentication or authorization is requested when a specific service is accessed by other Bluetooth-enabled devices. If 2 devices are connecting for the first time, or if 2 devices do not have a trusted relationship, then the same pass-key must be provided on both sides to complete the authentication. This mode allows you to assign different access rights for each service supported by the server.
- High (security mode 3, link-level enforced security). If either of 2 devices is in security mode 3, authentication is required to establish a connection between 2 Bluetooth devices. The pass-key must be provided on both sides to complete authentication.

Wi-fi also creates a wireless networking problem, due to the distance possibilities associated with increased coverage range.[13] The wi-fi components and software used in the present research offer WEP (Wired Equivalency Protocol) or WPA (Wi-fi Protected Access) encryption. Security flaws in the WEP standard allow hackers to violate protective measures easily. WPA is a far stronger protocol that fixed the weaknesses in WEP. In practical terms, wireless transmission is secure and remains within the confines of the intended range. Although data were transmissible within an ICU, range restrictions of Bluetooth and wi-fi prevented connection even one floor outside of the ICU or one building away from my medical center.

Conclusions

The careful reader may be tempted to ask why we want to have all of these data. There are several reasons, including higher accuracy of recorded ventilator settings and monitored values when compared to manual transcription, and the detection of ventilator changes that were made in the absence of a respiratory therapist, when the adjustments were made, how often set alarms were violated, the duration of the event, and how the patient was affected. This method of data acquisition offers a higher degree of surveillance with possibilities of producing error free information for research.

A higher frequency of data recording, compared to the intermittency common to the respiratory care profession of every 2–4 hour ventilator checks, provides accuracy, detail, and the ability to "reconstruct" clinical events that may otherwise be unnoticed. Reconstruction of unattended and unwitnessed events is often highly speculative and lacking specific detail. The added frequency of data capture features the potential for significantly superior recording and surveillance of a dynamically changing patient condition, which may benefit patient outcomes.

The frequency of surveillance in the present study increased to an interval of 60 seconds, from the traditional and standard interval of 2–3 hour recording. Although there are ventilators that log each adjustment or alarm violation, there is no industry standard to require manufacturers to implement this. Internal logs are purged as the capacity of the internal memory is exceeded, and the clinician is not allowed to download or print this valuable information without expensive third-party solutions. Our ability to network and collect the data appears to be a significant benefit. This method of data acquisition is a step toward objectivity that identifies and digitally records settings and measured ventilator values surrounding clinical events. These include ventilator identification, date-and-time stamping, the logging of silenced alarm duration, and the amount of time until restoration of clinical values that no longer violated these alarms. The ability to download and archive these data is, to our knowledge, not a feature that has been reported before.

The benefits of increased surveillance and data capture have educational opportunities to demonstrate the effects of ventilator adjustment on the measured data points. With a computer these data may be stored for analysis and, as desired, graphically displayed.

Although not tested, the potential exists to wirelessly network additional ICU equipment that has an RS232 port, using the same serial servers and software network described in the present paper. Much of the data generated in today's ICU can be recorded and made available for analysis. Unfortunately, the majority of these data are not recorded and may hold clues that upon inspection could possibly lead to improvements in practice and outcomes.

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