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Using "off-the-shelf" tools for terabyte-scale waveform recording in intensive care: Computer system design, database description and lessons learned☆

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ABSTRACT

Until now, the creation of massive (long-term and multichannel) waveform databases in intensive care required an interdisciplinary team of clinicians, engineers and informaticians and, in most cases, also design-specific software and hardware development. Recently, several commercial software tools for waveform acquisition became available. Although commercial products and even turnkey systems are now being marketed as simple and effective, the performance of those solutions is not known. The additional expense upfront may be worthwhile if commercial software can eliminate the need for custom software and hardware systems and the associated investment in teams and development.

We report the development of a computer system for long-term large-scale recording and storage of multichannel physiologic signals that was built using commercial solutions (software and hardware) and existing hospital IT infrastructure. Both numeric (1 Hz) and waveform (62.5–500 Hz) data were captured from 24 SICU bedside monitors simultaneously and stored in a file-based vital sign data bank (VSDB) during one-year period (total DB size is 4.21 TB). In total, vital signs were recorded from 1175 critically ill patients. Up to six ECG leads, all other monitored waveforms, and all monitored numeric data were recorded in most of the cases.

We describe the details of building blocks of our system, provide description of three datasets exported from our VSDB and compare the contents of our VSDB with other available waveform databases. Finally, we summarize lessons learned during recording, storage, and pre-processing of physiologic signals.

Abbreviations: AWF, airway flow; AWP, airway pressure; BIS, bispectral index; CSV, comma separated values; DAS, direct attached storage; DB, database/databank; DL, data library; GUI, graphical user interface; HDD, hard disk drive; HRR, heart rate recovery; HRV, heart rate variability; ICU, intensive care unit; ITC, Information Technology Center; LAN, local area network (Intranet); RAID, redundant array of independent disks; SAN, storage area network; SBT, spontaneous breathing trial; SICU, Surgical Intensive Care Unit; VS, vital sign; VSDB, vital sign data bank.

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1. Introduction

The intensive care unit (ICU) is a unique environment where physiologic signals of every patient are continuously and comprehensively monitored, often for days and weeks. The physiologic signals displayed by a bedside monitor belong to two distinct types: high frequency "continuous" waveforms (such as ECG) and low frequency (≤1 Hz) numeric data (such as heart and respiration rates) that are typically (with a few exceptions such as e.g. temperature) derived from the corresponding waveforms (e.g. heart rate is derived from the ECG signal). For a recent review of the vital sign monitoring in the ICU, see e.g. [1]. Following the development of computer technology during the last two decades, substantial collections of patient vital signs (both waveforms and numeric data) have been acquired from ICU bedside monitors and stored in different types of databases, databanks (DBs), "data libraries" (DLs) and "waveform archives". Currently available waveforms DBs include MIMIC [2], MIMIC-II [3] (most of these data are freely available on Physionet, www.physionet.org, see [4] for details), IMPROVE [5–7], IBIS [8–12] and CSL [13]. The number of patients in these databases varies from a few dozen to several thousands, and the length of waveform recordings varies from a few hours to several days (see [14,15] for a review). Other databases such as SIMON [16–18] contain only numeric vital signs. Suggestions and recommendations regarding vital sign acquisition and data formats are discussed in [19–21].

Until now, the creation of massive (long-term and multichannel) databases (such as listed above) required either additional software tools provided by bedside monitor manufacturers or in-house built computer systems (examples of the in-house built waveform acquisition computer systems include SWE [22], PDAS [23] and AidDiag [24]). Both approaches rely on interdisciplinary teams that include ICU clinicians, engineers and informaticians and frequently require custom software and hardware development. Recently however, third party commercial software for vital sign acquisition, such as TrendFace (www.ixellence.com), BedMasterEx (www.excel-medical.com), Rugloop (www.demed.be), Mobius (www.integra-ls.com) or ICUpilot (www.microdialysis.se) became available. Such programs commonly work only with a specific model of bedside monitor from a particular manufacturer. Some of them record only numeric data while others can also record waveforms. It remains unclear whether these and similar commercial software will eliminate the need for custom tools for development of large-scale waveforms databases.

The goal of our project was to assemble a system for massive (high-frequency and multichannel) long-term recording of vital signs from critically ill patients using exclusively commercially available "off-the-shelf" solutions (both software and hardware) and existing hospital IT infrastructure. We describe the computer system we have built, procedures of data recording, storage and post-processing, provide description of our DB (vital sign databank, VSDB) and compare it with the existing DBs listed above. We summarize our experience and discuss the lessons learned during this multistage process (recoding, storage and post-processing). We address main problems and questions that typically arise during such a large scale (terabyte-size) waveform databasing:

- how to organize long-term large-scale waveform acquisition process;
- where to store the data;
- how to deliver the acquired data to collaborators that are located at several spatially separated institutions.

2. Computer system setup for waveform recording, storage and post-processing

This observational study was approved by the Washington University Human Protection Organization (WU-HRPO). The setup of the data acquisition system was completed in October 2005, and data recording was performed during a one-year period from October 2005 to October 2006.

2.1. *Hardware and software setup*

Our computer system (Fig. 1) consists of three separate components that are located in three spatially separated buildings at Washington University Medical Center:

(1) Surgical Intensive Care Unit (SICU) at Barnes-Jewish Hospital, where the data was recorded and initially accumulated;
(2) Washington University Medical School Information Technology Center (ITC), where the data was stored;
(3) Our research lab (Department of Surgery, Washington University School of Medicine), where the data was post-processed and analyzed.

All buildings are connected by 100 Mbps Intranet (LAN) protected by a firewall. Below we provide a detailed description of each of the three components.

Barnes-Jewish Hospital SICU has 24 beds, each equipped with Philips IntelliVue^{TM} MP70 bedside monitor.[1] We set up five identical workstations (Dell Power Edge SC1425 Server, 2.8 GHz dual Intel Xeon processor, 1 GB of RAM and two 80 GB HDDs with RAID 1 configuration ["mirrored" configuration which provides a real-time data backup but reduces capacity to only 50%] running 32 bit MS Windows Server 2003)[2] in the SICU (labeled as "SICU Servers" in Fig. 1) and built a special small 100 Mbps network that connects bedside monitors to these servers (five monitors per server). IntelliVue bedside monitors were connected to the SICU Servers using 24 Lantronix UDS100 RS232 to LAN (DB9F/RJ45F) convertors and Lantronix Com Port Redirector software (www.lantronix.com).

In our project we used TrendFace Solo software (www.ixellence.com) because at the time the project was designed (the beginning of 2005) it was the only software that

[1] Philips Medical Systems, Andover, MA, www.healthcare.philips.com/au/products/patient_monitoring/products/intellivue_mp70_mp60/index.wpd.

[2] We chose the same hardware (Dell Servers) and software (Windows Servers) as was used by our hospital IT department, since our goal was to take advantage as much as possible of the existing infrastructure, support and skills of our IT department.