Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.JournalofSurgicalResearch.com

Association for Academic Surgery

A noncontact RF-based respiratory sensor: results of a clinical trial

Spence Madsen, BS,[a] *Jordan Baczuk, BS,*[a] *Kurt Thorup, BS,*[a] *Richard Barton, MD,*[b] *Neal Patwari, PhD,*[a] *and John T. Langell, MD, PhD, MPH, MBA*[b,c,*]

[a] *Department of Electrical Engineering, University of Utah, Salt Lake City, Utah*
[b] *Department of Surgery, University of Utah, Salt Lake City, Utah*
[c] *Center for Medical Innovation, University of Utah, Salt Lake City, Utah*

ARTICLE INFO

Article history:
Received 5 December 2015
Received in revised form
17 January 2016
Accepted 9 March 2016
Available online 24 March 2016

Keywords:
Surgery
Respiratory rate
Monitors
Radio frequency

ABSTRACT

Background: Respiratory rate (RR) is a critical vital signs monitored in health care setting. Current monitors suffer from sensor-contact failure, inaccurate data, and limited patient mobility. There is a critical need for an accurate and reliable and noncontact system to monitor RR. We developed a contact-free radio frequency (RF)–based system that measures movement using WiFi signal diffraction, which is converted into interpretable data using a Fourier transform. Here, we investigate the system's ability to measure fine movements associated with human respiration.

Materials and methods: Testing was conducted on subjects using visual cue, fixed-tempo instruction to breath at standard RRs. Blinded instruction-based RRs were compared to RF-acquired data to determine measurement accuracy. The RF-based technology was studied on postoperative ventilator-dependent patients. Blinded ventilator capnographic RR data were collected for each patient and compared to RF-acquired data to determine measurement accuracy.

Results: Respiratory rate data collected from 10 subjects breathing at a fixed RR (14, 16, 18, or 20) demonstrated 95.5% measurement accuracy between the patient's actual rate and that measured by our RF technology. Ten patients were enrolled into the clinical trial. Blinded ventilator capnographic RR data were compared to RF-based acquired data. The RF-based data showed 88.8% measurement accuracy with ventilator capnography.

Conclusions: Initial clinical pilot trials with our contact-free RF-based monitoring system demonstrate a high degree of RR measurement accuracy when compared to capnographic data. Based on these results, we believe RF-based systems present a promising noninvasive, inexpensive, and accurate tool for continuous RR monitoring.

Human and animal testing: Human subject approval for this trial was granted by our University Institutional Review Board in compliance with Federal Laws. Every subject entered in to the trails described in this paper received and signed an IRB-approved.

* *Corresponding author*. Center for Medical Innovation, University of Utah, 10 North 1900 East Eccles Library, Room 15, Salt Lake City, Utah 84132. Tel.: +1 801 587 7281; fax: +1 801 587 3632.

E-mail address: john.langell@hsc.utah.edu (J.T. Langell).

0022-4804/$ – see front matter © 2016 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.jss.2016.03.018

Introduction

Respiratory insufficiency is a leading cause of cardiopulmonary arrest in the acute care hospital setting. An American Heart Association sponsored study of 14,720 inpatient adult cardiac arrest events found that respiratory insufficiency was the proximate cause of 37% of all cases of inpatient cardiac arrest.[1] Furthermore, the 2009 HealthGrades Patient Safety in American Hospitals Study, based on Medicare data, showed that postoperative respiratory failure was the third leading cause of medical errors in U.S. hospitals; occurring in 17 of every 1000 patients and responsible for >5000 deaths annually, at a cost of >$1.8 billion each year.[2]

Respiratory rate monitoring of at-risk patients with or without concurrent continuous pulse oximetry is used in the inpatient setting in an effort to identify early stage respiratory insufficiency and prevent cardiorespiratory arrest. Respiratory rate is one of the most critical vital signs monitored in the health care setting, and yet, it is one of the least reliable metrics available to clinicians.[3] The standard manual method of counting a patient's respiratory rate by trained clinical staff has been shown to be inaccurate and frequently goes unmeasured. A study of patients requiring a medical emergency team intervention in the acute care hospital setting found that 77% of patients suffering an adverse event had a vital sign missing from the chart just before the event and the most frequently missing measurement was respiratory rate (RR).[4,5] Several technologies have been developed in an effort to automate RR measurements and improve the accuracy of the data. A disadvantage of all of the solutions currently available for use in the clinical setting designed for continuous RR monitoring require some level of patient-sensor contact leading to tethering of the patient to the device. Additionally, current technologies suffer from data loss due to inadequate device-patient contact. The most frequently used methodologies for measuring RR in nonintubated patients include intermittent manual counting, thoracic impedance pneumography using ECG leads, and continuous nasopharyngeal tube capnography.[6] The most accurate method is invasive monitoring through ventilator-acquired capnography in intubated patients. Even the most accurate of these invasive and semi-invasive systems suffer from data unreliability due to movement artifact, sensor-contact failure, inaccurate data acquisition, and limited patient mobility.[7] Given the importance of RR in identifying patients at risk of impending respiratory distress, there is a critical need for an accurate, reliable, and costeffective, noncontact system that will allow monitoring in the clinical setting.

In an attempt to address this issue, a contact-free radio frequency (RF)–based respiratory sensor was developed in our laboratory. It uses standard off-the-shelf wireless devices to measure changes in the radio channel caused by inhalation and exhalation of the patient. These measurement changes are used and to estimate the breathing rate of a stationary person. The system has been used to estimate breathing rate and location in a home.[8-10] Existing studies used only one participant in an idealized setting who was told to breathe at a constant rate. No study has confirmed the performance of the system across a variety of people or those in a postoperative care setting. In this clinical pilot study, we sought to investigate the ability of the RF-based respiratory sensor to accurately measure a subject's RR in a healthy control population and in mechanically ventilated patients in the immediate postoperative period after undergoing a midline sternotomy and open-heart surgical procedure.

Materials and methods

Contact-free RF-based respiratory sensor development

The transmitter and receiver system previously described in[10] was further developed to use standard WiFi (IEEE 802.11n) transceivers to make measurements of received signal strength (RSS). The key benefit of 802.11n is its use of multiple input multiple output, which in our case allows us to measure the nine pairwise channels between the three antennas (standard monopoles) on each transceiver, providing us with nine times as many RSS measurements compared to the single antenna system previously described.[11] For this prototype, we use a Lenovo laptop with a Intel WiFi 5300 card, collecting measurements with CSITool[11] and Ubuntu Linux 10.04. One computer runs a script that transmits in the 5.8-GHz band, via injection mode, data packets more than 10 times per second. The other laptop records the RSS on the nine channels (between three transmit antennas and three receive antennas) for each packet received.

Respiratory rate calculations

At each time, the most recent 30 seconds of RSS values recorded is converted into a breathing rate estimate. First, for each channel's RSS data, the average (DC) value is removed. Second, the power spectral density (PSD) function is computed for each channel for a range of frequencies that are considered to be possible breathing rates, for which we use 6.0 to 40.0 breaths per min (BPM). Next, the average of all nine PSD functions is computed. Finally, we take the frequency at the maximum of the average PSD to be the breathing rate estimate.

Although not implemented for this test, the sensor could also include an automatic motion detector and a "no breathing" detector. If the subject is moving, the RSS variance is very high, and the motion of their chest cannot be distinguished from their larger motions; however, algorithms can classify the RSS data as due to either breathing or larger motions.[9] Furthermore, if the PSD within the possible breathing rate range is too low, the algorithm could decide that breathing is not present and raise an alarm.[8]

Respiratory rate measurements in rate-controlled healthy subjects

Initial feasibility studies were conducted using our RF-based respiratory sensor on healthy volunteers in a nonclinical setting. Subjects were instructed to breathe at a prescribed fixed respiratory rate of 14, 16, 18, or 20 BPM. An application in LabVIEW provides visual cues to a subject to inhale and exhale