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A proof of concept study of acoustic sensing of lung recruitment during mechanical ventilation

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ABSTRACT

Advancements in health technologies are crucial to support healthcare professionals, improve patient outcomes, and best utilize increasingly scarce and under-demand healthcare resources. This research presents an initial proof-of-concept study of simple, non-invasive monitoring techniques used in Mechanical Ventilation (MV), which is the primary therapy for Acute Respiratory Distress Syndrome (ARDS). The high levels of inter-patient variability seen in patients with ARDS have resulted in much speculation about the ideal method of determining ventilation settings, such as tidal volume (Vt) and Positive End Expiratory Pressure (PEEP). One of the oldest and simplest methods is acoustic sensing of recruitment and lung condition. This project involves using a digital recording stethoscope to monitor the acoustic output of patients in the Intensive Care Unit (ICU) during mechanical lung ventilation. During lung recruitment, 'crackles' can be heard within the chest cavity with a stethoscope. These crackles vary significantly, depending on the status of the patient's respiratory system and are used as an indicator of the level of alveolar recruitment. This preliminary, proof-of-concept study focused on crackle detection and involved gathering sound samples from patients in the Christchurch Hospital ICU with evidence of crackles in the chest cavity. Frequency based analysis showed that crackles can be detected as emissions with higher power levels between 100 and 300 Hz (subject to patient variability). The ability to non-invasively record, detect and quantify the intensity of crackles could provide immediate feedback to clinicians and, in the long term, aid in the optimization of ventilator therapy.

1. Introduction

Mechanical Ventilation (MV) is a core therapy in the Intensive Care Unit (ICU) and is associated with increased length of stay, as well as adding significant extra cost per patient day [1]. Patients with respiratory failure require MV to support the work of breathing. In particular, patients with acute respiratory distress syndrome (ARDS) or respiratory failure are ventilated using positive pressure to maintain alveoli recruitment at the end of expiration to maintain lung volume. There are many causes of respiratory failure, and more importantly, responses to treatment can be equally diverse and highly patient-specific. Thus, patient-specific optimal ventilator settings potentially improve patient care and outcome [2,3]. However, there is little or no consensus to select patient-specific optimal ventilator settings with several iterations of the ARDSNet tables that many, but not all, clinicians use as a basis [4,5]. Clinicians often resort to experience, intuition or generalised approaches to select MV settings [6–10].

In particular, the positive end expiratory pressure (PEEP) selected is a careful balance of increasing pressure to maximise recruitment without causing ventilator induced lung injury (VILI) [11]. However, this compromise can be difficult as optimum PEEP is patient-specific, and too low PEEP allows repeated recruitment and derecruitment, which also causes damage. Hence, there is a need to be able to better measure and detect patient-specific lung condition in real-time.

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In this regard, the recruitment of alveoli and conducting airways during inhalation can be heard with the aid of a stethoscope and these transient emissions are known as 'crackles' or 'rales'. Petàk et al. [12] showed that a larger amount of alveoli and airways transitioning from un- recruited to recruited during a breathing cycle, which is undesirable and more likely to result in VILI, results in higher levels of emissions. However, Petàk et al. [12] also showed that these emissions can be recorded with a commercial microphone inserted on the endotracheal tube in ventilated pigs, and that there is a strong correlation between these sounds and the status of the respiratory system, which is especially useful during recruitment manoeuvres and the monitoring of tidal ventilation.

There has been some research examining automated event detection methods for identification of crackles, with some promising results [13–15]. Other research has focused on the presence of crackle sounds in collapsed lungs *in-vitro* [16,17]. However, the non-invasive detection, recording and analysis of crackles *in-vivo* in human lungs has not been a focus of recent research and many prior works required an invasive tracheotomy, which would not be typical in routine clinical settings.

This study focuses on a proof of concept demonstration of the non-invasive ability to record and analyse recruitment related crackles without the insertion of an additional endotracheal tube or other invasive procedure. The ability to detect and analyse crackles would enable non-invasive bedside monitoring of a patient's respiratory system and recruitment, which would provide information on when a patient's state of recruitment changed, indicating that they potentially needed a change in MV settings or a further recruitment manoeuvre. It is thus a proof of concept study to assess a first effort at non-invasive, real-time breath to breath monitoring of recruitment status to enable improved patient care and outcomes.

2. Methods

2.1. Data acquisition

Ethics approval was obtained to acquire data under the Ethical Guidelines for Observational Studies: Observational Research, Audits and Related Activities, NEAC, December 2006 (reference number URB/12/EXP/035) from the Upper South Island Ethics Committee (New Zealand). Three sensors were tested in this study to assess their capability for non- invasive detection and recording of crackles *in vivo*. Ultrasonic sensors and a simple acoustic microphone were found to be unsuitable for accurate recording of lung crackles due to poor signal to noise characteristics, and are thus not presented here.

This study focuses on the successful use of a Littman 3200 Recording Stethoscope (3 M Corporation, St Paul, MN) to record the crackle sound characteristics of recruitment acoustics. The Littman recording stethoscope was used to sample the lung acoustics at 4 kHz. This frequency yields a Nyquist frequency of 2 kHz, which should enable the capture all important lung crackle frequency content.

Patients were selected for recruitment in this proof of concept study based on the identification of the presence of crackles by an intensive care specialist during routine examination. Factors considered for patient selection were evidence of crackles during auscultation, diagnosis, respiratory health and diagnosis, and whether the patient was undergoing mechanical ventilation. In this initial study, stethoscope recordings were taken from 5 patients. This cohort yielded 3 patients (Patients 3–5) where crackles were clearly heard and there were good quality recordings and no difficulties with the stethoscope or measurement process. There were a total of 6 audio recordings made for these 3 patients with 1 recording for Patient 3, 2 recordings for Patient 4 and 3 recordings for Patient 5.

Patients were of diverse condition to prove the concept. The limited number of patients and recordings with crackles heard by the clinician, are enough to provide a range of examples for verification, but not for testing clinical outcomes. The three patients each had different diagnoses and levels of mechanical ventilation, ranging from no ventilator or breathing assistance, to those with respiratory difficulty but spontaneously breathing with some ventilator assistance (invasive or non-invasive), to full controlled mechanical ventilation with the patient receiving complete support for their work of breathing. The ventilator settings, when ventilated, were not recorded for this proof of concept study, as the sole criteria for inclusion was the presence of crackles and there is no attempt to associate these crackles with ventilator mode or level of pulmonary dysfunction. More specifically, it is a broad study to determine if crackles can be identified and develop the necessary methods, rather than a clinical analysis comparing modes of ventilation and recruitment as determined via sensing these crackles.

Recordings were taken using the recording stethoscope from patients while in the semi-fowlers position (supine position with head elevation). Readings were taken by an experienced clinician at both the anterior and posterior chest surfaces. The recordings were then transferred onto a laptop via Bluetooth and playback was possible using Zargis StethAssist software (3 M Corporation, St Paul, MN). It is important to note that the use of this specific stethoscope does not preclude any similar device or sensor, and is thus generalizable.

2.2. Data analysis

The analysis of the recordings was completed using Matlab (The Mathworks, Natick, MA). Each recording was converted from the recording stethoscope default file format into an .mp3 file and then analysed individually. The analysis involved conversion from .mp3 into .wav format. Frequency and Power Spectral Density (PSD) analyses were performed using this .wav input formatted data.

The first step was to find a means of visualising the recruitment related crackles. The Matlab function '*spectrogram*' was utilised to generate both the classic spectrogram and the PSD for the data. Examples of these plots are shown in Fig. 1. The plots in Fig. 1 show the spectrogram, which is a plot of signal magnitude (color) over time and frequency. The second (bottom panel) is the power spectral density (PSD), which shows the power or squared magnitude (color) versus time and frequency, where the PSD by its formulation as the square of the magnitude (energy) at a frequency thus separates more distinctly the differences between high and low frequency ranges of the signal. The window length was approximately 0.05s, with no overlap. Both plots present an indication of the relative strength of different frequency content against time. The PSD showed much clearer, more consistent differentiation in signal characteristics than the spectrogram and it was for this reason the detection methods were based on the PSD.

2.3. Crackle detection methods

Two detection methods based on different processing of the signal file are presented and compared in the following sections.

2.3.1. Method 1–mean power

This method is based on the mean power of the signal within an analysis band, set at 100–300 Hz. The analysis band was varied to investigate the influence on detection accuracy and patient variability, but 100–300 Hz was determined to be the best analysis band for these limited patient results, as a first proof of concept.