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Clinical paper

A new physiological model for studying the effect of chest compression and ventilation during cardiopulmonary resuscitation: The Thiel cadaver☆

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ABSTRACT

Background: Studying ventilation and intrathoracic pressure (ITP) induced by chest compressions (CC) during Cardio Pulmonary Resuscitation is challenging and important aspects such as airway closure have been mostly ignored. We hypothesized that Thiel Embalmed Cadavers could constitute an appropriate model.

Methods: We assessed respiratory mechanics and ITP during CC in 11 cadavers, and we compared it to measurements obtained in 9 out-of-hospital cardiac arrest patients and to predicted values from a bench model. An oesophageal catheter was inserted to assess chest wall compliance, and ITP variation (ΔITP). Airway pressure variation (ΔPaw) at airway opening and ΔITP generated by CC were measured at decremental positive end expiratory pressure (PEEP) to test its impact on flow and ΔPaw. The patient's data were derived from flow and airway pressure captured via the ventilator during resuscitation.

Results: Resistance and Compliance of the respiratory system were comparable to those of the out-of-hospital cardiac arrest patients (C_{RS}^{TEC} 42 ± 12 vs C_{RS}^{PAT} 37.3 ± 10.9 mL/cmH_2O and Res^{TEC} 17.5 ± 7.5 vs Res^{PAT} 20.2 ± 5.3 cmH_2O/L/sec), and remained stable over time. During CC, ΔITP varied from 32 ± 12 cmH_2O to 69 ± 14 cmH_2O with manual and automatic CC respectively. Transmission of ΔITP at the airway opening was significantly affected by PEEP, suggesting dynamic small airway closure at low lung volumes. This phenomenon was similarly observed in patients.

Conclusion: Respiratory mechanics and dynamic pressures during CC of cadavers behave as predicted by a theoretical model and similarly to patients. The Thiel model is a suitable to assess ITP variations induced by ventilation during CC.

Abbreviations: ITP, intrathoracic pressure; CC, chest compressions; TEC, Thiel Embalmed Cadavers; Paw, airway pressure; PEEP, positive end expiratory pressure; C_{RS}, compliance; Res, resistance; Vt, tidal volume.

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Introduction

Cardiac arrest represents 1–5 per 1000 hospital admissions worldwide, leading to major health care burden and morbid consequences. Despite improvement in medical care the mortality and the neurological morbidity are still high [1,2]. Although progress has been made regarding the techniques and results of Cardio-Pulmonary Resuscitation (CPR), many uncertainties remain regarding the exact pathophysiology at play, and there is room for improvement of the technique [3]. Several reasons explain why research is difficult and often disappointing in that area [4]. Obviously, pathophysiological research in patients is difficult to perform, as recordings opportunities are limited. Animal studies, mostly using pigs, have been very useful but have also limitations [5,6]. Their thorax geometry and differences with humans, such as collateral ventilation explain why the effects of ventilation and compression can be difficult to extrapolate [7]. This is a barrier to understanding the behaviour of intrathoracic pressures, and for the study of ventilation during CPR, which place and techniques have not been elucidated. In addition, very few studies focused on the conducting airways, which may experience airway closure as suggested by seminal as well as more recent observations [8,9]. Safar initially reported that chest compressions (CC) in volunteers were capable of generating ventilation at the mouth but was not anymore the case in real cardiac arrest situations [10]. These observations were confirmed a decade ago by *Deakins* et al. in a series of patients showing extremely low ventilation associated with CC [11]. Experimental data and recordings in out-of-hospital cardiac arrest patients from our group have similarly indicated that the effects of CC at the airway opening required the addition of small levels of external pressure to generate flow and ventilation [12,13].

We first designed a realistic mechanical lung-thorax model explaining that ventilation during CPR took place below functional residual capacity and therefore why the addition of a small level of positive pressure at the mouth may preserve lungs volumes and ventilation without impeding negative recoil pressure during decompression [9]. It also suggested the existence of flow limitation and airway closure, compatible with findings in resuscitated patients [9]. The limit of our mechanical model was the lack of chest wall and of real intrathoracic pressure measurements, which are the drivers of the effects of compression on circulation.

To further explore this aspect of CPR, we sought a model that would mimic the human respiratory conditions observed during cardiac arrest thereby allowing realistic measurements of intrathoracic pressure during CPR. Fresh cadavers have been proposed in this setting [14,15], but new preservation technics held more promises for ventilation [16,17]. Indeed, the Thiel embalmed Cadavers (TEC) are submitted to a special preparation that preserve tissue elastic properties and textures close to living patients, seemed very suitable [18,19]. In addition, their anatomy allowed bag-mask ventilation, laryngoscopy and tracheal intubation [17]. We hypothesized that TEC could be an appropriate model for studying experimental ventilation and intrathoracic pressure (ITP) during CPR. The objectives of our study were to characterize a series of Thiel cadavers to determine if: 1) their respiratory mechanics, including lung and chest wall partition, were comparable to out-of-hospital cardiac arrest (OHCA) patients under mechanical ventilation; 2) their behaviour during CPR was comparable to what was predicted by our previously published lung model [9]; 3) their behaviour during CPR reproduced the observations made in patients, including a possible pressure-dependent phenomenon of airway closure.

Methods

Experimental settings and equipment in TEC

TEC are human corpses embalmed after a method described by Walter Thiel, an Austrian professor of anatomy [20,21]. It is a process of several months using very little formaldehyde, various salts and alcohol; the aspect is close to the living anatomy and preserves elasticity and flexibility [22,23]. The main vessels are mostly collapsed and contain very little remaining of the fixation fluid. The corpses were used from a specific donation program of the anatomy laboratory of UQTR (Université du Québec à Trois-Rivières) and experiments were conducted in accordance with Canadian regulation after ethic committee approval (CER-14-201-08-03.17). TEC were intubated and mechanically ventilated with a Monnal T60 ventilator (Air Liquide Medical Systems, Antony, France). After ventilation and recruitment period, if required, suctioning was performed with a single-use catheter via the endotracheal tube in order to remove the preservation fluid from the airways and lung. A systematic chest x-ray was performed in order to validate endotracheal tube proper positioning and to verify proper lung aeration. It also allowed the assessment of any visible pleural or parenchymal pathology.

Flow and Airway Pressure (Paw) were measured at the airway opening using a Pneumotachograph (Fleisch n°3, Lausanne, Switzerland) positioned proximally to the endotracheal tube and connected to two pressure transducers (Validyne MP45, Northridge, CA, USA) and processed with the AcqKnowledge software (AcqKnowledge 3.7.3, Biopac Systems, Goleta, CA). Volume was measured as the integral of flow.

An oesophageal balloon (NutriVent™, Sidam s.r.l., Mirandola, Italy) was inserted to measure oesophageal pressure (Peso), in order to separate chest wall from lung contribution to respiratory system mechanics and describe ITP. A modified occlusion manoeuver adapted from Baydur, illustrated in appendix (Supplementary Fig. 1), was done to insure proper placement of the oesophageal balloon [24]. An illustration of the curve obtained during ventilation and at the initiation of CC is presented in appendix (Supplementary Fig. 2).

Ventilation and mechanics measurements

To first expand collapsed lungs and standardize "lung volume history", recruitment manoeuvres were systematically performed during the first 30 min of the experiment. Static respiratory mechanics characteristics, namely the respiratory system, lung and chest-wall compliance, as well as resistance were calculated after 30 min of ventilation using end-inspiratory and end-expiratory pauses as described [25] and with the following setting: Volume control (VC), Tidal volume of 6 mL/kg per Predicted Body Weight (PBW), Respiratory rate (RR) of 10/min and a minimal positive end-expiratory pressure (PEEP) of 5 cmH_2O.

To assess the stability and reproducibility of the Thiel model over time while applying intermittent CC periods between measures, three periods of 5 min of manual CC (100/min) were interspersed with 45 min of VC ventilation.

Manual CC were performed, but to standardize CC as close as possible to human CPR we also used automated devices (Lucas™-Jolife AB/Physio-control, Lund, Sweden; AutoPulse® – Zoll Sunnyval, CA, USA). During CC the ventilator was set according to international recommendations (RR 10/min, Vt 6 mL PBW) using a specific pressure controlled mode of ventilation that allows combination of continuous CC and ventilation (CPV Air Liquide Medical Systems Antony France); the latter is synchronized with CC, limit the upper pressure rise at 20 cm H_2O and set the lower pressure at 5 cm H_2O with a respiratory rate at 10/min.