Sensors and Actuators A 273 (2018) 113–120

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Respiratory trigger signal generation by means of a stretchable sensor array

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ARTICLE INFO

Article history:
Received 23 October 2017
Received in revised form 8 February 2018
Accepted 15 February 2018

Keywords:
Respiration monitoring
Artificial respiration
Trigger signal generation
Flexible systems
Stretchable systems
Systems in foil
Sensor array patch

ABSTRACT

Respiratory monitoring is a clinical method which helps to examine the medical condition of patients. Patients diagnosed with types of respiratory distress are often supported through artificial respiration. To be able to adapt and synchronize airway pressures and flows to the patient's own breathing for improved respiration efficiency, intelligent sensors are needed to detect the beginning and ending of the breathing cycle. An ultra-thin and stretchable 6×6 sensor array with skin-like properties is presented that is used to generate a trigger signal which is suitable to control and synchronize artificial respiration with the patient's own breathing. Stretchability of the sensor array is achieved by fs-laser structuring of the thin polyimide sensor substrate resulting in small sensor islands connected via slender meandering electrical leads. The resulting stretchable sensor grid is embedded in layers of PDMS whereby a skin-friendly sensor patch is created. To simulate respiration an externally ventilated dummy is used. The principle of trigger signal generation from multiple sensor signals is based on a self-developed algorithm that first evaluates the signal quality of each sensor based on adjustable parameters. Only the sensors selected as suitable are then used to calculate an averaged scaled signal, which is taken for trigger point detection. The best results were typically obtained when quality factures are set to a level where about half of the sensors are contributing to the trigger detection, leading to a trigger delay of about 80 ms relative to the pressure reference signal. It could also be shown that the algorithm can resume the trigger point detection within 2–3 s, after manually applying disturbances which could similarly occur in the clinical environment. The results show that the skin-friendly sensor patch provides suitable trigger signals for artificial respiration which are robust against drop out of single sensors, non-ideal sensor patch positioning on the thorax and mechanical irritations.

1. Introduction

Respiration monitoring is a widely used clinical method which is nowadays applied for all age classes, from preterm infants to elderly people. Since the respiratory rate is one of the four vital signs of the human body (besides body temperature, pulse rate and blood pressure), sensing its fluctuations is very important [1] because it can often directly indicate the medical condition of a patient and warn of various clinical deteriorations (dyspnea: short of breath, tachypnea: abnormal rapid breathing) or even of an impending total respiratory arrest (apnea) [2]. Patients diagnosed with any type of respiratory distress are often supported by applying artificial respiration, which can mainly fall in two categories: an invasive one, which is applied through a tracheal tube, and a more gentle and comfortable non-invasive method through a respiratory mask [3]. Although invasive respiration techniques have improved the medical treatment substantially, clinicians are moving away from usual intubation and search for non-invasive alternatives, especially for the ventilation of preterm infants, which are very prone to any kind of medical intervention [4]. Non-invasive respiration can for example increase survival rate by preventing "bronchopulmonary dysplasia" (BPD) [5]. One conventional non-invasive respiration method is the application of a "constant positive airway pressure" (CPAP), which prevents the lung from collapsing and hence supports own breathing of the patient [6]. Another non-invasive respiration method, which delivers more support to the infant than CPAP, is called intermittent positive pressure ventilation (NIPPV). This technique combines CPAP with intermitted pressure increases by generating peak pressures slightly higher than baseline CPAP. NIPPV alone already reduces work of breathing and synchronized NIPPV (SNIPPV) can reduce rate of reintubation [7]. It was also shown that synchronization of NIPPV can improve its effectiveness [8]. Generally, synchronization of ventilator inflations with the patient's own spontaneous breathing should lead to adequate

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https://doi.org/10.1016/j.sna.2018.02.022
0924-4247/

gas exchange at lower airway pressures, reducing baro/volutrauma, air leaks and ventilation duration [9], which again can prevent BPD [10].

To be able to adapt airway pressures and flows to the patient's own breathing (synchronization), intelligent sensors are needed to detect the beginning and ending of the breathing cycle [11–15]. Existing synchronization systems use different approaches to detect the patient's own breathing; the electrical impedance tomography (EIT) [11] for example uses electrodes applied to the thorax which can measure its impedance changes during breathing, but it is very prone to motion artefacts and shows a relatively slow sensor response. Respiratory inductance plethysmography (RIP) [12] measures chest wall and abdominal movements via elastic bands and is a well-known and good functioning technique in respiration monitoring for adults. Unfortunately there are currently almost no readily available RIP systems for preterm infants [4]. Most commonly used systems for preterm infants are pneumatic abdominal capsules like the "Graseby capsule" (GC) [13] which show fast sensor response but are also very prone to motion artefacts. Since usually only one single capsule is used, it needs also a very accurate placement and runs the risk of relatively easy misplacement through body movements. Another system, called neurally adjusted ventilatory assist respiration (NAVA) [14] detects the breathing by measuring the electrical activity of the diaphragm; a relatively large and expensive electrode array is invasively applied to the diaphragm, limiting the usability for very small infants.

Foil-based microsystems that can be easily attached to bodies with non-planar shapes have received increasing attention in recent years. They are characterized by light weight and ultra-thin design that offers the flexibility required for a wide range of applications such as wearable electronics [16], structural health monitoring [17] and medical diagnostics [18]. However, flexibility alone is no longer sufficient when it comes to conformal application directly on the elastic human skin in order to achieve perfect shape adaption and wearing comfort. The concept of stretchable electronic systems [19] is much younger than flexible electronics [20]. It can be dated back to a paper published in 2001, which surveys the state-of-the-art and research issues that need to be resolved in order to make sensitive skin a reality [21]. Since then the recognized need for elasticity led to the development of numerous new materials and manufacturing technologies for stretchable electronics [22]. Own previous works include micro fabrication and characterization of a purely flexible sensor array [23] as well as conversion into a stretchable format with investigations on elasticity, shape adaptation and preliminary examination for trigger point recognition [24].

In contrast to the previously published works [23–25], this paper focuses on the realization of a stretchable sensor array by additional laser and embedding processes and specific algorithms developed for respiratory trigger signal generation based on 36 individual sensor signals. The use of such a foil-based stretchable sensor array for respiratory triggering could provide a promising alternative to existing synchronization systems [11–15] and could overcome their typical drawbacks, especially in the application for preterm infants. The idea is to use the sensor as a non-invasive system by applying it in the transition between chest and abdomen to measure the typical oscillating deformations induced by breathing. It's ultra-thin and light-weight format with skin-like elastic properties allows perfect adaption to the body and thereby causes minimum stress to the infant, which makes it much more comfortable in comparison to other systems. The use of multiple sensors, evenly distributed on a 2D surface, could help to eliminate motion artefacts from the triggering signal and the drop out of one or even more sensors wouldn't cause a failure of the entire system. A multiple sensor structure could additionally minimize the risk of displacement and allow an easy placement by the operator. Since the lateral size of the sensor array can easily be adapted, it is applicable to any body size, even for very small preterm infants.

2. Design of the stretchable sensor array

A 6×6 sensor matrix foil as described earlier [23] is cut with fs-laser pulses to remove all parts of the polyimide foil which are not covered by sensors or electrical leads, resulting in small rigid sensor islands connected via slender meandering electrical leads. Afterwards, the already stretchable sensor array is placed on a 200 μm thick polydimethylsiloxane layer (PDMS) applied to a glass substrate. A further 200 μm thick PDMS top layer is applied by spin coating to cover the sensors. After the PDMS has cured, the outer contour of the sensor is structured again using a laser. Finally, a stretchable sensor array with skin-like properties can be peeled from the carrier substrate. Fig. 1 (a) shows the peeled off and

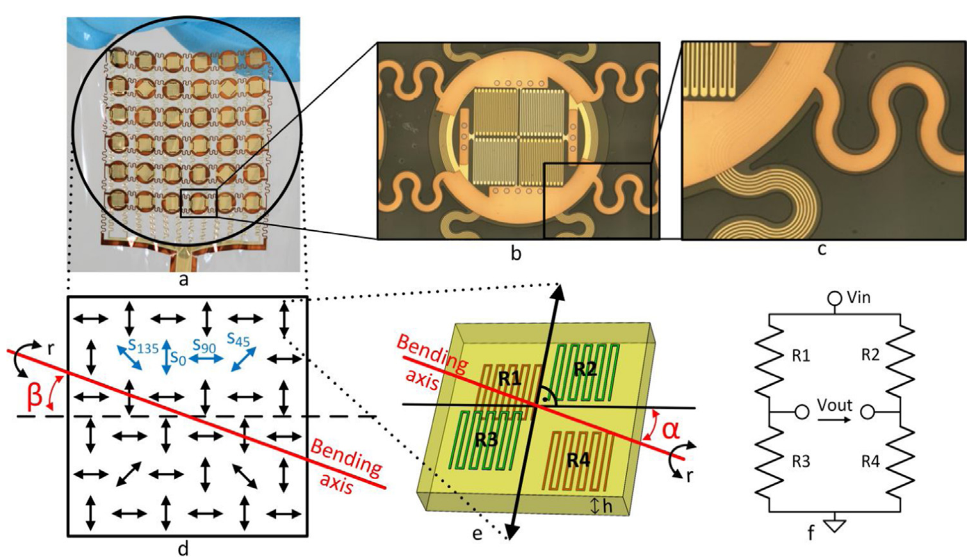

Fig. 1. (a) 6×6 sensor array embedded in two layers of PDMS stretched by hand, (b) magnified view of one single sensor island structured with a fs-laser, (c) magnified view of slender meandering leads (d) indication of four different sensor orientations ($\mathbf{s}_0$, $\mathbf{s}_{45}$, $\mathbf{s}_{90}$, $\mathbf{s}_{135}$) within the 6×6 sensor array and definition of bending angle β for the entire sensor foil, (e) illustration of the double-sided sensor design and definition of bending angle α for one single sensor element, (f) illustration of the appropriate connection to a full Wheatstone bridge.