文章编号: 1007 - 4252(2021) 04 - 0004 - 281

柔性可穿戴式呼吸传感监测系统研究进展

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摘要: 柔性可穿戴式呼吸传感监测系统包含柔性呼吸传感器和微型化电路,集信号传感、存储、传输和处理等功能于一体,具有体积小、准确性高、操作方便简单以及制备成本低等特点,其应用范围大于目前临床上常用的多导睡眠仪,可满足对呼吸系统疾病长期监测和早期诊断的需求。首先介绍了呼吸传感器的工作原理; 然后以呼吸监测的实现方式为标准将呼吸传感监测系统分为两类——直接呼吸监测法和间接呼吸监测法,具体讨论了不同的呼吸监测位置和工作模式; 最后,对柔性可穿戴式呼吸传感监测系统进行了相应的总结和展望,为相关研究者提供参考。

关键词: 柔性可穿戴器件; 呼吸传感器; 呼吸监测系统
中图分类号: TP212 **文献标志码:** A

Recent Progress of Flexible Wearable Respiratory Sensing and Monitoring System

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Abstract: The flexible wearable respiratory sensing and monitoring system includes flexible respiration sensors and integrated circuits, containing multiple functions of signal sensing, storage, transmission and processing. The system has the characteristics of small size, high accuracy, simple operation, and low cost, which can be widely used in practice and the application range is larger than that of polysomnography, commonly used in clinical field. The respiratory sensing system can meet the needs of long-term monitoring and early diagnosis of respiratory diseases. Firstly, the working principle of the respiration sensor is simply introduced. Then, the respiratory monitoring systems are divided into two categories, direct monitoring and indirect monitoring system, based on the implementation methods of systems. Specifically,

收稿日期: 2021-07-13; **修订日期:** 2021-07-22
基金项目: 国家重点研发计划课题(2020YFB2008503) ; 国家自然科学基金资助项目(No.61974088) .
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the different monitoring locations and working modes are discussed. Finally, a brief summary and prospect of the flexible wearable respiratory sensing and monitoring system are proposed to provide a reference for the interested researchers.

Key words: Flexible wearable sensors; Respiration sensor; Respiratory monitoring system

0 引言

近年来,由于大气污染、吸烟、人口老龄化以及其他因素,使得呼吸系统疾病已成为世界上发病最广泛的疾病之一[1-4],是继恶性肿瘤和心脑血管疾病之后的第三大致死疾病[5-7],已严重危害到国人的生命健康。全球疾病负担报告(global burden of disease study, GBD)显示[8],国人五大死亡风险因素分别是吸烟(约 270 万人死亡)、高血压(260 万人死亡)、不健康饮食(202 万人死亡)、空气污染(185 万人死亡)和高血糖(107 万人死亡),这些因素会直接或间接地诱导呼吸系统疾病的发生,提高国人的发病率和致死率[9]。因此,呼吸系统疾病正越来越受到人们的关注,对呼吸系统疾病的预防、早期监测和早期诊断方法也逐渐受到研究者的重视。

目前在临床医学领域,常采用多导睡眠分析仪(polysomnography, PSG)对呼吸状况进行监测[10-12]。PSG 通过采集脑电、眼电和肌电信号,对呼吸、动脉血氧饱和度、脑电图、心电图等指标进行连续监测,对睡眠呼吸症状的严重程度做出准确判断[13]。然而,PSG 在实际应用中存在诸多不足,例如,在监测过程中受试者身体多处需要连接传感器和电极,对受试者的睡眠状况造成影响,导致监测结果不能反应真实情况[14,15];监测过程需要在专业的睡眠室中进行,设备操作复杂,成本极高,无法推广到日常使用[16,17]。患者常因 PSG 使用的限制而无法及时进行睡眠呼吸状况监测,错过早期诊断和治疗的最佳时期,导致疾病严重后治疗效果变差,生活质量降低。因此,对具有高度准确性、稳定性、操作方便简单、成本低的柔性可穿戴式呼吸监测系统的研究正越来越受到关注[18,19]。呼吸监测系统需要包括呼吸传感器、信号收集与存储电路、无线通讯模块以及信号接收器(或手机软件)等,所有模块均需要满足微型化、可穿戴、稳定性好、使用安全性高等特点,因此对传感器的设计与微加工、电路的设计与制备方面具有较高的要求[20-22]。

1 呼吸传感器工作原理

呼吸信号的监测方法有很多,可根据是否直接测量呼吸气流分为直接呼吸监测法和间接呼吸监测法。其中,直接呼吸监测法多采用热阻式传感器,基于热阻和热传导效应测量呼吸气流引起传感器电阻的变化,通过电路处理模块得到呼吸气流的速度或流量。此外,也可通过监测呼吸气体的湿度、气压、温度等条件来反映呼吸状况[23-25]。间接呼吸监测法多采用应变传感器,通过测量呼吸时胸部或腹部皮肤拉伸引起的应力变化来反映呼吸状况。此外,也可通过监测人体睡眠姿势、心率、血氧饱和度等指标来间接反映人体呼吸情况[26-28]。

1.1 热阻式流速传感器

香港科技大学 W. Xu 等人基于热阻原理制备了微型流量传感器[29-33],其结构如图 1 所示。该热阻微热流量(thermoresistive micro calorimetric flow, TMCF)传感器包含两种封装类型——开放式和通道式,分别用于气体和液体流量的测量。TMCF 传感器的结构组成包含一个位于薄膜中心的微型加热器和两个分别位于上游和下游的热阻传感器,整体结构悬空于通过反应离子刻蚀和 XeF_2 刻蚀形成的硅凹槽上方。当没有流体输入时,传感器在流向方向上的温度曲线是对称分布的;当存在输入流体时,可以通过测量 TMCF 传感器的上下游热阻器的温差输出,基于对流传热原理将其与输入流速确认对应关系。所制备传感器对氮气流的归一化灵敏度比以往的互补金属氧化物半导体流量传感器高出两个数量级,但该流量传感器的应用受限于稳定的工作环境,需要与额外设计的微通道结合才能体现高灵敏度的特点。

1.2 应变式呼吸传感器

加州大学 M. Chu 等人提出一种可穿戴式柔性应变传感器用于同时监测人体呼吸速率和呼吸量[34-37],传感器的结构和测试结果如图 2 所示。当人体正常呼吸时,胸腔和腹部会随着呼吸发生周期

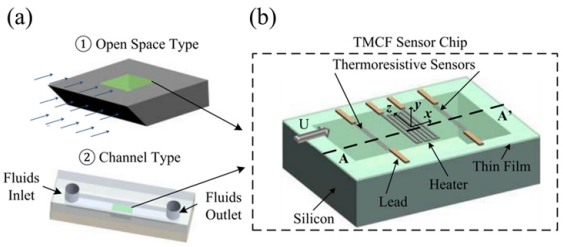

图 1　具有两种封装类型的 TMCF 传感器—(a) 开放空间型和通道型以及(b) 传感器组装示意图[29]

Fig. 1 TMCF sensors with two package types — (a) open space type and channel type and (b) the diagram of sensor assembly[29]

性的形变，同时该位置的皮肤表面应变力也会周期性的变化，从而反应出人体呼吸的状况。该应变传感器的设计外形类似创可贴，其电阻随着应变的改变而变化，因此可通过将传感器贴于胸腔和腹部来间接测量呼吸信号。基于 Kono 和 Mead 二人提出的计算原理[38-41]，可将腹部和胸腔的周期性信号转换为呼吸速率和呼吸量。系统可测量各种运动状态下的呼吸信号，并通过小型无线蓝牙模块将采集信号传输到移动端，应用于慢性呼吸系统疾病患者在日常环境下的连续呼吸监测。

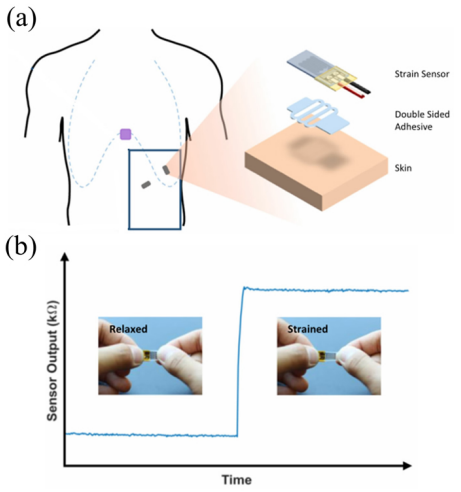

图 2　可穿戴式呼吸监测系统，应变传感器贴于胸腔和腹部皮肤表面(a)，可监测处于放松和拉伸状态的信号(b)[34]

Fig. 2 The wearable respiratory monitoring system with strain sensors attached to the skin surface of chest and abdomen (a), which can monitor signals in relaxed and stretched states (b)[34]

2　直接呼吸监测法

2.1　植入式呼吸监测系统

日本广岛市立大学 M. Shikida 等人提出了一种导管呼吸传感系统[42-46]，将呼吸监测传感器与原位观察系统结合，可准确观察肺部的局部病变。该监测系统将带有医用篮钳的管式流量传感器和光学纤维镜组成的导管系统集成化，在肺部的狭窄气道中进行原位测量，其结构和应用场景如图 3 所示。传感器包含两个加热器，将其组装到圆管表面形成管状气体流量传感器，同时，导管内部安装医用篮钳并固定在管的中心位置。光学纤维镜能够实时观察植入位置的状态，确保测量部位满足实验要求。最终集成的带有医用篮钳和光纤镜的管式流量传感器系统的外直径为 5.0 mm，足够植入人体或动物的肺部气道中。此外，他们还开发了与之匹配的软件系统并成功地植入兔子体内，检测了呼吸气流波形和气道内的光学图像，实现了观察和原位测量的一体化，可用于肺部原位病变的观察和检测。然而，由于将该呼吸监测系统植入肺部气道所引起的不适感较为强烈，因此不推荐用于长期的连续呼吸监测。

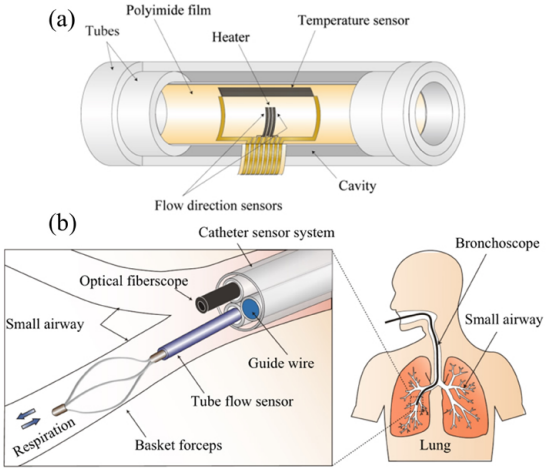

图 3　导管型流量传感器和呼吸监测系统示意图，该系统集成了(a) 气体流量传感器、(b) 医用篮钳以及光纤镜[42]

Fig. 3 Schematic diagram of catheter-type flow sensor and respiratory monitoring system, which integrates (a) flow sensor, (b) medical basket forceps and optical fiberscope[42]

2.2　便携式多功能监测系统

清华大学 Z. Cao 等人提出一种结合微型流量

传感器的无线便携式监测系统[47,48]，用于呼吸系统疾病的日常监测，其结构如图 4 所示。微型热膜流量传感器贴附在柔性导管表面，呼吸气流由鼻插管收集后进入柔性导管内部，通过流量传感器得到呼吸气流信号。采用商用三轴加速度计测量在呼吸监测过程中的身体姿势，用于辅助判断测量的结果。采用指尖脉搏血氧仪测量外围血氧饱和度，测量结果与呼吸信号结合后用于对睡眠健康状况进行综合判断。该系统通过蓝牙模块进行无线数据通信，采集的数据可以传输到移动端或电脑终端，便于医生进行远程分析，用于对阻塞性睡眠呼吸障碍、慢性阻塞性肺疾病和哮喘病的前期诊断。该系统广泛采用商用传感器和零件，体积小，生产效率高，具有一定的商用推广性。

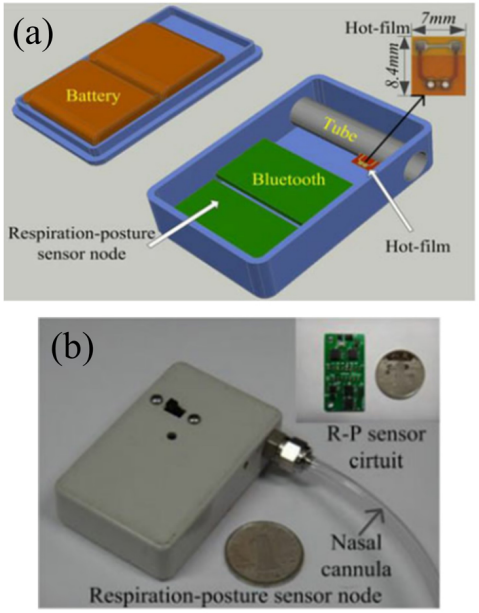

图 4 呼吸—姿势传感系统的(a)内部组成、(b)外部形貌及其信号处理电路图[47]

Fig. 4 The diagrams of internal composition (a), external appearance and signal processing circuit (b) of respiration-posture sensing system[47]

2.3 面罩式呼吸监测系统

中国科学院 Y. Li 等人提出一种基于双轴取向聚丙烯(biaxially oriented polypropylene，BOPP)薄膜的纤维法布里-珀罗(F-P)传感器并用于呼吸监测过程[49]，如图 5 所示。通过膜拉伸法制造 BOPP 膜，采用 3D 打印设备制造螺母和具有微通道结构的螺栓，使得光纤能够包裹在微通道中，最后将螺母和螺栓组合形成具有复合结构的光纤 F-P 传感器，并且可固定在专业用于呼吸领域的医用呼吸面罩上。由于 BOPP 薄膜的杨氏模量低且厚度薄，因此呼吸传感器具有高压力灵敏度，可以准确地监测呼吸过程中的压力变化，可准确区分出在一个呼吸循环内的四种压力变化过程，并得到呼吸波形、频率、吸气持续时间和幅度、呼气持续时间和幅度以及吸气和呼气的周期性变化。由于与医用呼吸器结合，因此抗干扰性好，可靠性高，监测准确度高，对人体无伤害，有望在呼吸疾病监测中得到推广。

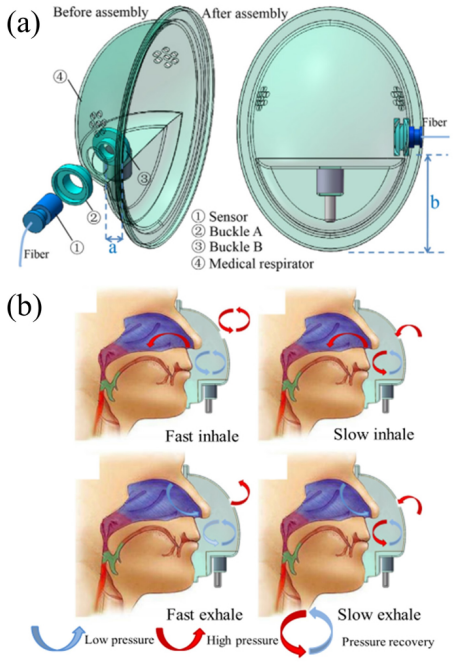

图 5 (a)与医用面罩组装的呼吸传感器示意图;(b)可区分一个呼吸循环内的四种压力变化过程[49]

Fig. 5 Schematic diagram of the breathing sensor assembled with a medical respirator (a), which can be used to distinguish four kinds of pressure changes in a breathing cycle (b)[49]

此外，清华大学 Y. Pang 等人提出一种基于多孔石墨烯网络的湿度传感器[50]，也可与医用呼吸面罩结合并用于呼吸监测，如图 6 所示。通过使用氧化石墨烯、PEDOT: PSS 和银胶体对多孔石墨烯进行改性，从而提高传感器性能。在不同的相对湿度下研究了基于多孔石墨烯网络的传感器湿度特性，用于监测人体的不同呼吸模式，包括口呼吸和鼻呼吸、正常呼吸和深呼吸等。此外，还对比了该湿度传感

器浸水前后的信号变化，证明了对连续监测水份变化的能力。由于传感器的灵敏度高，工作稳定性好，也有望应用于临床呼吸监测。

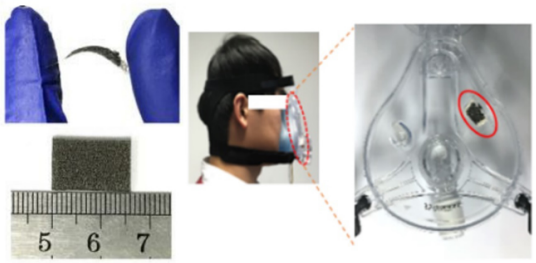

图 6　基于多孔石墨烯的呼吸湿度传感器，可集成到医用面罩内部用于临床呼吸监测 [50]

Fig. 6 The respiratory humidity sensor based on porous graphene, which can be integrated into a medical respirator for clinical breathing monitoring [50]

2.4　鼻下呼吸监测系统

清华大学 R. Zhu 教授课题组提出一种智能带状呼吸传感系统 [51]，如图 7 所示，可用于实时健康监测 [52-54]。该系统包括一个单片集成的柔性热膜流量传感器-粘附在柔性硅胶薄膜表面，一个封装了蓝牙模块的小型信号输出、采集、调节电路，可拆卸的小型纽扣电池，以及安装于移动设备的信号收集、处理软件。流量传感系统可直接贴附于鼻下皮肤表面采集呼吸气流信号，进行长期的连续呼吸监测，避免了使用不舒适的鼻插管。单个芯片上集成了惠斯通电桥，通过计算使得采集信号更加准确可靠。实验证实该系统可至少佩戴运行八小时以上，稳定覆盖了睡眠周期，因此可获取全面的睡眠呼吸参数，这对于阻塞性睡眠呼吸暂停、慢性阻塞性肺病和哮喘病的诊断非常重要。

类似地，清华大学 X. Feng 等人开发了一种类皮肤混合集成电路(skin-like hybrid integrated circuits, SHIC)用来进行长期呼吸监测 [55-60]，其结构组成和使用方法如图 8 所示。SHIC 可贴附于鼻周围皮肤表面，敏感单元置于鼻下位置，可直接测量鼻呼吸信号。传感单元为可拉伸薄膜型温度传感器，与所设计柔性电路模块结合后，形成完整的可穿戴呼吸监测系统。温度传感器以聚酰亚胺为基底，以金为敏感材料制备为蜿蜒图形，外层为半透膜封装层，提高器件透气性。此外，还设计并制备了具有信号输出、信号采集、转换和无线传输的柔性电路模

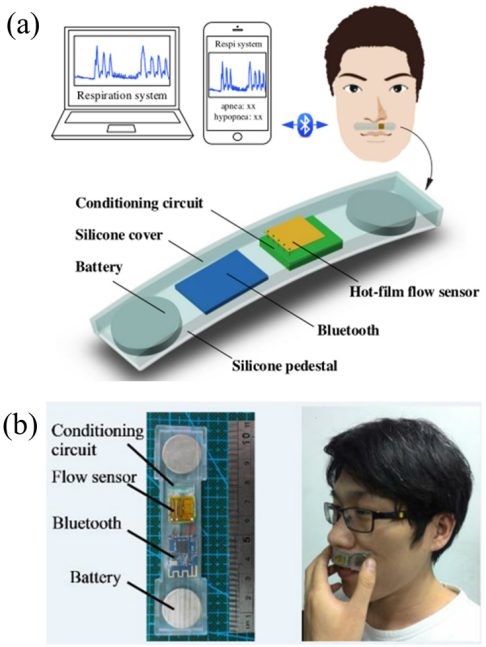

图 7　(a) 鼻下式智能传感系统示意图、(b) 实物样品以及使用者佩戴图 [51]

Fig. 7 (a) Schematic diagram of under-nose smart sensing system and (b) real pictures of the sample and subject [51]

块，使用定制的手机软件程序记录和查看呼吸信号，可以在包括锻炼、饮水和睡觉在内的各种日常活动中监测人体的呼吸情况。测量结果表明，SHIC 在静态和动态场景下均能连续有效地跟踪呼吸模式，能够准确测得运动前后以及睡眠过程中呼吸频率、幅度的变化，能够用于对睡眠呼吸暂停等呼吸疾病的监测，在个性化医疗应用和连续健康监测中均具有应用价值。

2.5　鼻腔内呼吸监测系统

上海交通大学 H. Zhang 等人提出了一种可穿戴的超细柔性传感器，可伸入鼻腔内用于睡眠呼吸监测 [61]，其结构和使用方法如图 9 所示。通过采用自主研制的可编程紫外线曲面光刻系统 [62-67]，在柔性聚酰亚胺导管表面原位制造呼吸传感器。导管的外径仅为 300 mm，具有良好的柔韧性和生物相容性 [68]，伸入鼻腔后不会引起不适感。选择金微线圈作为敏感单元 [69]，基于热阻原理检测呼吸信号。此外，由于鼻腔内环境稳定，传感器不会受到风、环境温度等外界因素的直接干扰，因此抗外界因素干扰强。此外，传感器同时具有响应速度快、灵敏度高、

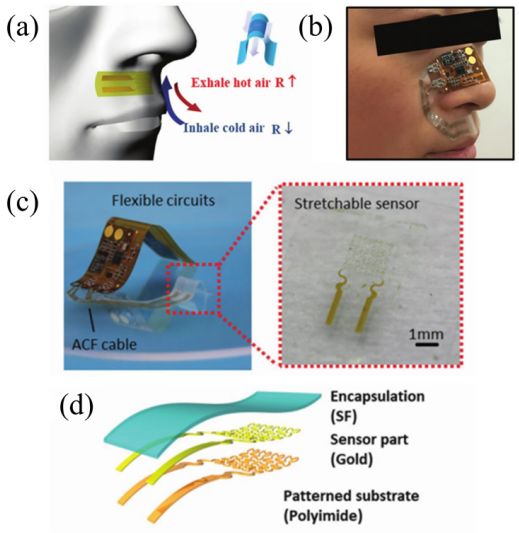

图 8 (a-b) 用于连续呼吸信号监测的 SHIC 使用场景图; 该系统由多个模块组成(c),包括温度传感器(d)、能源供应模块和电路处理模块[55]

Fig. 8 (a-b) The SHIC usage scenarios for continuous breathing signal detections. The system consists of multiple modules (c), including temperature sensors (d), energy supply modules, and processing circuit [55]

耐用性好、工作稳定等特点。在多种模拟呼吸系统疾病的条件下进行了信号测试,包括哮喘、鼻塞、呼吸暂停、低通气和口呼吸,结果显示该监测系统可明显区分正常和异常的呼吸信号。因此,该可穿戴式鼻内呼吸监测传感器在睡眠呼吸系统疾病的前期监测和睡眠健康评估方面具有很大的潜力。

由于直接呼吸信号监测系统的准确性和可靠性高,目前已有多家公司推出相关健康监测产品用于呼吸状况监测,如瑞思迈医疗器械有限公司(北京,中国)分别推出家用和医用的智能呼吸监测仪[70],已获得专业医生认可[71-73],云中飞电子有限公司(深圳,中国)推出面罩式睡眠呼吸监测仪[74],已达到医用级传感监测精度。由于该类可穿戴式呼吸监测系统能够直观地反映受试者的真实呼吸状况[75],因此更容易结合相关呼吸系统疾病的症状,实现对特定呼吸系统疾病的早期诊断。

3 间接呼吸监测法

在实际测量中,若要把可穿戴式呼吸监测系统植入被监测者的生活中,需要实现高舒适性、稳定性和高灵敏度。其中,将传感系统制备于纺织衣物中

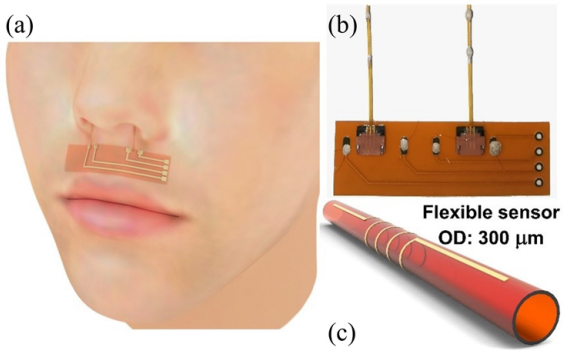

图 9 (a) 可伸入鼻腔内的柔性呼吸监测传感器; (b-c) 其中独立的监测单元能够同步地测量两鼻腔内的呼吸信号[61]

Fig. 9 (a) Flexible respiratory monitoring sensor that can be inserted into the nasal cavity, in which the independent sensing units (b-c) can simultaneously detect breathing signals in the two nasal cavities [61]

的方法已被证实是可行的。重庆大学 J. Yang 等人提出一种可穿戴纺织电子设备系统[76],能够同时对多个生理信号进行采集,如图 10 所示。该纺织传感器采用导电纱线,能够和普通商用尼龙纱线混合编织形成衣物。他们构建了摩擦电全纺织传感器阵列(triboelectric all-textile sensor array, TATSA)的几何编织模型,使得导电纱线和尼龙纱线在线圈横列和纵行方向上以环圈单元的形式互锁,并发现 TATSA 的工作原理可以从外力刺激和感应电荷两方面解释。应力会出现在两根纱线的接触表面上,导电纱线和尼龙纱线表面上的应力会随着外力的增加而增加,从而导致两根纱线之间的接触和挤压。一旦释放外力,两条纱线就会分开并相互远离,两者之间的接触分离运动引起电荷转移,从而相应的电势也发生变化。将 TATSA 缝制到衣服的不同部分,可以同时监视动脉脉搏和呼吸信号。结合软件处理系统,使得 TATSA 可用于心血管疾病和阻塞性睡眠呼吸暂停的长期和非侵入式的健康监测,在定量分析某些慢性疾病方面显示出巨大的优势。

此外,清华大学 Y. Zhang 等人首次证明了碳化丝织物(carbonized silk fabrics, CSF)可用于制造超拉伸和高灵敏度的应变传感器[77,78],如图 11 所示,该传感器在检测人体肢体运动和局部细微运动方面表现出卓越的性能。在基于 CSF 的应变传感器中,横向的纺织纱由平行纤维组成,纵向的纺织纱由加捻纤维组成,当织物表面发生拉伸等形变时,CSF 也

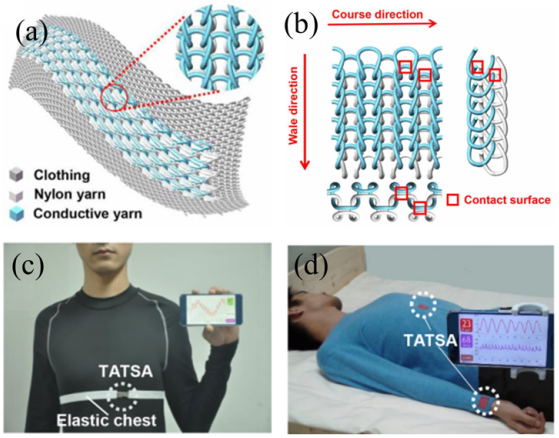

图 10　(a-b) TATSA 的结构以及和衣服组合的示意图; (c-d) 使用者可佩戴 TATSA 监测系统测量呼吸信号和脉搏[76]

Fig. 10 (a-b) Schematic diagram of TATSA structure and its combination with clothes; (c-d) the subject can wear the TATSA monitoring system to measure the respiratory signal and pulse[76]

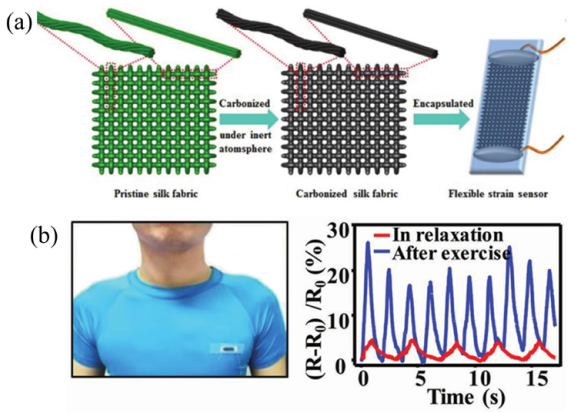

图 11　(a) 基于碳化丝织物的可穿戴应变传感器，可监测人类日常活动引起的应变信号，如(b) 监测呼吸带动胸部的应力变化[77]

Fig. 11 (a) The wearable strain sensor based on carbonized silk fabric for the monitoring of human daily activities, such as (b) the breathing signals on the chest[77]

同时发生形变并产生应力，在一定范围内，其电阻随应力的增大而线性增大，从而能够反映出人体穿戴部位的运动状况。CSF 应变传感器具有传感范围宽、高灵敏度、快速响应和高耐用性的优势，显示出在可穿戴设备和智能机器人中的巨大应用潜力。此外，这一概念可以扩展到其他织物中，如棉、莫代尔等，为可穿戴应变传感器的低成本和可扩展提供新的方向。

除此之外，还可采用非接触式方法间接测量人体睡眠情况下的呼吸状况，目前已有多家公司推出商业化产品，如 Sleepace 享睡(深圳，中国) 智能睡眠床垫[79]、MegaHealth 兆观(上海，中国) 超宽带雷达睡眠监测系统[80] 和梦加睡眠监测仪[81] 等。非接触式的呼吸监测法对被测试者没有任何干扰，因此能够真实地反映受试者的呼吸状况。目前，该类智能健康监测设备需要与呼吸医学专业领域展开合作，进一步验证在专业疾病检测领域的可行性[82-84]。

4　总结与展望

柔性可穿戴式呼吸传感监测系统集柔性传感器和微型化电路于一体，既可以准确地测量人体呼吸信号，又扩展了呼吸监测的使用空间，具有体积小、重量轻、操作简单等特点，被监测者可以自主操作仪器，在日常生活中监测呼吸状况并积累大量呼吸数据以供专业医生参考。目前，该研究领域已受到众多研究者和商业化公司的重视，极大地推动了柔性呼吸传感器的研究进展，提出了众多基于不同监测原理的呼吸传感系统或商业化产品，具有广大的应用市场和价值。同时，对柔性可穿戴式呼吸传感监测系统的研究也促进了日常呼吸数据与呼吸系统疾病诊断的结合，提高了疾病早期诊断的可能性。本综述主要从传感器的工作原理和呼吸监测系统的实现方式(直接监测和间接监测) 的角度，对国内外柔性可穿戴式呼吸监测系统的研究工作进行了概括性的阐述，旨在让对该领域感兴趣的研究者快速找到合适的研究要点，进一步促进呼吸监测系统领域的完善和发展。最后对柔性可穿戴式呼吸传感监测系统的发展趋势做如下主要概况和展望:

(1) 提高呼吸传感器的集成度和柔软性。为了实现日常化的呼吸监测，可穿戴式呼吸监测传感系统的佩戴舒适性需要进一步提高，只有监测系统对呼吸信号采集过程的影响尽可能小，才能够使得采集到的呼吸数据尽可能真实、可靠。

(2) 增强呼吸传感器的工作稳定性和可靠性。在推广柔性可穿戴式呼吸监测系统的过程中，传感系统需要适应复杂的使用环境，因此必须对多种环境因素——如温度、湿度、弯折、环境风等具有很强的抗干扰能力，减少干扰信号在所测数据中的占比，提高呼吸监测过程的可靠性。

(3) 探索日常呼吸信号与特定呼吸系统疾病之间的关联性。呼吸系统疾病会直接或潜在地影响患者的呼吸模式,通过对呼吸传感监测系统所采集数据的分析,并与临床上疾病患者表现的症状相关联,能够寻找到二者之间的潜在联系,并尽早地进行诊断、治疗,从而提高患者的治疗效果。

(4) 将呼吸信号与其他人体信号相结合,综合地体现被监测者的真实活动。单一的呼吸数据所体现的信息量非常有限,只有与体温、心率、肢体运动、血压、血氧饱和度等多种信号结合,才能够真实地反映被监测者的活动,并进一步融入到人机一体化和大数据采集的发展潮流中。

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