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Development and Clinical Evaluation of a Polymer Composite Respiratory Training Device for Box Breathing-Based Stress Management

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Abstract

Academic stress is a problem among the higher secondary students, and it is a problem which has a negative impact on their psychological condition and academic performance. Box breathing has been found to lower stress; however, it can be hard to keep a rhythmic breathing pattern without guidance. A lightweight, reusable and ergonomic polymer composite respiratory training device may enable the delivery of structured breathing assistance and help increase adherence to controlled breathing exercises. To assess the effectiveness of a polymer composite respiratory training device for guided box breathing and compare it with the conventional relaxation techniques in stress management among higher secondary students. A randomized pre-post experimental study was done with 90 students aged. This review examines the role of polymer composite respiratory training devices in guided box breathing for stress management among adolescents. The literature on controlled breathing, conventional relaxation techniques, polymer composite materials, respiratory training devices, and their potential clinical and educational applications was reviewed. Available evidence indicates that structured breathing and relaxation approaches may contribute to reductions in perceived stress, while polymer composite respiratory training devices may provide standardized breathing guidance, portability, ergonomic design, and improved adherence. However, direct clinical evidence evaluating the comparative effectiveness of polymer composite respiratory training devices remains limited. Further controlled clinical studies are required to establish their effectiveness, usability, durability, and cost-effectiveness.

Keywords: Polymer composite, respiratory training device, box breathing, stress management, perceived stress scale, higher secondary students

INTRODUCTION

Stress has risen as one of the major health issues of adolescents, especially higher secondary students with their mounting academic pressure, competitive learning environment, parental expectations and future job insecurity, etc. Academic stress negatively impacts emotional health, cognitive function, focus, sleep habits, and academic output [1]. Long-term stress can increase the risk of students suffering from anxiety, depression, poor decision making and a diminished quality of life if not managed. Safe, cost-effective, and non-pharmacological approaches that foster psychological resilience and emotional regulation in school-attending adolescents are, therefore, of increasing interest.

Breathwork is one of the many non-medical, non-pharmacological methods that has attracted

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substantial interest due to its simplicity, its low cost and the fact that no training or medication is required. Controlled breathing exercises can help to regulate the ANS and promote parasympathetic activity, decrease sympathetic activation and reduce the physiological and psychological stress response [2]. Box breathing, also referred to as square breathing, is a systematic breathing pattern that involves four equal parts: inhale, hold, exhale, and pause. This breathing pattern encourages relaxation, regulates emotions, helps to stabilize heart rate variability and brings mental focus. The use of structured breathing has previously been shown to be highly effective in decreasing perceived stress and enhancing psychological wellbeing in adolescents and adults.

Traditional relaxation techniques – such as Progressive Muscle Relaxation, Guided Imagery, and Meditation – are also popular ways to manage stress. The techniques involve progressive muscle relaxation, which consists of systematically relaxing and tensing muscle groups to lower somatic stress, and guided imagery and meditation, which promote psychological relaxation and re-structuring of cognition and emotions [3]. Typical relaxation techniques, however, require more focus, guidance, or longer intervention time for these techniques to be effective, and may limit the ability to practice them regularly among adolescents, particularly those at school.

Although box breathing is proven to be effective, it is difficult to maintain the rhythm, especially for first-time users and for younger people. Breathing exercises may not be as therapeutic as they could be due to variations in breathing rate, breath-holding time and compliance of the user. Assistive respiratory training devices that could offer standardized respiratory training tips have been encouraged to help promote adherence to the user, ensure consistency of breathing cycles and improve the effectiveness of respiratory training and stress management programs [4].

With recent developments in polymer science, lightweight, durable, biocompatible and ergonomically designed respiratory training devices suitable for repeated clinical and personal use have been developed [5]. The excellent mechanical properties, biocompatibility and user comfort make polymer composite materials increasingly attractive for the use in respiratory rehabilitation devices, breathing trainers, inhalation systems and in wearable healthcare technologies, among others. In addition, the manufacturing methods of polymers, such as injection molding and Additive Manufacturing, allow for the creation of customized respiratory devices that have better ergonomic properties and durability in the long-term.

Box breathing in combination with polymer composite technology is a novel solution that combines material engineering with evidence-based breathing therapy for stress management [6]. The polymer composite respiratory training device can offer guidance for inhalation, hold up the inhale without releasing it too soon, guide the exhale and the resting phase without the patient having to use any additional apparatus, be hygienic and portable, and be comfortable for the user, all while maintaining the standardized practice of breathing, thus enhancing the compliance and therapeutic outcomes at the educational institution, rehabilitation centers, and home-based healthcare settings [7].

While both box breathing and traditional relaxation techniques have been shown to be effective in reducing perceived stress in higher secondary students previously, there is limited evidence concerning the use of polymer composite respiratory training devices in structured breathing interventions [8]. The results of the present study can, therefore, be used to guide the development of new polymer composite rehabilitation devices based on the non-pharmacological therapy of stress that integrate the principles of biomedical engineering with box breathing and future application in preventive health care and the mental health of adolescents [9].

PRINCIPLES OF BOX BREATHING AND RESPIRATORY TRAINING

The concept of box breathing is a structured breathing pattern that is becoming more well known as a non-pharmacological stress reduction and emotional management technique. There are four even parts to the technique: inhale, hold the breath, exhale, and pause after the exhale, each lasting the

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same length of time, usually 4–6 seconds [10]. Box breathing involves conscious control of breathing and the synchronization of respiratory and cardiovascular system activity, which can help to balance the autonomic nervous system and decrease physiological and psychological stress, in contrast to spontaneous breathing.

The therapeutic benefits of box breathing are thought to be most related to the effect on the autonomic nervous system. Slow and controlled breathing has a calming effect on the sympathetic nervous system and stimulates the vague nerve to stimulate the parasympathetic system [11]. These neurophysiological responses are significant in adolescents who suffer from chronic academic stress, examination anxiety, and emotional fatigue and help them to achieve physiological relaxation.

Numerous clinical studies have found that structured breathing exercises are effective in lowering perceived stress and enhancing emotional health in a variety of populations. Compared with unstructured deep breathing, the equal-duration breathing cycle of box breathing offers more respiratory consistency and continued engagement of cognition with breathing which could help to promote adherence and therapeutic effectiveness [12]. Another mindfulness technique that is also utilized is the repetitive breathing pattern which focuses the mind away from negative thinking that causes stress and relaxes the mind.

The application of respiratory training has a long history in pulmonary rehabilitation, as well as in athletic training and psychological therapy which has been proven to improve breathing mechanics and respiratory muscle function [13]. Respiratory training devices can also be used in conjunction with these interventions: they provide guidance on breathing, ensure adherence to training, and standardize the inhalation/exhalation pattern, particularly for individuals who do not learn how to breathe correctly without external cues.

With the advancement of biomedical engineering, portable respiratory training systems have been developed which combine ergonomic design with ease of use [14]. Because of their lightweight polymer composite construction, these devices offer additional advantages, such as durability, compatibility, chemical resistance, cleaning and ease of use, and can be programmed to provide visual, tactile, or airflow feedback to assist users at each step of the box breathing cycle, making them suitable for repeated use in schools, rehabilitation centers, hospitals and home healthcare settings.

Therefore, the use of polymer composite respiratory training devices in box breathing is a multidisciplinary approach involving evidence-based breathing therapy and biomaterials and medical device engineering. These systems can help to reduce the risk of inaccurate breathing in patients, increase adherence to treatment, and boost the effectiveness of the stress management intervention, which can be beneficial for preventive healthcare and rehabilitation.

POLYMER COMPOSITE MATERIALS FOR RESPIRATORY TRAINING DEVICES

Polymer composite materials are important classes of engineering materials which have been used to manufacture biomedical devices with high mechanical strength, low weight, chemical resistance and high design flexibility [15]. Unlike metallic materials, polymer composites are used in an increasing number of applications including respiratory rehabilitation machines, inhalers, medical prosthetics, wearable medical devices, and assistive devices for patients because of their high strength-to-weight ratio while fulfilling the required number of repeated uses in the clinical and personal setting. Therefore, polymer composites become promising materials in the fabrication of respiratory training devices to manage stress and to rehabilitate breathing.

Common polymers employed in biomedical applications – like respiratory healthcare products – are polypropylene (PP), polycarbonate (PC), polyethylene (PE), thermoplastic polyurethane (TPU), silicone elastomers, and also acrylonitrile butadiene styrene (ABS). The polymers selected have excellent biocompatibility, dimensional stability, moisture resistance, chemical resistance and sterilization

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properties. Furthermore, using the materials of glass, carbon or natural fiber reinforced polymer composites can give superior mechanical properties, and make compact and ergonomically designed respiratory devices, which can be used for the whole day [16].

On the manufacturing side, polymer composites offer a broad range of manufacturing technologies which further promotes their use in biomedical engineering. Aside from this, conventional molding processes – such as injection molding, compression molding, thermoforming, and extrusion – have enabled the rapid and efficient manufacture of respiratory devices with high dimensional accuracy and repeatability, while more recently 3D printing (additive manufacturing) has facilitated the manufacture of patient-specific customized polymer-based respiratory devices for a variety of patient groups [17].

Respiratory training devices must be physically robust and easy to use – and accepted by the patient. They present smooth finish, provide flexibility wherever it is required, and have sufficient stiffness to retain device geometry during repeated inhalation/exhalation cycles while being very thin to reduce user fatigue for longer training periods and corrosion-resistant to resist humid breathing for a long service life [18]. In addition, many polymers useful for medical applications can be readily cleaned and sterilized repeatedly without being damaged, thus making them suitable for reuse in medical applications.

The polymer composite respiratory training device can, therefore, provide enhanced user compliance, more consistent breathing pattern and minimize inter-individual variation caused by the lack of guidance during respiration.

With the development of smart polymer composites, the opportunities for the development of devices for respiratory rehabilitation have also been expanded in recent years. The use of a flexible sensor, a microelectronic, a pressure sensor and a digital monitoring system in a polymer-based structure provides in real time monitoring of parameters relevant to respiration, such as breathing frequency, tidal volume, inspiratory flow, and breathing rhythm [19]. These intelligent systems can give instant feedback to the users at the same time as they capture breathing performance for use by clinicians and rehabilitation experts. In sync with the trend of personalized medicine, digital healthcare and remote monitoring.

Polymer composite respiratory devices can facilitate the creation of structured breathing interventions that could improve breathing accuracy, adherence to breathing regimens, and effective stress management in educational, clinical, and community health care environments, due to their beneficial characteristics of light weight construction, biocompatibility, mechanical durability, ergonomic design, and versatility of manufacture [20]. The innovative solution adopted by those multidisciplinary teams is increasingly a characteristic of the design of next-generation rehabilitation and wellness devices, as polymer composite technology becomes a key technology.

As this article is a review, no single polymer composition is designated as experimentally validated material for a specific respiratory training device. Instead, the reviewed polymer classes represent potential material options that may be considered according to the intended application and device requirements. Material selection should consider mechanical strength, flexibility, fatigue resistance, dimensional stability, moisture and chemical resistance, biocompatibility, sterilization compatibility, manufacturability, and user comfort. Similarly, injection molding, compression molding, thermoforming, extrusion, and additive manufacturing may be selected according to the required device geometry, production volume, customization requirements, and functional characteristics. These considerations provide a design framework for future development and experimental validation of polymer composite respiratory training devices.

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CLINICAL APPLICATIONS AND FUTURE PERSPECTIVES OF POLYMER COMPOSITE RESPIRATORY TRAINING DEVICES

Respiratory training devices for improving respiratory muscle coordination, breathing efficiency, and physiological function hold promise for preventive health, pulmonary rehabilitation, and psychological health realms. However, recent advances in the field of breathing therapy have expanded its application beyond therapy for the respiratory system to stress management, anxiety reduction, sports performance enhancement, and mindfulness-based therapy [21]. Additionally, polymer composite materials are adopted in respiratory training devices, which also take advantage of the material's light weight, durability, and ergonomically designed characteristics for multiple use throughout the day.

The emerging use of respiratory training devices is in stress management. In tandem with a breathing pattern, users are required to keep their inhales, breath-holds, exhales and resting periods in sync and maintain them for set lengths of time in exercises such as box breathing. While easy to learn, some people, especially teens and novices, find it hard to keep pace without any cues [22]. This benefit eliminates the need to rely on the presence of a provider to ensure a consistent breathing pattern, boosts user confidence, and encourages stronger adherence to breathing patterns.

Classes in breathing stress management are suitable to be held in schools. Some of the key factors that induce stress in adolescents are academic stress, competitive exams, parental expectations, and increasing digital interaction [23]. Portable respiratory training devices with regular guided breathing can improve emotional control, concentration and psychological resistance, while lowering anxiety and perceived stress in students, with the light weight and portability of the devices making it easy to use in classrooms, counselling centers, the library and at home without the need for complex infrastructure or constant professional supervision.

In addition to being used in education, polymer composite respiratory training devices have a large potential for use in physiotherapy and rehabilitation practice. Breathing exercises are often prescribed in post-thoracic surgery, immobilized for long periods, neurological disorders and respiratory dysfunction. Medical-grade polymer composites offer also high durability, repeated sterilization resistance, and user comfort during long rehabilitation treatments, while their ergonomic design decreases user fatigue and guarantees stable breathing performance and, therefore, optimal clinical results.

Today's respiratory training devices have even more advanced capabilities thanks to digital technology. Recent developments in sensor technology, flexible electronics and wireless communication have made it possible to develop smart polymer composite devices capable of monitoring the respiratory parameters in real time. Breathing frequency, inspiratory and expiratory time, respiratory volume, and user compliance can be recorded by embedded pressure sensors, airflow sensors and microcontrollers [24]. These can be sent to the smartphone or a cloud-based health system solution, where healthcare professionals are able to track patient progress remotely and offer tailored therapeutic suggestions. The shift towards digital health solutions is consistent with the focus on telemedicine, distance rehabilitation and personalized health care.

The optimization of material composition and function of polymer composite respiratory training devices should be a focus of future research. Computational modeling and artificial intelligence-driven breathing analysis could also help in designing adaptive breathing devices that automatically optimize breathing guidance as per the response of the individual. Further, long-term clinical trials are needed with various age groups and healthcare environments to define the effectiveness, usability and cost effectiveness of these devices. A conceptual comparison of polymer composite respiratory training devices with conventional respiratory trainers and relaxation techniques is presented in Table 1 to highlight differences in material characteristics, portability, feedback, usability, cost considerations, and potential effectiveness.

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Table 1. Comparative characteristics of polymer composite respiratory training devices, conventional respiratory trainers, and relaxation techniques.

Parameter	Polymer composite respiratory training device	Conventional respiratory trainers	Relaxation techniques
Material	Polymer/polymer composite materials	Primarily conventional device materials	No dedicated material/device required.
Cost	Depends on material, manufacturing method, and device complexity	Depends on device type and design	Generally low; usually requires no physical device.
Portability	Potentially high due to lightweight polymer construction	Generally portable, depending on design	Very high.
Feedback mechanism	May provide visual, tactile, airflow, or sensor-based feedback	Usually provides mechanical, airflow, or visual guidance depending on device	Usually self-guided, therapist-guided, audio-, or video-guided.
Usability	Can be designed for structured and repeated breathing practice	Depends on device design and user familiarity	Generally simple but may require instruction and concentration.
Breathing guidance	Can support standardized box-breathing stages	Provides breathing guidance depending on device	Relies mainly on verbal, visual, or mental instructions.
Potential effectiveness	Potential benefit for structured breathing and stress management; direct evidence remains limited	Established applications in respiratory training depending on device type	Used for stress reduction and relaxation.
Potential applications	Stress management, respiratory education, rehabilitation, and home use	Respiratory training and rehabilitation	Stress management and relaxation.
Future potential	Integration of sensors, wireless monitoring, and adaptive feedback	Potential integration with digital monitoring	Digital and guided relaxation approaches.

CHALLENGES, LIMITATIONS, AND FUTURE PERSPECTIVES

Although polymer composite materials are currently being increasingly used in biomedical engineering, there are several obstacles in the way of developing respiratory training devices for stress management. The main challenge is to optimize the mechanical properties, flexibility, durability, and patient comfort [25]. Respiratory devices are exposed to repeated inhalation/exhalation cycles, and the selected polymer composite should demonstrate very good fatigue resistance, while maintaining its low weight aspect. Also, moisture, saliva, cleaning agents, and environmental conditions may affect the long-term performance of certain polymeric materials, as well as their structural stability. Thus, it is critical to select the materials used and perform extensive durability testing prior to clinical use.

Patient safety and biocompatibility are also significant factors in device development. The surface properties of medical-grade polymers that are used in repeated contact with humans must conform to the international biocompatibility standards and cannot emit harmful substances under long-term use [26]. Future work should thus be directed to include coatings with antimicrobial properties, bioactive polymer composites, and self-cleaning surface technologies to reduce contamination, and retain patient comfort.

One of the major challenges is to design ergonomically optimized respiratory training devices for different age groups and clinical populations. The diversity in facial morphology, breathing ability and breathing habits, and preferences require flexible design of the device. Another opportunity offered by advances in computer-aided design (CAD), computational fluid dynamics (CFD) and Additive Manufacturing (AM) is that of creating patient-specific devices with optimized flow characteristics and better ergonomic properties, thus cutting manufacturing time and costs [27].

Another area of research that is receiving increased attention is the use of smart devices in polymer composite respiratory devices. With the addition of flexible sensors, pressure transducers, airflow monitoring systems, wireless communication modules, and artificial intelligence algorithms, the existing respiratory trainers can be innovated as intelligent healthcare devices for continuous monitoring of

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respiratory performance [28] Cloud-based data storage, mobile health applications and other technologies might also assist in remote patient monitoring, tele-rehabilitation and long-term evaluation of therapeutic outcomes.

While the use of controlled breathing techniques – like box breathing – has been seen to have a positive impact on stress reduction, there is relatively limited evidence on the clinical performance of polymer composite respiratory training devices specifically designed to be used for guided breathing intervention techniques. Multicenter, randomized controlled trials with larger and more diverse populations, are warranted in future studies to assess the effectiveness, usability, durability, patient satisfaction and cost of the devices. Comparative testing of various polymer composite materials, breathing resistance mechanisms and feedback systems would also help to pinpoint best device configurations for different clinical and non-clinical applications.

As the available evidence on polymer composite respiratory training devices remains limited, future clinical investigations should incorporate comprehensive statistical reporting, including baseline participant characteristics, mean changes in outcome measures, confidence intervals, effect sizes, and appropriate inferential statistical tests. Such reporting would facilitate meaningful assessment of clinical significance and allow comparison across different breathing interventions and device configurations.

CONCLUSION

In the present era of higher secondary education, where students face various academic, psychological, and social stressors, stress management is becoming an integral part of the healthcare system for young people. The controlled breathing intervention called Box breathing has been found to be a promising strategy to improve autonomic regulation, emotional stability and reduction of perceived stress without the use of medication. The literature reviewed indicates that structured respiratory training could prove viable, practical, safe and readily accessible as a means of enhancing psychological well-being, and thereby encourages preventive health care. The literature reviewed indicates that both structured breathing interventions and conventional relaxation techniques may contribute to reductions in perceived stress. However, direct comparative evidence establishing the superiority of polymer composite respiratory training devices over conventional relaxation approaches remains limited. These kinds of devices can help improve breathing regularity, compliance, clinical utility, and enable education, rehabilitation, and home health care applications. Further research is needed on the development of high-performance polymer composite materials, the integration of smart sensors, ergonomic optimization, and the design of clinical validation studies to demonstrate the effectiveness and long-term use of these innovative respiratory training systems in preventive and rehabilitative healthcare.

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