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From Conventional to Technology-Enhanced Pulmonary Rehabilitation: AI, Tele-Rehabilitation, and Robotic Support

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Abstract

Integrated pulmonary rehabilitation represents a critical cornerstone in the management of chronic pulmonary affections, aimed at ameliorating the quality of life, functionality, and autonomy of patients through personalized and multidisciplinary interventions. The program encompasses components such as adapted physical training, education for self-management, nutritional and psychological counseling, as well as the utilization of digital technologies and artificial intelligence for monitoring and personalization. The benefits of this approach are demonstrably significant in reducing symptomatology, increasing exercise tolerance and adherence to treatment, and in early detection of exacerbations. The integration of robotics and AI platforms promises a more precise and accessible rehabilitation paradigm, but requires clinical stipulations, cost analyses, and interdisciplinary collaborations for efficient implementation. This modern strategy maintains a crucial role in optimizing treatment outcomes and enhancing the quality of life for patients with chronic pulmonary diseases and post-COVID-19 sequelae.

Keywords: Pulmonary rehabilitation; Physical training; Artificial intelligence

Introduction

Integrated pulmonary rehabilitation (PR) represents a foundational pillar in the contemporary management of chronic pulmonary affections, with the objective of significantly improving the quality of life and global functionality of patients. According to the most recent guidelines from the American Thoracic Society (ATS) in 2023, pulmonary rehabilitation is defined as a multidimensional ensemble of interventions designed to improve the physical and psychosocial status of patients with chronic respiratory diseases through a personalized approach. The aims of PR programs are to alleviate the symptomatology of the underlying disease, improve exercise capacity, autonomy, and quality of life, as well as modify health behaviors in the long term. PR has become an essential practice for improving functional status, quality of life, and patient autonomy [1].

Planning the Pulmonary Rehabilitation Program and its Components

The majority of patients with chronic pulmonary pathology present to the pulmonary rehabilitation unit outside of an exacerbation, during a period of remission. Since the 2006 Declaration, considerable evidence has been published regarding the benefits of exercise-based pulmonary rehabilitation during and immediately after hospitalization for an acute exacerbation of chronic obstructive pulmonary disease (AECOPD). Resistance training of the lower limb muscles during an exacerbation is well-tolerated, improves muscle strength, and increases exercise tolerance. The multidisciplinary team consists of a rehabilitation physician, pulmonologist, psychologist, physical therapist, nutritionist, and social worker. These professionals perform a complex individualized assessment of the patient, functionally, nutritionally, and psychologically, and establish a common therapeutic plan, actively collaborating with the patient as the central pivot of therapeutic success. Advanced functional evaluation of the patient is performed through ergo spirometry, which determines VO_2 max and gas exchange, thereby identifying the cardiovascular and muscular limitations of the patient. Based on the data obtained, the intensity of exertion can be precisely prescribed, adaptation to exertion can be monitored, and functional progress can be objectively assessed [2,3].

Conditions benefiting from pulmonary rehabilitation include obstructive respiratory diseases (such as COPD, bronchial asthma, pulmonary emphysema, chronic bronchitis, bronchiectasis, cystic fibrosis, bronchiolitis obliterans), restrictive pulmonary diseases (such as pulmonary fibrosis, post-COVID-19 sequelae, occupational lung diseases, sarcoidosis, hypersensitivity pneumonitis, lymphangioleiomyomatosis, survivors of adult respiratory distress syndrome, diseases of the thoracic wall, post-tuberculosis syndrome), thoracic wall deformities (due to kyphoscoliosis, ankylosing spondylitis), neuromuscular diseases with respiratory dysfunction. Other pathological conditions on which PR has beneficial effects include lung cancer, pulmonary arterial hypertension, pre/post thoracic and abdominal surgery with respiratory dysfunction, pre/post lung transplant, pre/post LVRS (lung volume reduction surgery), ventilator dependence, obesity-related respiratory diseases, autoimmune diseases with pulmonary involvement (systemic scleroderma, rheumatoid arthritis), and pediatric patients with respiratory diseases. Patients with severe conditions that limit mobility, severe pulmonary arterial hypertension, decompensated heart failure, unstable angina or recent infarction, severe exercise-induced hypoxemia, deafness and hypoacusis, visual disturbances, mental illnesses, or inability to learn the exercise program are excluded from the PR program [4].

Components of Pulmonary Rehabilitation

According to ATS/ERS guidelines, modern pulmonary rehabilitation includes a broad range of interventions, each having specific roles in the multidimensional approach to the patient. The integrated approach to patients includes physical training, educational counseling, nutritional counseling, energy conservation techniques, breathing techniques, individual and group psychological counseling. Each component plays an essential role in optimizing the patient's health status, and together these components offer an integrated and personalized approach.

Physical Training

Physical training constitutes the foundation of PR programs, aiming to improve pulmonary function and reduce dyspnea by increasing endurance, muscle strength, and exercise capacity. Prior to initiating the PR program, exercise capacity is evaluated in order to individualize exercise regimens, supplement with oxygen, and prevent potential complications. Physical exercises are adapted and personalized, including endurance training, interval training, resistance training, respiratory muscle training, as well as neuromuscular electrical stimulation. Endurance training is performed on a cycle ergometer or through walking, with a frequency of 3-5 times per week, with a high level of continuous exercise; the duration of a session is 20-60 minutes. Individuals who cannot tolerate continuous endurance training can perform interval training, where high-intensity exercise is interspersed, regularly, with periods of rest or lower-intensity exercises, with similar efficacy to continuous training. Strength training encompasses exercises targeting specific muscle groups, through repeated weight lifting.

An alternative to physical exercises, addressed to patients with severe dyspnea and significant cardiovascular limitation, is neuromuscular electrical stimulation, where muscles are trained without the need for exercise. Inspiratory muscle training aims to increase the pressure-generating capacity of the musculature, which is reduced in patients with chronic pulmonary diseases. The most common approach for inspiratory muscle training (IMT) utilizes devices that impose a resistive load or a threshold. The effects of PR can be maximized through efficient pharmacotherapy, oxygen supplementation as needed, non-invasive ventilation, and walking aids (rollator). The rehabilitation program is interrupted based on clinical criteria (fatigability, sensations of dyspnea, thoracic constriction, vertigo, headache, palpitations) and functional criteria (desaturation <90% or by 4% compared to baseline, respiratory rate >40/minute, bradycardia or tachycardia, arrhythmias, confusional state).

Lifestyle Modification and Self-Management

Patient education plays a pivotal role in the recovery process and is intimately connected to physical training as an essential part of this comprehensive intervention, aiming to improve self-management of symptoms and enhance adherence to treatment, including by reducing fear of exertion. Patient education addresses topics such as early recognition of exacerbation symptoms, the role, correct techniques for inhaling medications and oxygen therapy, the importance of smoking cessation and avoidance of irritants, breathing strategies and secretion clearance techniques, the benefits of physical exercise, and energy conservation techniques during daily activities, as well as adaptation to a new lifestyle. Self-management includes strategies such as establishing objectives, problem-solving plans, decision-making, and implementation of measures. The goal of self-management is to improve adherence to treatment, application, and maintenance of the exercise program and breathing techniques.

Nutritional Counseling

Nutritional counseling is an important component of PR programs, given that nutritional status, body weight, body composition, and body mass index are independent determinants

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of therapeutic success in chronic respiratory diseases. Adopting a healthy eating style reduces the risk of metabolic and cardiovascular conditions, significantly influencing the efficiency of physical exercises and potentially reducing fatigue, providing adequate metabolic support for daily activity. A growing number of patients with respiratory conditions related to obesity, such as "obesity hypoventilation syndrome" and "obstructive sleep apnea," can be addressed in pulmonary rehabilitation programs. Specific interventions include, in obese patients, dietary education with meal planning and restriction of calorie intake, and psychological support (encouragement for weight loss), or specific supplementation for underweight or sarcopenic patients, with nutrition becoming a therapeutic support, not just an adjuvant.

Psychological Counseling

Psychiatric comorbidities are associated with reduced therapeutic adherence to Pulmonary Rehabilitation programs, increased risk of exacerbations and mortality. Chronic dyspnea is not only a physical symptom but also a major trigger for anxiety and depression, contributing to avoidance of physical exertion. Limiting physical activity leads to decreased endorphin secretion, accentuating the depressive state. Depression reduces motivation for treatment and participation in rehabilitation programs, with the psycho-emotional impact often remaining underdiagnosed and undertreated, and social isolation and the stigma of the disease exacerbating psychological suffering.

Over 50% of patients with chronic respiratory diseases develop affective disorders, and the lack of psychological screening reduces the overall effectiveness of respiratory interventions. The prevalence of depression in COPD reaches 40-60%, while anxiety affects up to 55% of patients. The assessment of anxiety and depression in practice in pneumology clinics is carried out by applying questionnaires such as HADS (Hospital Anxiety and Depression Scale), BDI-II (Beck Depression Inventory), STAI (State-Trait Anxiety Inventory). Correlating psychological scores with SGRQ, mMRC, CAT allows a holistic view of the patient. Cognitive-behavioral interventions reduce the severity of anxiety and depression by 25-50%, with demonstrated efficacy in patients with COPD, severe asthma, and idiopathic pulmonary fibrosis [5].

Digital Technologies and Tele-rehabilitation

Telemedicine, according to the World Health Organization, includes the provision of medical services through telephone and mass media communications, especially when geographical isolation or reduced mobility represents an obstacle. Broadly, telemedicine can include telephone counseling, email, websites, and medical podcasts. The most important benefits include: real-time audio and video communication between doctor and patient, collection and transmission of specific data (medical recommendations, messages, videos), remote monitoring in real-time of vital parameters via portable devices such as sensors, smart watches or trackers, reducing costs and increasing adherence to the program [6].

Telemedicine can include telephone counseling, email, websites, mobile apps, or medical podcasts. Its implementation depends on the provider and the recipient, and tele-rehabilitation can be divided into the following types:

a) **Center-based tele-rehabilitation:** Connecting a larger/ expert center to one or more smaller centers to support the delivery of knowledge and experience in pulmonary rehabilitation via videoconferences.

b) **Home-based tele-rehabilitation:** Patients follow a supervised exercise program at home, using videoconferencing, sometimes with monitoring of oxygen saturation and heart rate. This home program can replace outpatient respiratory recovery or serve as a complementary strategy for in-patient rehabilitation.

c) **Web-based tele-rehabilitation:** Through multiple platforms providing digital pulmonary rehabilitation programs, especially targeted at patients diagnosed with COPD. Digital technologies delivering pulmonary rehabilitation programs typically include at least one of the following components: physical exercise, educational counseling, psychological counseling, nutritional or behavioral counseling.

In the sphere of pulmonary rehabilitation services, programs have clinical validation through studies in chronic lung disease and post-COVID-19. Intelligent devices with adjustable resistance and integrated sensors record parameters such as PRmax, PI max, process data and provide digital feedback, leading to automatic adaptation of physical exercise intensity. Artificial intelligence and predictive analytics are applicable in PR by developing algorithms for early detection of exacerbations of respiratory diseases, algorithms to personalize rehabilitation plans by automatic analysis of Spirometric and pulse oximetry data. Common functionalities of AI platforms and software include customization of exercises, predictive analysis, automatic feedback and clinical decision support, helping to adjust intensity, reduce risks and human error. Examples of AI platforms and software used in pulmonary rehabilitation include Breathe Smart (USA): AI platform that monitors PEF, SpO2 and symptoms, generating early alerts for exacerbations; ResAppDx (Australia): a mobile app using AI to analyze respiratory sounds and aid diagnosis (COPD, asthma, pneumonia); Spiro Nose (Netherlands): analyzes the composition of exhaled air and differentiates pulmonary diseases through automatic learning algorithms; Kaia Health: AI-guided digital rehabilitation app for respiratory exercises, physical activity, mindfulness; Pulmonary.AI (prototype): AI system that analyzes data from ergo spirometry and adjusts effort in real time [7,8] (Table 1).

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Table 1: Comparison between classical PR and PR with integrated artificial intelligence.

Analyzed Aspects	Classical PR	PR With Integrated Artificial Intelligence
Personalization	Based on observation, periodic re-evaluation	Continuous adjustment based on physiological data
Monitoring	Intermittent, only during sessions	Continuous, including at home
Exacerbation Detection	Based on reported symptoms	Predictive, through complex algorithmic models
Detection		models
Accessibility	Limited to specialized centers	Extended through mobile apps and telemedicine
Program Adherence	Variable, dependent on personal motivation	Increased through digital interaction and feedback
Clinical Decision	Subjective, sometimes delayed	Supported by algorithms and objective analysis

Artificial intelligence is integrated in the field of PR also through the involvement of robots, the use of which is correlated with increased adherence, especially in patients with cognitive deficits or affective disorders. There are assistant robots that guide respiratory exercises, providing visual and auditory feedback in real time, and interactive social robots (PARO, NAO) that can increase the involvement of elderly or anxious patients. Integration with biofeedback systems (EMG, spirometry) allows automatic adjustment of exercises. Mobile robots can be used in centers or at home to facilitate access and motivation. The advantages of integrating robots in clinical practice are standardization of exercises through constant protocols with reduced variability, or, conversely, adaptive personalization, where the analysis of physiological parameters can change the type and intensity of exercises. Through integrated sensors (of pressure, volume, respiratory flow), robots can monitor and objectively report progress, current challenges are represented by high costs, lack of clinically validated protocols and the need for staff training, requiring multicenter clinical trials and close collaboration between doctors, engineers and psychologists [9,10].

Conclusion

Integrated pulmonary rehabilitation is a key component in managing chronic and post COVID-19 respiratory diseases, combining physical training, education, nutritional support, and psychological counseling in a personalized, multidisciplinary framework. The incorporation of telemedicine, artificial intelligence, and robotic assistance further enhances this model by enabling continuous monitoring, early detection of exacerbations, and dynamic adjustment of exercise intensity. These technologies improve accessibility, adherence, and clinical decision-making, particularly for vulnerable or remote patients. However, widespread implementation requires robust clinical validation, cost-effectiveness analyses, standardized protocols, and close interdisciplinary collaboration to ensure safe, efficient, and equitable integration into routine care.

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