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Twelve-Week Air Stacking Training Improves Cough Effectiveness and Lung Volumes in individuals with spinal cord injury: A Single-Center Retrospective Cohort Study.

Objective: To determine whether daily air stacking (AS) over 12 weeks improves cough effectiveness and pulmonary volumes in individuals with spinal cord injury (SCI). **Methods:** This retrospective study analyzed the records of individuals with SCI who received AS training at the *Los Coihues* Clinic in Chile. Participants performed AS exercises five days per week for 12 weeks. Pulmonary function was assessed at baseline and after the intervention, including peak cough flow (PCF) in four conditions (spontaneous, with AS, with manually assisted cough [MAC], and combined AS+MAC), vital capacity (VC), maximum insufflation capacity (MIC), maximum inspiratory pressure (MIP), and maximum expiratory pressure (MEP). Paired t-tests were used to compare pre and post-intervention values, with significance at $p < 0.05$. **Results:** Twenty individuals (19 men; mean age 38.8 ± 13.1 years) with cervical (85%) and thoracic (15%) SCI were included. Significant improvements were observed after 12 weeks in VC (2.41 ± 0.91 vs. 3.01 ± 1.06 L; $p = 0.004$), MIC (3.80 ± 0.96 vs. 4.48 ± 0.96 L; $p = 0.006$), MIP (71.2 ± 26.2 vs. 88.9 ± 26.5 cmH_2O; $p < 0.001$), and PCF in all conditions: spontaneous ($p < 0.001$), with AS ($p = 0.03$), with MAC ($p = 0.02$), and with combined AS+MAC ($p = 0.02$). No significant change was found in MEP. **Conclusions:** Twelve weeks of daily AS training significantly improved cough effectiveness and pulmonary function in individuals with SCI. These sustained improvements may enhance airway clearance and respiratory health in this population.

KEYWORDS: Spinal cord, Cough, Vital Capacity; Pulmonary Rehabilitation; Respiratory Function Tests; Physiotherapy (Techniques).

Introduction

Spinal cord injury (SCI) results from damage to the spinal cord, causing a range of neurological impairments. This injury can arise from traumatic events such as accidents or falls or nontraumatic causes such as infections or tumors (Rouanet et al., 2017). SCI incidence is significant, with estimates ranging from 250.000 to 500.000 new cases globally each year (World Health & International Spinal Cord, 2013). Its consequences significantly impair quality of life, including chronic pain, dysfunctions in bowel, bladder, and sexual activity, spasticity, and notably, respiratory complications (Benedetti et al., 2022; Winslow & Rozovsky, 2003). These respiratory complications are particularly concerning, especially in individuals with higher-level cervical injuries (Bach et al., 2020).

Respiratory complications in SCI arise primarily from weakness or paralysis of respiratory muscles, such as the diaphragm and intercostals, which compromises spontaneous ventilation and cough effectiveness (Benedetti et al., 2022; Kang et al., 2006). This reduction in cough efficiency makes it challenging for these individuals to clear their airways effectively, increasing morbidity and mortality rates (Crew et al., 2010).

The management of respiratory complications in SCI involves multiple strategies, including respiratory muscle training, noninvasive ventilation, and assisted cough techniques (Bach et al., 2020; Chatwin et al., 2003; Torres-Castro, Monge, et al., 2014a). Among cough assistance options, mechanical insufflation-exsufflation provides standardized support by simulating a strong cough, while manual techniques offer flexibility and can be applied by trained healthcare providers or caregivers (Chatwin & Simonds, 2020).

Air stacking (AS) is a manual technique in which successive volumes of air are delivered using a resuscitation bag to achieve supramaximal lung inflation. This results in increased intrathoracic pressure, enhanced peak cough flow (PCF), and greater airway clearance by exceeding the patient's spontaneous vital capacity (Sarmento et al., 2017; Torres-Castro, Monge, et al., 2014b). Additionally, AS may help reduce microatelectasis and promote thoracic expansion (Crew et al., 2010).

The acute physiological benefits of AS have been documented in terms of secretion clearance, oxygenation, and pulmonary function parameters such as vital capacity (VC), peak expiratory flow (PEF), and forced expiratory volume in one second (FEV_1) (DeVivo et al., 2011; Jeong & Yoo, 2015). However, limited research has been conducted to evaluate how sustained use of these techniques might improve overall respiratory health in individuals with SCI (Shin et al., 2019; Torres-Castro, Vilaró, et al., 2014).

AS techniques in neuromuscular diseases have shown a decrease in dyspnea based on training in the technique, which supports using this type of intervention in individuals with impaired lung function (Pellegrino et al., 2021).

Comparisons with other low-cost respiratory interventions, such as volumetric incentive spirometry, suggest that AS may be more effective over short periods (An & Shin, 2018); however, its clinical utility over time remains underdocumented.

While AS has shown short-term benefits in cough assistance and pulmonary function, robust evidence on its long-term effectiveness is still lacking. In

particular, it is unclear whether prolonged AS training leads to sustained improvements in vital capacity and peak cough flow. To address this gap, we evaluated the effects of a 12-week AS intervention on pulmonary function and cough effectiveness in individuals with SCI.

Methods

A retrospective analysis of an anonymized database of people hospitalized with SCI who received the AS technique at the *Los Coihues* Clinic between January 2014 and January 2023 was carried out. Ethical approval was obtained from the Bioethics Committee of the Eastern Metropolitan Health Service, Santiago, Chile (07-03-2023). This study was performed following the "Strengthening the Reporting of Observational Studies in Epidemiology" (STROBE) Guidelines (Von Elm et al., 2007).

This study involved no active intervention; all the data analyzed were previously collected as part of standard clinical care and stored in an anonymized format to ensure patient confidentiality. The study included records of individuals aged 18 years or older who were diagnosed with SCI and classified as AIS A or B, with a PCF value of less than 270 L/min and a vital capacity (VC) of less than 80% of the predicted value, the ability to understand instructions and normal glottis function. We excluded records of individuals with ventilator support, tracheostomy, respiratory disease exacerbation during the previous month, and smoking habits of >10 packs/year. Records of individuals with missing data or noncompliance with the AS protocol were excluded. The analyzed data included the initial assessments and those conducted at the 3-month follow-up, along with clinical and demographic variables. A total of 28 database entries were initially

reviewed. Eight records were excluded due to missing follow-up data (n = 6) and tracheostomy or ventilator dependence (n = 2) or documented respiratory comorbidities and recent exacerbations (n = 6). Thus, 20 participants were included in the final analysis.

To enter the AS protocol, users had to have a medical indication for respiratory therapy 5 times a week. The AS training protocol involves patients performing two sets of 10 repetitions five days per week. Each repetition will consist of achieving maximum insufflation capacity (MIC) in coordination with the patient undergoing the procedure, who will notify the patient when they are not achieving maximum inhalation capacity with this assistance. The AS technique was administered via a manual resuscitation bag (model 5345, Manual Resuscitation Bags LIFESAVER, Hudson, Temecula, CA, USA) connected to the patient via a corrugated tube and mouthpiece. The physiotherapist assisted the individuals in achieving their MIC by manually compressing the bag until the lungs were fully inflated. The initial and 12-week follow-up records were as follows: PCF without assistance (PCF), PCF with air stacking (PCF+AS), PCF with manually assisted cough (PCF+MAC), and PCF after combined AS and MAC (PCF+AS+MAC). Cough values were evaluated via a Mini Wright flowmeter (Clement Clarke International, Essex, England). The VC and MIC values were assessed via the EasyOne® Connect spirometer (ndd Medizintechnik AG, Zurich, Switzerland). The MIC maneuver was defined as the maximum amount of air that can be exhaled after repeated insufflation with the AS. The evaluation was conducted according to the European Spirometry Standard of the European Respiratory Society (ERS) (Graham et al., 2019). The maximal inspiratory pressure (MIP) and maximal expiratory pressure (MEP) were evaluated with a PCE-P05 digital

manometer (Torres-Castro et al., 2019). The analyzed data pertained to the initial assessments and those conducted at 12 weeks.

The data were analyzed using the statistical software SPSS v28 (IBM Statistics, Armonk, NY, USA) and JASP v0.18.3 (JASP Team, 2025). The analysis included an assessment of normality using the Shapiro–Wilk test, calculation of descriptive statistics for the data, and a pre-post comparison using Student's t-test for related samples. Effect sizes (Cohen's d) and their 95% confidence intervals were calculated for each outcome using paired-sample statistics. Differences were considered statistically significant at $p < 0.05$.

Results

Records of 20 individuals, comprising 19 men and one woman, with a mean age of 38.8 ± 13.1 years and varying levels of SCI, were analyzed. The distribution of injury levels was 85% cervical and 15% thoracic (Table 1). Comparisons between baseline and 12-week values are as follows: VC 2.41 ± 0.91 vs. 3.01 ± 1.06 L ($p = 0.004$, Cohen's d = 0.75, 95% CI of mean difference: 0.23–0.97); MIC 3.80 ± 0.96 vs. 4.48 ± 0.96 L ($p = 0.006$, d = 0.83, 95% CI: 0.29–1.07); MIP 71.2 ± 26.2 vs. 88.9 ± 26.5 cmH_2O ($p < 0.001$, d = 1.34, 95% CI: 11.53–23.97); MEP 33.5 ± 10.9 vs. 39.1 ± 19.5 cmH_2O ($p = 0.32$, d = 0.33, 95% CI: –2.42–13.72); PCF 207.5 ± 108.4 vs. 267.0 ± 119.1 L/min ($p < 0.001$, d = 1.52, 95% CI: 41.12–77.88); PCF+AS 343.5 ± 126.9 vs. 389.0 ± 119.8 L/min ($p = 0.03$, d = 0.58, 95% CI: 9.04–81.96); PCF+MAC 282.5 ± 116.9 vs. 336.5 ± 126.4 L/min ($p = 0.02$, d = 0.65, 95% CI: 15.25–92.75); PCF+AS+MAC 409.5 ± 137.9 vs. 471.0 ± 129.5 L/min ($p = 0.02$, d = 0.66, 95% CI: 17.62–105.4) (Table 2). All variables except MEP showed statistically significant improvements. Effect sizes ranged from moderate

to very large, with the greatest changes observed in MIC, PCF and MIP. Detailed values for VC and PCF are provided in Figures 1 and 2.

Discussion:

This study evaluated the effectiveness of the AS technique in improving respiratory function and cough efficacy in patients with SCI who were applied daily for a 12-week period. Statistically significant improvements were observed in key pulmonary function variables, including the VC, MIC, and PCF. Notably, the PCF increased significantly both under the first cough assessment conditions and when AS was combined with MAC, achieving values of effective cough. These findings suggest that the continuous application of AS may enhance cough effectiveness in the short term, immediately after the intervention, and may contribute to improvements in baseline pulmonary function, which is crucial for preventing respiratory complications in individuals with tetraplegia.

At baseline, participants with tetraplegia presented low PCF values. However, when the AS technique was applied during the inspiratory phase and MAC for the expiratory phase, there was a significant increase in the PCF, effectively transforming the cough maneuver into an efficient technique for secretion clearance. After 12 weeks of intervention, there was an increase in both the basal vital capacity and the basal PCF, which may play a role in the prevention of respiratory complications and comorbidities, with a potential effect to generate greater participation in rehabilitation programs, reduction of hospitalization or hospital readmissions, improvement in dyspnea, among other benefits described in the literature. These changes were statistically significant and demonstrated moderate to large effect sizes and confidence intervals supporting the clinical

relevance of the observed improvements. However, these results should be interpreted with caution due to the study's retrospective nature and the absence of a control group.

Some studies have described the immediate effectiveness of the AS technique in improving the cough mechanism, particularly through hyperinflation and manual assistance (Kang et al., 2006; Torres-Castro, Vilaró, et al., 2014). These findings align with our results, reinforcing the idea that AS leads to significant increases in the PCF, as it is crucial for secretion mobilization and reducing respiratory infections in tetraplegic individuals (Hyun et al., 2023).

However, the impact of AS over a more extended period, such as 12 weeks, as observed in our study, positions it as an important extension of prior work and supports the hypothesis that longer-term AS training may offer clinical benefits. While studies such as Bach et al. have focused primarily on acute effects, our findings provide evidence for sustained improvements in lung function and cough capacity (Bach, 2012). These findings are consistent with those of Sarmento et al., who reported the benefits of AS in improving vital capacity in patients with amyotrophic lateral sclerosis (ALS) (Sarmento et al., 2017). Similarly, Jeong et al. reported significant improvements in lung function among individuals with SCI following a six-week program (Jeong & Yoo, 2015). However, comparing their findings with those of our study reveals that the improvements observed in our cohort were better than those reported.

Specifically, we documented a more significant absolute increase in vital capacity (0.60 L vs 0.36 L) and a higher percentage change (31.8% vs 24.2%). Similarly, the improvement in PCF was marginally more significant in our study in absolute terms (59.5 L/min vs 56.5 L/min) and markedly higher in percentage terms (35.2%

vs 27.7%). These differences may be related to the extended duration of the intervention in our study, which spanned 12 weeks compared to the six weeks in the previous study. This extended duration may also reflect individual characteristics or intervention protocol differences. Nonetheless, differences in participant characteristics and lack of standardized co-intervention tracking may have contributed to these variations.

Although this finding was unexpected, it is possible that part of the improvement in MIP could be attributed to spontaneous respiratory neuroplasticity, previously described after cervical SCI, where functional recovery may occur over time even without specific interventions (Randelman et al., 2021). This improvement may reflect underlying respiratory neuroplasticity, though this was not directly assessed in our study.

The findings of this study support the potential efficacy of AS in enhancing baseline pulmonary function and cough efficiency over time, and they also suggest that prolonging the duration of the intervention may yield even greater benefits. Future studies are encouraged to investigate the effects of longer training programs and to examine individual-specific factors that could influence the extent of these improvements.

Although the mechanisms of respiratory impairment differ between neuromuscular diseases and spinal cord injuries, the improvements observed under both conditions suggest that AS is a low-cost, easily executable intervention that can be administered by healthcare personnel or caregivers with minimal training. This makes AS not only effective technique but also a practical and accessible technique for both clinical and home settings that could be used

regularly as a preventive intervention to decrease respiratory complications in those populations.

The results obtained in this study have significant clinical implications. The increase in VC is especially relevant, as it has been shown to correlate with life expectancy in SCI patients (Stolzmann et al., 2008). Improvements in the VC and MIC suggest increased lung capacity and a greater ability to cough effectively, reducing the risk of complications such as pneumonia and recurrent respiratory infections (Shin et al., 2019).

The improvement in the PCF, particularly when AS was combined with MAC, further underscores the clinical value of these interventions. Combining AS with MAC produced PCF values that improved substantially and approached functional thresholds, making this combination an essential component of respiratory rehabilitation for tetraplegic individuals. These improvements can lead to better airway clearance and potentially reduce respiratory morbidity, one of the leading causes of mortality in patients with high-level SCI (Reid et al., 2010). However, these clinical implications should be interpreted with caution, given the small sample size and the predominance of male participants, which may limit the generalizability of the findings.

Moreover, the sustained improvements in lung function, particularly in the baseline PCF and VC, may indicate that regular AS training holds potential for long-term benefits, though this warrants confirmation in prospective trials. This long-term impact has been less documented in the literature, and our findings offer new evidence supporting its continued use as part of an ongoing rehabilitation program that could be considered a preventive intervention.

The AS technique is not only effective but also practical. It is a low-cost, noninvasive intervention that can be easily implemented in hospital and home settings (Torres-Castro, Monge, et al., 2014a). The ability of caregivers or family members to be trained in applying this technique at home offers a significant advantage, potentially reducing the frequency of hospitalizations related to respiratory complications. Furthermore, as AS does not require advanced equipment, it is an accessible option even in resource-limited settings (Torres-Castro, Monge, et al., 2014a).

Despite these findings, this study is not without limitations. First, the retrospective design means there was no strict control over interventions, and the study population exhibited various chronic conditions. These factors could have introduced variability in the results. Additionally, the small sample size (n=20), while sufficient for statistical significance, limits the generalizability of the findings. Although the sample size exceeded the calculated minimum for statistical power, the generalizability of the results is still constrained, particularly given that only one woman was included in the study, with a male predominance (95%). In addition to not having a control group, the extrapolation of these results is further limited to the broader SCI population. Furthermore, we did not record the use of maintenance bronchodilator therapy, and it is possible that some participants received other concurrent motor or respiratory interventions as part of their rehabilitation program, which could have influenced outcomes.

The level of SCI also plays a role in influencing the results, with a greater proportion of individuals having cervical injuries than thoracic injuries (Lu et al., 2024). Individuals with higher levels of injury typically present with greater respiratory compromise, as discussed by Brown et al., which could have

influenced the degree of improvement observed (Brown et al., 2006). Additionally, individual motivation may have been a factor, especially given the long periods of hospitalization experienced by many participants, which could have affected the outcomes. Another limitation of this study is the heterogeneity in the time since injury among participants, which may influence the magnitude of the observed improvements in cough efficacy and lung function. However, to our knowledge, no studies have specifically compared the effects of disease duration on these outcomes. Future research should address this gap by evaluating whether the chronicity of the injury modulates the response to AS interventions.

Conclusion

Individuals with high levels of SCI treated over 12 weeks with a combination of AS and MAC may experience clinically meaningful improvements in pulmonary function and VC and may support airway clearance, mucus drainage efficiency, and PCF during this period.

Given its practicality, low cost, and ease of implementation, AS is a valuable addition to respiratory rehabilitation programs. Future research should explore its long-term benefits on quality of life and healthcare resource utilization.

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Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest concerning the research, authorship, and/or publication of this article.

Data Availability Statement

The datasets generated and analyzed during the current study are not publicly available due to ethical restrictions; however, they are available from the corresponding author upon reasonable request.

Author Contributions

GM: Conceptualization, methodology, investigation, data curation, formal analysis, writing—original draft, supervision, and project administration.

MOY: Conceptualization, methodology, and writing—review and editing.

ES: Investigation and writing—review and editing.

TM: Investigation, data curation, and writing—review and editing.

GRL: Investigation, data curation, and writing—review and editing.

RVU: Methodology, formal analysis, validation, and writing—review and editing.

GF: Methodology, formal analysis, validation, and writing—review and editing.

VR: Methodology, formal analysis, validation, and writing—review and editing.

GG: Validation and writing—review and editing.

JV: Validation and writing—review and editing.

RTC: Conceptualization, supervision, and writing—review and editing.

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514 **Tables and Figures:**

Table 1 Baseline patients' characteristics	
Sex (M/F)	19/1 (F5%)
Age (years), mean (SD)	38.8 ± 13.1
Weight (kg), mean (SD)	77.1 ± 14.6
Height (m), mean (SD)	1.72 ± 0.07
BMI (kg/m^2), mean (SD)	25.9 ± 4.6
Injury time (months), median (p25-p75)	5 (3.6-23)
Injury level (%), frequency (percentage)	
- Cervical	17 (85%)
- Thoracic	3 (15%)
Classification ASIA (%), frequency (percentage)	
- A	14 (70%)
- B	6 (30%)

515
516 Table 1. Characteristics of the study population. The data are presented as the
517 mean (standard deviation), median (interquartile range), or frequency
518 (percentage), as appropriate. BMI: body mass index. ASIA A: Complete spinal
519 cord injury. No sensory or motor function is preserved below the level of the injury;
520 ASIA B: Incomplete spinal cord injury. Sensory function is preserved below the

level of the injury, including the sacral segments (S4-S5), but no motor function is preserved below the neurological level.

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6 | Table 2 - Pulmonary Function Variables | | | | | | |
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8 | Variable | Baseline | 12 weeks | *Δpre-post ± SD (Δ%)* | 95% CI | Cohen's d | *p value* |
9 | VC (L) | 2.41 ± 0.91 | 3.01 ± 1.06 | 0.60 ± 0.80 (31.8%) | 0.23–0.97 | 0.75 | 0.004 |
10 | MIC (L) | 3.80 ± 0.96 | 4.48 ± 0.96 | 0.68 ± 0.82 (21.5%) | 0.29–1.07 | 0.83 | 0.006 |
11 | MIP cmH_2O | 71.2 ± 26.2 | 88.9 ± 26.5 | 17.8 ± 39.3 (28.8%) | 11.53–23.97 | 1.34 | <0.001 |
12 | MEP cmH_2O | 33.5 ± 10.9 | 39.1 ± 19.5 | 5.7 ± 10.9 (20.9%) | –2.42–13.72 | 0.33 | 0.32 |
13 | PCF (L/min) | 207.5 ± 108.4 | 267.0 ± 119.1 | 59.5 ± 39.3 (35.2%) | 41.12–77.88 | 1.52 | <0.001 |
14 | PCF+AS (L/min) | 343.5 ± 126.9 | 389.0 ± 119.8 | 45.5 ± 77.9 (21.0%) | 9.04–81.96 | 0.58 | 0.03 |
15 | PCF+MAC (L/min) | 282.5 ± 116.9 | 336.5 ± 126.4 | 54.0 ± 82.8 (30.6%) | 15.25–92.75 | 0.65 | 0.02 |
16 | PCF+AS+MAC (L/min) | 409.5 ± 137.9 | 471.0 ± 129.5 | 61.5 ± 93.8 (22.9%) | 17.62–105.4 | 0.66 | 0.02 |

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25 546 Table 2. Pulmonary function values at baseline and after 12 weeks. Data are expressed as mean ± standard deviation. The column
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27 547 “Δpre-post ± SD (Δ%)” shows the absolute change and its standard deviation, along with the percentage change in parentheses. All
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29 548 variables except MEP showed statistically significant improvements ($p < 0.05$). Effect sizes (Cohen’s d) and 95% confidence intervals
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31 549 (CI) for the mean difference are also provided to support clinical interpretation. Abbreviations: AS: air stacking; cmH2O: centimeters
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33 550 of water; L: liters; L/min: liters per minute; MAC: manually assisted cough; MEP: maximal expiratory pressure; MIC: maximum
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35 551 insufflation capacity; MIP: maximal inspiratory pressure; PCF: peak cough flow; VC: vital capacity.
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Figure 1. Changes in vital capacity (VC) and maximum inspiratory capacity (MIC) between baseline and after 12 weeks of intervention. Data are presented as mean ± standard deviation (SD), with two-sided error bars. Measurements are expressed in liters (L). The * indicates statistically significant differences ($p < 0.05$).

Figure 2. Peak cough flow (PCF) changes under different conditions (PCF, PCF+MAC, PCF+AS, PCF+AS+MAC) between baseline and after 12 weeks of intervention. Data are presented as mean ± SD, with two-sided error bars. Measurements are expressed in liters per minute (L/min). The * indicates statistically significant differences ($p < 0.05$); *** indicates highly significant differences ($p < 0.001$).