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Yoga-based breathing exercises performed in a salt-cave environment versus a standard clinical setting in smokers: a randomized controlled trial salt-cave breathing exercises in smokers

Uğur Bağcı¹ , Hasan Kerem Alptekin² , Sefa Haktan Hatik^{3*} and Emine Büşra Aydın⁴

Abstract

Background To investigate the effect of a speleotherapy environment on spirometric parameters in smokers and to compare the outcomes with those of the same yoga-based breathing exercise program performed in a standard clinical setting.

Methods This randomized controlled clinical trial included 60 adult smokers aged 18–65 years who were allocated to a speleotherapy group ($n = 30$) or a control group ($n = 30$). Both groups received the same physiotherapist-supervised yoga-based breathing exercise program for 6 weeks, twice weekly, in 50-minute sessions; the only difference was the intervention setting. Forced vital capacity, forced expiratory volume in 1 s, peak expiratory flow, and forced expiratory volume in 1 s/forced vital capacity were assessed at baseline, week 3, and week 6. Physical activity, functional exercise capacity, and quality of life were also evaluated. Data were analyzed using linear mixed-effects models with group, time, and group $\times$ time interaction as fixed effects and participant as a random effect.

Results Both groups showed improvements over time in spirometric and secondary outcomes. In the linear mixed-effects model analysis, the primary spirometric outcome, forced expiratory volume in 1 s, showed a significant group $\times$ time interaction in favor of the speleotherapy group. Significant group $\times$ time effects were also observed for 6-minute walk distance and selected quality-of-life domains, whereas broader spirometric superiority across forced vital capacity, peak expiratory flow, and forced expiratory volume in 1 s/forced vital capacity was limited.

Conclusion The findings suggest that the treatment environment may influence selected respiratory and functional outcomes in smokers. Yoga-based breathing exercises were associated with improvements in spirometric outcomes in both settings. The additional effect of the salt-cave environment on respiratory outcomes was limited, with a significant between-group difference observed only for forced expiratory volume in 1 s. The salt-cave setting may also

*Correspondence:

Sefa Haktan Hatik

haktanhtk@gmail.com; sefahatik@sinop.edu.tr

Full list of author information is available at the end of the article

be associated with greater improvements in functional capacity and selected quality-of-life outcomes, but broader pulmonary benefits or an independent speleotherapy effect cannot be concluded from the present findings.

Trial registration ClinicalTrials.gov, NCT07737587. Retrospectively registered on 30 July 2026.

Keywords Smoking, Speleotherapy, Spirometry, Exercise therapy, Quality of life

Introduction

Although global tobacco use has shown a downward trend in recent years, it remains a highly prevalent public health concern. The World Health Organization reports that the prevalence of tobacco use among individuals aged ≥ 15 years has declined since 2000; however, projected estimates for 2025–2030 indicate that tobacco use will persist [1]. Exposure to cigarette smoke is associated with airway inflammation and structural and functional alterations in the respiratory system, and it is widely recognized as a major risk factor for multiple respiratory diseases, particularly chronic obstructive pulmonary disease (COPD) [2]. In clinical practice, these adverse effects can be monitored using spirometric indices; increasing smoking exposure has been linked to impairments in measures such as forced expiratory volume in 1 s (FEV_1), forced vital capacity (FVC), and the ratio of forced expiratory volume in 1 s to forced vital capacity (FEV_1/FVC), as well as to longer-term declines in lung function [3, 4]. Moreover, even among individuals with a history of smoking whose spirometry appears “preserved” (i.e., without demonstrable airflow obstruction), clinically meaningful respiratory symptoms and exacerbations may still occur, suggesting that the smoking-related respiratory burden is not confined to conventional obstruction-based criteria alone [5]. Accordingly, investigating complementary and rehabilitative approaches that may help support lung function in smokers is of clear clinical relevance.

Speleotherapy is administered within the microclimate of subterranean environments such as salt caves or salt mines and is commonly considered a complementary modality within the broader context of respiratory rehabilitation [6–8]. The potential effects of speleotherapy are generally discussed in relation to relatively stable environmental conditions, such as low irritant and allergen exposure, limited variability in temperature and humidity, and, in some settings, exposure to salt particles. However, because airborne environmental exposure parameters were not directly measured in the present study, the observed outcomes cannot be specifically attributed to salt particle exposure or to cave-specific microclimatic mechanisms [9, 10]. Clinical studies evaluating speleotherapy-related respiratory outcomes—such as trials in asthma/allergy populations and programs combining speleotherapy with rehabilitation components in chronic respiratory conditions—suggest that it is a

feasible and researchable adjunctive approach [7, 8, 11]. In smokers, given smoke-related airway sensitivity and chronic irritation, speleotherapy delivered in a comparatively low-irritant, low-allergen, and stable environment may, at least theoretically, reduce environmental burden on the airways and thereby support measurable changes in respiratory function outcomes (e.g., spirometry) [6, 9].

Although speleotherapy/halotherapy has long been used as an adjunctive option in a range of chronic respiratory conditions, the current evidence base remains limited and is marked by substantial heterogeneity across studies. Early systematic reviews noted that the number of studies evaluating speleotherapy in asthma was small and that methodological limitations made it difficult to draw reliable conclusions, highlighting the need for higher-quality randomized trials with longer-term follow-up [12]. Similarly, a review of halotherapy in the context of COPD concluded that the available data were insufficient to support routine clinical recommendation and underscored the need for better-designed studies to clarify efficacy [9]. Moreover, the published clinical literature varies considerably with respect to target populations (e.g., allergic rhinitis/asthma, older adults with chronic respiratory problems), treatment settings (natural subterranean salt caves/mines vs. halo-chambers), session dose and program duration, and the frequent co-delivery of speleotherapy with additional components such as exercise-based pulmonary rehabilitation or structured breathing training—factors that complicate attribution of outcomes specifically to speleotherapy [8, 11]. This variability is particularly consequential for smokers, in whom evidence regarding speleotherapy-related changes in spirometric indices (FEV_1 , FVC, FEV_1/FVC , PEF) remains insufficiently defined; despite smoke-induced airway injury and irritation, spirometry-focused data in this subgroup are comparatively scarce. Consequently, studies that directly examine the effects of speleotherapy on spirometric parameters in smokers are warranted to address this gap in the literature.

In this study, we examine whether speleotherapy delivered in a salt cave/salt therapy center environment in smokers leads to measurable changes in spirometric parameters (FVC, FEV_1 , PEF, and FEV_1/FVC) compared with the same breathing exercises performed under non-cave conditions. Given that the available speleotherapy literature is limited and heterogeneous—with variability in treatment settings, protocol duration, and

outcome measures—drawing firm conclusions, particularly for spirometry-based endpoints, remains challenging. Within this context, our study aims to evaluate the potential added contribution of the speleotherapy environment using standardized spirometric assessment and to generate evidence on whether a relatively simple, accessible, and non-invasive approach may represent a clinically meaningful option to support respiratory function in smokers. Accordingly, the primary objective is to compare changes in spirometric outcomes (FVC, FEV₁, PEF, and FEV₁/FVC) following a 6-week breathing-exercise program conducted inside a salt cave versus the same program conducted outside the cave. We hypothesize that participation in the speleotherapy setting will result in significant differences in spirometric parameters compared with the control condition.

Materials and methods

The study was designed as a randomized controlled clinical trial with a pre-test, mid-test, and post-test assessment schedule and was conducted at the Iğdır Tuzluca Salt Therapy Center. Eligible participants were adult smokers who volunteered to take part in the study. A total of 60 participants were enrolled and allocated into two groups ($n=30$ per group). Ethical approval was granted by the Gümüşhane University Rectorate Scientific Research and Publication Ethics Board (meeting no. 2022/6; 26 October 2022; decision no. E-95674914-108.99-137405). All participants received detailed study information, and written informed consent was obtained prior to participation.

Inclusion criteria were: age 18–65 years; voluntary participation with written informed consent; ability to ambulate and cooperate with assessments; literacy; daily smoking for at least the past 12 months according to World Health Organization and ICD criteria; and BMI < 30 kg/m² to exclude obesity. Smoking status was determined by self-report. Participants were eligible if they reported daily smoking for at least the previous 12 months; however, detailed smoking exposure variables such as pack-years, daily cigarette consumption, nicotine dependence, smoking duration, smoking cessation attempts, and changes in smoking behavior during the intervention were not systematically assessed. Exclusion criteria were: orthopedic, neurological, or neuromuscular conditions that could limit walking or affect testing; physician-diagnosed chronic cardiopulmonary disease, including COPD; history of lung surgery; bleeding disorders; acute dyspnea; hemoptysis; and uncontrolled severe hypertension.

Assessments were scheduled at three time points in both groups: baseline, week 3, and week 6. At baseline, all participants underwent spirometry, and FVC, FEV₁, PEF, and FEV₁/FVC were recorded. In addition, physical

activity, functional capacity, and health-related quality of life were evaluated using the IPAQ, the 6MWT, and the WHOQOL-BREF, respectively. At the mid-intervention assessment (week 3), spirometry was repeated in both groups and the same spirometric outcomes (FVC, FEV₁, PEF, and FEV₁/FVC) were re-measured. At week 6, spirometry was performed again and the IPAQ, 6MWT, and WHOQOL-BREF were re-administered to allow comparable tracking of changes over the intervention period.

Participants were assigned to either a Control group or a Speleotherapy group. Following randomization, breathing-exercise training was scheduled individually and appointments were arranged for each participant. Both groups received the same breathing-exercise program, delivered over 6 weeks, twice weekly, in 50-minute sessions (including rest intervals as needed). The intervention sessions were conducted at the Tuzluca Salt Therapy Center (Iğdır/Tuzluca) for the speleotherapy group and at a private clinic for the control group. Thus, the only difference between groups was the intervention setting; the exercise content, session duration, and number of sessions were identical in both groups.

Spirometry measurement

Spirometric measurements were obtained using a portable Contec SP80B spirometer in accordance with ATS/ERS standardization recommendations [13]. The device calibration/quality-control procedure was performed before measurements according to the manufacturer's recommendations. Measurements were conducted under standardized conditions with infection-control precautions, including hand hygiene and single-use consumables/in-line filters. Participants were assessed in an appropriate seated posture, and environmental conditions were recorded. To minimize acute influences, participants were instructed to avoid smoking/e-cigarette/waterpipe use within 1 h before testing, alcohol consumption within the preceding 8 h, and vigorous exercise within 1 h before the test [14].

For each assessment session, participants performed three forced expiratory maneuvers under standardized verbal instruction and supervision. Maneuvers were checked for acceptability, including adequate start of expiration, absence of coughing during the first second, absence of air leak or mouthpiece obstruction, and adequate continuation of expiration. The best acceptable values were recorded for analysis. All measurements were conducted as pre-bronchodilator spirometry; bronchodilator reversibility testing was not performed.

The recorded parameters were forced vital capacity (FVC), forced expiratory volume in 1 s (FEV₁), peak expiratory flow (PEF), and the FEV₁/FVC ratio. FVC and FEV₁ were reported in liters, PEF in L/s, and FEV₁/FVC as a percentage [15]. Spirometry is a widely used,

objective, and non-invasive method for supporting the presence or absence of lung disease, quantifying functional impairment, and monitoring the effects of exposures and therapeutic interventions [13, 14].

International Physical Activity Questionnaire–Short Form (IPAQ-SF)

Physical activity level was assessed using the International Physical Activity Questionnaire–Short Form (IPAQ-SF; 7 items), which records the frequency (days/week) and duration (minutes/day) of walking, moderate-intensity, and vigorous-intensity activities performed during the previous 7 days, as well as daily sitting time. Total physical activity was calculated as MET-min/week by summing domain scores using standard IPAQ MET values (walking 3.3 MET, moderate 4.0 MET, vigorous 8.0 MET) according to the IPAQ scoring protocol, and participants were categorized into physical activity levels where applicable [16]. The Turkish version of the IPAQ-SF has been shown to be valid and reliable by Sağlam and colleagues [17].

6-Minute Walk Test (6MWT)

Functional exercise capacity was assessed using the 6-minute walk test (6MWT). The test was performed on a flat, hard-surfaced corridor using a 30-m walkway with turning points marked at each end. Participants were instructed to walk as far as possible for 6 min; rest breaks were permitted as needed, but the timer was not stopped. Standardized instructions and standardized encouragement were used throughout the test. The 6MWT was administered twice, and the best (longest) 6-minute walking distance (m) was used for analysis [18, 19].

World Health Organization Quality Of Life–Bref (WHOQOL-BREF)

Health-related quality of life was assessed using the 26-item World Health Organization Quality of Life–BREF (WHOQOL-BREF). The questionnaire yields four domain scores—Physical Health, Psychological, Social Relationships, and Environment—and includes two additional items assessing overall quality of life and general health; domain scores were computed according to standard scoring procedures and were used in the statistical analyses [20, 21]. In the analyses, outcomes were reported as General Health Status (derived from the two global items) together with the four domain scores (Physical Health, Psychological, Social Relationships, and Environment). The Turkish version of the WHOQOL-BREF has been adapted and its validity and reliability have been reported by the WHOQOL-Turkey Group led by Erhan Eser and colleagues [22].

Speleotherapy

Speleotherapy is a form of “subterranean therapy” conducted in the distinctive microclimate of underground environments such as caves or salt mines, and in clinical practice it typically involves scheduled stays in underground salt chambers [6]. A closely related concept, halotherapy, has been defined as the inhalation of micronized dry sodium chloride (NaCl) aerosols in a room designed to simulate the environment of a natural salt cave [9]. Within this framework, halotherapy settings emphasize controlled or standardized indoor conditions, generation of dry salt aerosols, and maintenance of air quality, including reduced dust and allergen load [10]. Clinical examples of speleotherapy-based rehabilitation programs have been reported in underground salt chambers, such as the “Wieliczka” Salt Mine Health Resort, where outpatient programs lasting approximately 3 weeks have been implemented at a depth of 135 m with prolonged daily underground exposure [7, 8]. Speleotherapy has also been evaluated in different populations and combined with various rehabilitation components; for example, randomized controlled trials in allergic rhinitis and asthma have implemented speleotherapy within a 10-day program, highlighting the cave or mine environment as a defining feature of the intervention [11].

In the present study, the intervention sessions for the speleotherapy group were conducted at the Tuzluca Rock Salt Mine Salt Therapy Center, located in the Tuzluca district of Iğdır, Türkiye. The facility is approximately 2 km from the Tuzluca town center, covers an area of about 55 decares, and is situated at an altitude of approximately 1,075 m [23]. Previous investigations have characterized the Tuzluca Cave as a typical rock-salt cave, with chemical analyses of rock samples from different galleries indicating a predominantly sodium chloride composition ranging from 86% to 96%, with very low levels of bromine and potassium. Field measurements have also reported relatively stable climatic conditions, with an average internal air temperature of approximately 12 °C throughout the year and a relative humidity range of 41%–42% [24]. Based on these descriptive geological and climatic characteristics, the Tuzluca Salt Therapy Center was considered a suitable underground salt-cave environment for delivering the intervention in this study. However, these characteristics should not be interpreted as direct measurements of airborne salt aerosol exposure or as indicators of a quantified speleotherapy dose.

Yoga-based breathing exercise program

The yoga-based breathing exercise program implemented in this study was composed of pranayama-based controlled breathing techniques [25]. The main objectives were to (i) develop diaphragmatic breathing awareness, (ii) maintain nasal breathing, and (iii) deliver selected

pranayama techniques in a standardized sequence and dose. After diaphragmatic breathing instruction, the following techniques were applied: Suusi (three-phase yogic breathing), Kapalabhati, Ujjayi, Anuloma–Viloma/Nadi Shodhana, Bhastrika, Bhramari, and Agni Sar [25–27]. Techniques were performed, whenever feasible, in a seated position with nasal inhalation/exhalation, followed by a brief relaxation/rest period at the end of each session. Participants were monitored for symptoms and potential adverse events, including dizziness, increased dyspnea, chest discomfort, or intolerance during higher-intensity techniques. If symptoms occurred, the technique was discontinued and participants returned to normal breathing.

Both the control and speleotherapy groups received the same yoga-based breathing program, and all sessions were supervised by a physiotherapist. The intervention lasted 6 weeks, with two sessions per week, and each session was planned as 50 min (total 12 sessions). Sessions were delivered at the Tuzluca Salt Therapy Center (Iğdır/Tuzluca) for the speleotherapy group and at a private clinic for the control group; thus, the only between-group difference was the setting, while exercise content, session duration, and number of sessions were identical. The first session in week 1 was a 60-minute instructional session that included breathing awareness/assessment, encouragement of nasal breathing, chest breathing education, and diaphragmatic breathing training, followed by brief practice of each technique. The second session in week 1 and all sessions in weeks 2–6 followed a standardized protocol. Each 50-minute session consisted of: preparatory breathing control (5 min), diaphragmatic breathing (7 min), Suusi (5 min), Kapalabhati (4 min), Ujjayi (5 min), Anuloma–Viloma/Nadi Shodhana (6 min), Bhastrika (4 min), Bhramari (5 min), Agni Sar (4 min), and relaxation/rest (5 min), totaling 50 min.

Technique delivery was standardized as follows. Diaphragmatic breathing was introduced in the supine position (knees flexed; one hand on the abdomen and one on the chest) to promote movement awareness and was then reinforced in sitting with five deep breathing cycles. Suusi breathing was performed in sitting using a three-phase inspiratory expansion sequence (abdomen–lower ribs–upper thorax) and repeated for 10 cycles. Kapalabhati consisted of forceful nasal exhalations driven by abdominal retraction, delivered as cycles of 15 rapid exhalations in 10 s followed by 20 s of rest, continued for a total of 3 min (approximately 30 breaths/min). In Nadi Shodhana, the nostrils were alternately occluded using the right hand to complete a structured left–right breathing cycle, continued for 3 min. Agni Sar was performed as 10 repetitions of abdominal in–out movements during breath-hold following exhalation. Bhramari was applied for seven rounds, each comprising ~5 s of inhalation, a

2–3 s hold, and ~15 s of slow exhalation with a humming sound. Ujjayi consisted of slow nasal breathing with glottic control for 2 min, with the remaining time completed using low-intensity controlled nasal breathing. Bhastrika was delivered as sets of 10 forceful nasal inhalation–exhalation repetitions; 2–3 sets were completed with brief recovery intervals to achieve the target duration.

Randomization and allocation concealment

After baseline assessments, participants were stratified to enhance between-group balance based on key demographic and clinical variables, including age, sex, anthropometric characteristics, educational status, physical activity level, quality of life, and 6MWT performance. Within each stratum, participants with similar characteristics were grouped into matched pairs. Allocation within each matched pair was performed in a 1:1 ratio using a computer-generated random sequence prepared by an independent researcher who was not involved in participant recruitment, assessment, intervention delivery, or statistical analysis.

Allocation concealment was ensured using sequentially numbered, opaque, sealed envelopes. The envelopes were prepared in advance by the independent researcher and were opened only after completion of baseline assessments and confirmation of eligibility. Thus, group assignment was not known before enrollment and baseline testing. After allocation, participants were assigned either to the salt-cave group or to the control group.

Blinding

Because the intervention settings were clearly distinguishable, participant and provider blinding was not feasible. However, statistician blinding was implemented: the dataset was prepared with groups coded as A/B, and statistical analyses were conducted without disclosure of group identities. After analyses were completed, the codes were unblinded and results were assigned to the corresponding groups.

Sample size

In the present randomized controlled trial, the adequacy of the sample was justified based on the primary endpoint of the between-group difference in baseline-to-week 6 change in forced expiratory volume in 1 s (FEV₁), as this outcome best reflected the main respiratory objective of the study and corresponded to the primary treatment-effect contrast derived from the linear mixed-effects model. Because no previous randomized trial was identified that directly compared a speleotherapy environment plus a standardized breathing-exercise program with the same breathing-exercise program delivered in a standard clinical setting specifically in smokers, the required sample was estimated using a moderate-to-large

standardized effect size assumption (Cohen's $d = 0.75$). This assumption was considered reasonable in light of previous randomized breathing-intervention studies in chronic respiratory populations showing clinically meaningful between-group differences in respiratory or functional outcomes; for example, Kaminsky et al. (2017), in a randomized controlled trial of pranayama in patients with COPD, estimated that 18 participants per group would be required to detect a clinically relevant between-group difference with 80% power at $\alpha = 0.05$, and then increased recruitment to account for dropout [28]. Accordingly, assuming a two-sided α of 0.05, 80% power, a 1:1 allocation ratio, and an anticipated effect size of $d = 0.75$, the required total sample was approximately 58 participants. Therefore, allowing a small margin for possible attrition, the inclusion of 60 participants (30 per group) was considered appropriate and sufficient for the primary comparison.

Data analyses

Analyses were conducted using IBM SPSS Statistics (v26.0). Continuous variables are presented as mean $\pm$ SD and median, and categorical variables as n (%). All outcome variables were analyzed using linear mixed-effects models to provide a consistent analytical strategy across outcomes. For spirometric outcomes measured at three time points, including baseline, week 3, and week 6, the models included group, time, and the group $\times$ time interaction as fixed effects, with participant specified as a random intercept. For outcomes measured at two time points, including the 6MWT, IPAQ-SF, and WHOQOL-BREF domains, the same mixed-effects framework was applied using baseline and week 6 measurements. The primary treatment-effect estimate was the between-group difference in baseline-to-week 6 change derived from the group $\times$ time interaction. FEV₁ change was treated as the primary spirometric outcome. Holm adjustment was applied within predefined secondary outcome families, including secondary spirometric outcomes, functional/physical activity outcomes, and WHOQOL-BREF domains. Effect sizes were reported as Hedges g for between-group change-score differences. Statistical significance was set at two-tailed $p < 0.05$.

Results

A total of 60 participants were enrolled and randomized into two groups ($n = 30$ per group). All randomized participants received the allocated intervention, completed the 6-week follow-up assessment, and were included in the final analysis. No participant withdrew from the study, no loss to follow-up occurred, and no participant was excluded from the analysis. All participants completed the 12 scheduled intervention sessions, corresponding to 100% adherence in both groups. No protocol

deviation was recorded during the intervention period. The participant flow is presented in (Fig. 1).

Adverse events and intervention tolerance

No adverse events related to the intervention or spirometric assessment were reported during the study period. No participant withdrew because of intervention intolerance, dizziness, increased dyspnea, chest discomfort, or spirometry-related complications. All participants completed the 12 scheduled intervention sessions, corresponding to 100% adherence in both groups.

All participants met the eligibility criterion of daily smoking for at least the previous 12 months. However, detailed baseline smoking characteristics and changes in smoking behavior during the 6-week intervention were not available; therefore, these variables could not be included in the comparative analyses.

In the speleotherapy group, 56.7% of participants were male, with a mean age of 39.53 ± 11.83 years and a mean body mass index (BMI) of 25.48 ± 2.58 kg/m². In the control group, 46.7% of participants were male, with a mean age of 40.53 ± 12.23 years and a mean BMI of 25.97 ± 2.69 kg/m². Baseline absolute spirometric values and all outcome measurements are presented descriptively in (Table 1).

Linear mixed-effects models were used as the primary analytical approach for all outcomes. For the primary spirometric outcome, FEV₁, the baseline-to-week 6 increase was greater in the speleotherapy group than in the control group (between-group change mean difference [MD] = 0.43 L, 95% CI: 0.10 to 0.76; $p = 0.010$; Hedges $g = 0.61$). Among secondary spirometric outcomes, FVC and PEF showed positive between-group contrasts in favor of the speleotherapy group; however, these findings did not remain statistically significant after Holm correction (FVC: MD = 0.36 L, 95% CI: 0.05 to 0.68; $p = 0.022$; Holm-adjusted $p = 0.065$; PEF: MD = 0.81 L/s, 95% CI: 0.08 to 1.55; $p = 0.029$; Holm-adjusted $p = 0.065$). The FEV₁/FVC ratio did not show a significant between-group difference in change (MD = 2.49% points, 95% CI: -2.61 to 7.58; $p = 0.339$; Holm-adjusted $p = 0.339$). These results indicate that the additional respiratory signal was mainly limited to FEV₁ (Table 2).

For functional exercise capacity, the 6MWT improved more in the speleotherapy group than in the control group (MD = 51.00 m, 95% CI: 34.74 to 67.26; $p < 0.001$; Holm-adjusted $p < 0.001$; Hedges $g = 1.54$). For physical activity, the between-group difference in IPAQ-SF total score was not statistically significant in the mixed-effects model (MD = 164.42 MET-min/week, 95% CI: -118.53 to 447.36; $p = 0.255$; Holm-adjusted $p = 0.255$). For WHOQOL-BREF outcomes, group $\times$ time effects favored the speleotherapy group for General Health (MD = 4.17; $p = 0.037$), Physical Health (MD = 5.12; $p < 0.001$),

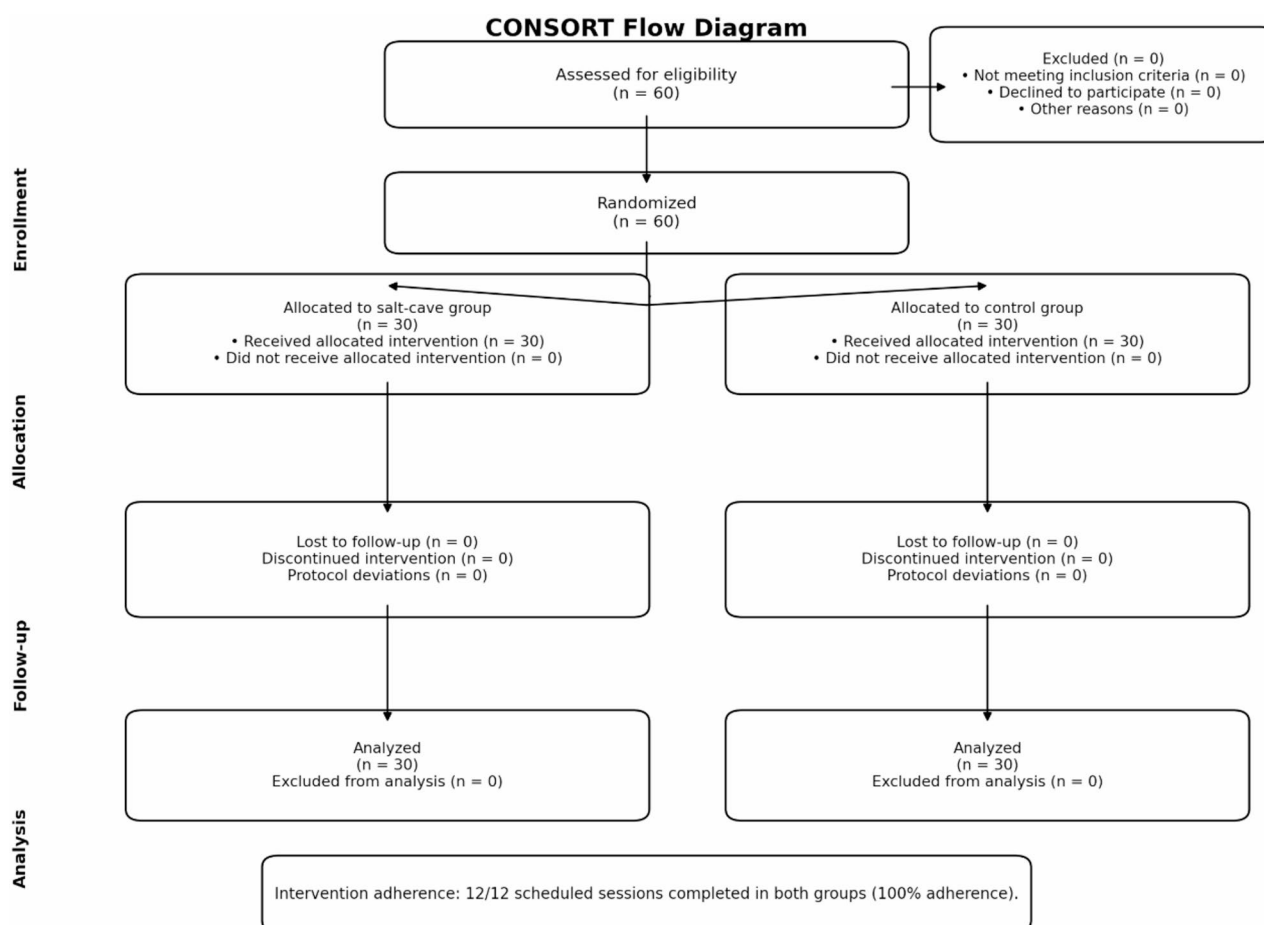


Fig. 1 CONSORT flow diagram showing participant enrollment, allocation, follow-up, and analysis

Psychological health (MD=5.00; $p<0.001$), Social Relationships (MD=6.11; $p<0.001$), and Environment (MD=2.40; $p=0.001$); all WHOQOL-BREF domains remained significant after Holm correction. The strongest between-group findings were therefore observed for FEV₁, 6MWT performance, and selected quality-of-life domains (Table 2).

Overall, the linear mixed-effects model findings indicated that the strongest between-group effects were observed for FEV₁, 6MWT performance, and WHOQOL-BREF domains, whereas evidence for broader spirometric superiority beyond FEV₁ was limited after multiplicity adjustment.

Discussion

A total of 60 participants were included, and the speleotherapy and control groups had comparable demographic characteristics. Descriptive findings indicated that both groups generally improved over time in pulmonary function parameters, functional capacity, physical activity level, and quality-of-life domains. In the linear mixed-effects model analysis, the primary spirometric outcome, FEV₁, showed a significant group ×

time interaction in favor of the speleotherapy group. Significant group × time interactions were also observed for 6MWT performance and selected WHOQOL-BREF domains, whereas the evidence for broader spirometric superiority across FVC, PEF, and FEV₁/FVC was limited. Therefore, these findings should be interpreted as possible setting-related differences associated with performing the same yoga-based breathing exercise program in the salt-cave environment rather than as evidence for an independent effect of speleotherapy alone. Breathing-focused interventions and rehabilitation approaches have been reported to improve different dimensions of quality of life. In adults and older individuals practicing Dan Jeon breathing, WHOQOL-BREF domains were found to be positively associated with favorable health behaviors, suggesting that breathing-oriented practices may be linked to quality-of-life outcomes [29]. Similarly, a comprehensive yogic breathing program has been reported to improve quality of life in individuals with diabetes [30]. Within the speleotherapy literature, quality-of-life gains may not be uniformly distributed across all domains, and more pronounced improvements may occur in specific subdomains; for example, following a program

Table 1 Descriptive values for pulmonary function, 6-minute walk test (6MWT), IPAQ-SF, and WHOQOL-BREF scores in the speleotherapy and control groups

Outcome	Time point	Speleotherapy group Mean $\pm$ SD (Median)	Control group Mean $\pm$ SD (Median)
FVC (L)	Pre-test	3.71 $\pm$ 0.97 (3.9)	3.51 $\pm$ 0.55 (3.6)
FVC (L)	Follow-up test	4.03 $\pm$ 0.94 (4.3)	3.72 $\pm$ 0.59 (3.7)
FVC (L)	Post-test	4.51 $\pm$ 0.61 (4.7)	3.95 $\pm$ 0.51 (4.1)
FEV1 (L)	Pre-test	2.84 $\pm$ 0.93 (2.5)	3.00 $\pm$ 0.60 (3.0)
FEV1 (L)	Follow-up test	3.46 $\pm$ 1.03 (3.6)	3.24 $\pm$ 0.59 (3.3)
FEV1 (L)	Post-test	3.90 $\pm$ 0.77 (4.0)	3.63 $\pm$ 0.55 (3.7)
PEF (L/s)	Pre-test	3.70 $\pm$ 1.69 (3.0)	3.71 $\pm$ 0.97 (3.4)
PEF (L/s)	Follow-up test	5.11 $\pm$ 2.09 (4.8)	4.09 $\pm$ 1.04 (4.0)
PEF (L/s)	Post-test	5.82 $\pm$ 2.05 (5.7)	5.02 $\pm$ 1.16 (5.0)
FEV1/FVC (%)	Pre-test	76.75 $\pm$ 13.34 (79.7)	85.13 $\pm$ 6.87 (85.7)
FEV1/FVC (%)	Follow-up test	85.33 $\pm$ 11.53 (89.1)	87.02 $\pm$ 6.73 (87.2)
FEV1/FVC (%)	Post-test	86.11 $\pm$ 10.83 (89.4)	92.00 $\pm$ 6.30 (93.4)
6MWT (m)	Pre-test	445.83 $\pm$ 59.68 (450.0)	443.17 $\pm$ 65.54 (462.5)
6MWT (m)	Post-test	530.50 $\pm$ 76.23 (547.5)	476.83 $\pm$ 63.74 (490.0)
IPAQ-SF total (MET-min/week)	Pre-test	873.45 $\pm$ 686.12 (814.5)	1246.93 $\pm$ 1398.47 (756.0)
IPAQ-SF total (MET-min/week)	Post-test	1565.58 $\pm$ 1174.47 (1208.8)	1774.65 $\pm$ 1757.83 (1080.0)
WHOQOL-BREF General Health	Pre-test	46.67 $\pm$ 21.00 (50.0)	47.50 $\pm$ 21.12 (43.8)
WHOQOL-BREF General Health	Post-test	65.00 $\pm$ 19.25 (62.5)	61.67 $\pm$ 21.76 (50.0)
WHOQOL-BREF Physical Health	Pre-test	56.55 $\pm$ 19.20 (57.1)	60.95 $\pm$ 15.66 (62.5)
WHOQOL-BREF Physical Health	Post-test	69.64 $\pm$ 16.98 (71.4)	68.93 $\pm$ 14.38 (71.4)
WHOQOL-BREF Psychological	Pre-test	46.81 $\pm$ 9.39 (45.8)	46.67 $\pm$ 8.92 (45.8)
WHOQOL-BREF Psychological	Post-test	62.08 $\pm$ 8.98 (62.5)	56.94 $\pm$ 8.29 (58.3)
WHOQOL-BREF Social Relationships	Pre-test	43.89 $\pm$ 13.83 (41.7)	40.56 $\pm$ 13.97 (41.7)
WHOQOL-BREF Social Relationships	Post-test	52.78 $\pm$ 14.73 (50.0)	43.33 $\pm$ 14.91 (41.7)
WHOQOL-BREF Environment	Pre-test	42.40 $\pm$ 6.75 (43.8)	44.90 $\pm$ 8.06 (43.8)
WHOQOL-BREF Environment	Post-test	47.81 $\pm$ 7.30 (46.9)	47.92 $\pm$ 8.22 (48.4)

Values are presented as mean $\pm$ SD (median). FVC and FEV₁ are reported in liters, PEF in L/s, FEV₁/FVC in percentage points, 6MWT in meters, and IPAQ-SF in MET-min/week. This table is descriptive; treatment effects were interpreted using linear mixed-effects models

incorporating spa therapy and speleotherapy in COPD, greater changes have been reported particularly in symptom-related dimensions of quality of life [31]. Moreover, observed improvements in quality of life in programs combining speleotherapy with exercise [11], along with reports that underground pulmonary rehabilitation may be associated with larger and more sustained effects in COPD [32], indicate that these interventions may exert a multi-component effect profile. In our study, improvements across quality-of-life domains were observed in both groups at the end of follow-up. However, between-group comparisons indicated greater improvements in the group performing the same yoga-based breathing exercise program in the salt-cave environment, particularly in the Physical Health, Psychological, Social Relationships, and Environment domains, whereas perceived General Health showed more limited between-group differentiation. This pattern is consistent with previous reports suggesting that speleotherapy-based or salt-cave rehabilitation programs may be associated with domain-specific, rather than uniform, quality-of-life changes. Accordingly, the present findings suggest that performing

the breathing-exercise program in a salt-cave environment may be associated with selected improvements in physical and psychosocial aspects of quality of life. However, these findings should be interpreted cautiously, as they may reflect the combined influence of structured breathing exercises, physiotherapist contact, the intervention setting, relaxation-related effects, and expectancy or contextual factors, rather than the independent effect of speleotherapy alone. Broader global ratings, such as perceived general health, may therefore show less separation between groups.

The IPAQ is widely used to monitor physical activity levels across diverse populations. Prospective clinical studies have reported that yoga-based programs can increase physical activity as assessed by the IPAQ [33], and several randomized trials have similarly documented post-intervention increases in IPAQ-measured physical activity following yoga programs [34, 35]. Cross-sectional evidence also suggests that IPAQ levels may be higher among individuals who practice yoga than among non-practitioners [36]. However, not all breathing-focused interventions yield clear between-group separation in

Table 2 Linear mixed-effects model results for all outcomes

Outcome	Salt-cave baseline	Control baseline	Salt-cave change (95% CI)	Control change (95% CI)	Between-group change MD (95% CI)	p	Holm-adjusted p	Hedges g
FVC (L)	3.71	3.51	0.80 (0.58 to 1.02)	0.44 (0.22 to 0.66)	0.36 (0.05 to 0.68)	0.022	0.065	0.51
FEV ₁ (L)	2.84	3.00	1.06 (0.83 to 1.30)	0.64 (0.40 to 0.87)	0.43 (0.10 to 0.76)	0.010	Primary outcome	0.61
PEF (L/s)	3.70	3.71	2.12 (1.60 to 2.64)	1.30 (0.79 to 1.82)	0.81 (0.08 to 1.55)	0.029	0.065	0.52
FEV ₁ /FVC (%)	76.75	85.13	9.36 (5.76 to 12.96)	6.87 (3.27 to 10.47)	2.49 (-2.61 to 7.58)	0.339	0.339	0.24
6MWT (m)	445.83	443.17	84.67 (73.17 to 96.16)	33.67 (22.17 to 45.16)	51.00 (34.74 to 67.26)	< 0.001	< 0.001	1.54
IPAQ-SF total (MET-min/week)	873.45	1246.93	692.13 (492.06 to 892.21)	527.72 (327.64 to 727.79)	164.42 (-118.53 to 447.36)	0.255	0.255	0.29
WHOQOL-BREF General Health	46.67	47.50	18.33 (15.57 to 21.10)	14.17 (11.40 to 16.93)	4.17 (0.26 to 8.08)	0.037	0.037	0.52
WHOQOL-BREF Physical Health	56.55	60.95	13.10 (11.44 to 14.75)	7.98 (6.33 to 9.63)	5.12 (2.79 to 7.45)	< 0.001	< 0.001	1.08
WHOQOL-BREF Psychological	46.81	46.67	15.28 (13.35 to 17.20)	10.28 (8.35 to 12.20)	5.00 (2.28 to 7.72)	< 0.001	< 0.001	0.90
WHOQOL-BREF Social Relationships	43.89	40.56	8.89 (6.63 to 11.15)	2.78 (0.52 to 5.04)	6.11 (2.91 to 9.31)	< 0.001	< 0.001	0.94
WHOQOL-BREF Environment	42.40	44.90	5.42 (4.41 to 6.43)	3.02 (2.01 to 4.03)	2.40 (0.97 to 3.82)	< 0.001	0.002	0.82

Change represents week 6 minus baseline. Between-group change MD represents the group $\times$ time interaction contrast for baseline-to-week 6 change derived from the linear mixed-effects model. FEV₁ was treated as the primary spirometric outcome; Holm-adjusted p values were calculated within predefined secondary outcome families: secondary spirometric outcomes (FVC, PEF, FEV₁/FVC), functional/physical activity outcomes (6MWT and IPAQ-SF), and WHOQOL-BREF domains. IPAQ-SF total score was calculated using vigorous, moderate, and walking activity; sitting time was recorded separately and not included in the total score

physical activity outcomes; for instance, in an inspiratory muscle training study, physical activity measures—including the IPAQ-SF—did not show a consistent advantage in favor of the intervention [37]. In our study, IPAQ-SF total scores increased over time in both the salt-cave and control groups; however, the linear mixed-effects model did not indicate a significant group $\times$ time interaction for IPAQ-SF total score. This finding suggests that the increase in physical activity level cannot be specifically attributed to the salt-cave environment. Physical activity is influenced not only by physiological capacity but also by behavioral and contextual factors, such as daily routines, motivation, exercise adherence, and environmental conditions, which may lead to improvements even in control conditions. Therefore, although both groups demonstrated higher IPAQ-SF scores after the intervention period, the present findings do not support a clear additional setting-related effect on physical activity.

Breathing exercises and yoga-based pranayama protocols have been shown in various studies to increase spirometric indices such as FVC, FEV₁, and PEF [38, 39]. Improvements in dynamic spirometry have also been reported when pranayama is combined with Surya Namaskar [40]. In contrast, the speleotherapy/halotherapy literature—while discussing potential benefits of subterranean salt environments—emphasizes that clinical effects may vary by population and outcome and that the available evidence remains heterogeneous [41,

42]. In COPD, programs incorporating speleotherapy have reported improvements in respiratory function and clinical outcomes [31], and underground pulmonary rehabilitation has been suggested to be associated with more pronounced and/or sustained effects for certain endpoints [32]. In the present study, FVC, FEV₁, PEF, and FEV₁/FVC increased over time in both groups; however, the between-group respiratory signal was limited mainly to FEV₁ and did not consistently extend to other spirometric parameters. This pattern suggests that any possible setting-related effect was limited and should be interpreted cautiously in the context of the co-delivered breathing-exercise program, repeated assessments, and other uncontrolled setting-related influences. Consistent with this cautious interpretation, speleotherapy in post-COVID syndrome has been reported to yield no marked gains in some respiratory outcomes [43]. Overall, these spirometric findings should be considered preliminary and hypothesis-generating. Broader pulmonary superiority or an independent speleotherapy effect cannot be concluded from the present data.

The literature indicates that exercise tolerance and functional capacity in respiratory diseases can improve with breathing-focused approaches and rehabilitation programs. A randomized controlled trial in COPD reported that pranayama practice may enhance exercise tolerance [28], and meta-analytic evidence has also discussed yoga-based interventions in relation to improvements in functional outcomes such as the 6-minute walk

distance [44]. Gains in functional performance have likewise been reported in programs combining speleotherapy with pulmonary rehabilitation; for example, spa plus speleotherapy approaches have been associated with improvements in clinical and functional outcomes [31], and pulmonary rehabilitation delivered in an underground environment has been proposed to support exercise tolerance [32]. In older adults with chronic respiratory disease, positive changes in dynamic balance and chest mobility following speleotherapy-combined programs further support the possibility of indirect benefits for functional capacity [8].

In the present study, 6MWT performance increased in both groups, which may be partly attributed to the common effects of the supervised yoga-based breathing exercise program, repeated exposure to functional testing, improved breathing control, and increased confidence during physical effort. However, the more pronounced increase observed in the salt-cave group suggests a possible additional setting-related contribution to functional capacity beyond the shared effects of the breathing-exercise program and structured follow-up. In our interpretation, this additional improvement may be related to the relatively stable, low-irritant, and relaxing characteristics of the salt-cave environment, which could have reduced perceived respiratory discomfort during breathing exercises and facilitated better tolerance to physical effort. Psychological and contextual factors, including novelty of the environment, relaxation response, motivation, and expectancy effects, may also have contributed to the larger improvement in walking performance. In addition, because salt therapy combined with exercise has been investigated using diverse protocols and variable levels of evidence, the magnitude and specificity of this functional effect should be interpreted cautiously [45]. Nevertheless, because environmental exposure parameters were not directly measured and both groups received the same breathing-exercise program, this finding should be interpreted as a possible setting-related effect rather than as evidence of an independent speleotherapy mechanism.

It should be emphasized that the present study did not evaluate isolated speleotherapy. Both groups received the same supervised yoga-based breathing exercise program, with comparable session frequency, session duration, physiotherapist contact, and structured intervention exposure. Therefore, the between-group findings should be interpreted as reflecting the possible additional contribution of performing the same breathing-exercise program in a salt-cave environment rather than the independent effect of speleotherapy alone. Moreover, the salt-cave setting may differ from the standard clinical setting in several uncontrolled dimensions, including temperature, humidity, acoustics, psychological novelty, relaxation response, travel context, and expectancy

effects. Because environmental exposure parameters were not directly measured, the observed differences cannot be specifically attributed to salt aerosol exposure or cave-specific microclimatic mechanisms. For this reason, the present findings should be viewed as exploratory rather than confirmatory. The study generates a hypothesis that the salt-cave environment may modify selected short-term responses to breathing exercise, but it does not prove a causal or mechanism-specific effect of speleotherapy.

This study has several limitations. First, it was conducted in a single region and across two implementation sites; therefore, generalizability to other settings and populations may be limited. The cohort also consisted largely of relatively healthy adult smokers, as individuals with obesity, severe COPD, major cardiopulmonary disease, or conditions affecting testing/intervention tolerance were excluded. Thus, the findings may not be generalizable to broader or clinically heterogeneous smoking populations. Second, the follow-up period was limited to 6 weeks, so the long-term persistence of the observed effects remains unknown. Participant and provider blinding was not feasible because the intervention settings were clearly different; however, statistical analyses were performed with coded group labels. Third, smoking-related variables were not comprehensively assessed. Smoking status was self-reported without biochemical verification, and pack-years, nicotine dependence, cessation attempts, and changes in smoking behavior were not systematically monitored. Therefore, unmeasured smoking-related changes may have acted as a potential confounder. Fourth, spirometric interpretation is limited because bronchodilator reversibility testing was not performed and percent-predicted values were not available. Although standardized procedures, three forced maneuvers, and device calibration/quality-control were used, spirometry remains effort-dependent; therefore, participant effort and a possible learning effect cannot be excluded. Fifth, environmental exposure characteristics of the salt-cave setting, including particulate concentration, airborne sodium chloride aerosol levels, particle size distribution, air ionization, microbial content, CO₂ concentration, and ventilation parameters, were not directly measured. Thus, the actual exposure dose remains unknown, limiting causal and mechanistic interpretation. Finally, although no intervention-related adverse events or spirometry-related complications were reported, adverse event monitoring was based on session-level clinical observation rather than a pre-specified structured grading system.

Conclusion

Across both groups, improvements were observed over time in pulmonary function parameters, functional

exercise capacity, physical activity level, and quality-of-life measures. In the linear mixed-effects model analysis, the primary spirometric outcome, FEV₁, showed a significant group $\times$ time interaction in favor of the salt-cave group. However, evidence for broader spirometric superiority was limited, as FVC and PEF showed only borderline effects after multiplicity adjustment, and FEV₁/FVC did not differ significantly between groups. Significant group $\times$ time interactions were also observed for 6-minute walk test performance and several WHOQOL-BREF domains, whereas physical activity level did not show a significant between-group change over time.

Overall, these findings suggest that performing the same yoga-based breathing exercise program in a salt-cave environment may be associated with favorable short-term effects on selected outcomes, particularly FEV₁, functional capacity, and some quality-of-life domains. These effects may reflect a possible setting-related contribution of the salt-cave environment in addition to the shared effects of supervised breathing exercise. Nevertheless, because environmental exposure parameters were not directly measured and both groups received the same breathing-exercise program, broader pulmonary benefits or an independent speleotherapy-specific mechanism cannot be concluded from the present data.

Abbreviations

FVC	Forced Vital Capacity
FEV ₁	Forced Expiratory Volume in 1 s
PEF	Peak Expiratory Flow
FEV ₁ /FVC	Ratio of FEV ₁ to FVC
WHO	World Health Organization
COPD	Chronic Obstructive Pulmonary Disease
ICD	International Classification of Diseases
6MWT	6-Minute Walk Test
IPAQ-SF	International Physical Activity Questionnaire –Short Form
WHOQOL-BREF	World Health Organization Quality of Life–BREF
ATS	American Thoracic Society
ERS	European Respiratory Society

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Human and animal rights

The research procedures involving humans complied with internationally accepted ethical principles, and no animal experimentation was undertaken in this study.

Authors' contributions

Conceptualization: U.B., H.K.A., S.H.H., E.B.A.; Methodology: U.B., H.K.A., S.H.H., E.B.A.; Software: U.B.; Validation: U.B., H.K.A., S.H.H.; Formal Analysis: U.B., H.K.A., S.H.H.; Investigation: U.B., H.K.A.; Resources: U.B., H.K.A., S.H.H., E.B.A.; Data Curation: U.B., H.K.A.; Writing – Original Draft: U.B., S.H.H.; Writing – Review & Editing: H.K.A., S.H.H.; Visualization: U.B., H.K.A.; Supervision: H.K.A., S.H.H., E.B.A.; Project Administration: H.K.A., S.H.H., E.B.A.; Funding Acquisition: U.B., H.K.A., S.H.H., E.B.A.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

Ethical approval for this randomized controlled clinical trial was granted by the Gümüşhane University Rectorate Scientific Research and Publication Ethics Board (meeting no. 2022/6; 26 October 2022; decision no. E-95674914-108.99-137405). All participants provided written informed consent before enrollment.

Consent for publication

Written informed consent for publication was obtained from all participants.

Competing interests

The authors declare no competing interests.

Author details

¹Department of Health Care Services, Yusufeli Vocational School, Artvin Çoruh University, Artvin, Türkiye

²Department of Physiotherapy and Rehabilitation, Health Sciences Faculty, Bahçeşehir University, İstanbul, Türkiye

³Department of Health Care Services, Türkeli Vocational School, Sinop University, Sinop, Türkiye

⁴Department of Therapy and Rehabilitation, Vocational School of Health Service, Gümüşhane University, Gümüşhane, Türkiye

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