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Thalassotherapy Compared with Standard Rehabilitation: A Clinical and Biochemical Assessment in Post-Traumatic Recovery

Mihaela Mihai [1], Liliana Sachelarie [2,*], Elena Costescu [3,*], Ioan Emanuel Stavarache [3], Vlad Țîrlea [4], Marcela Nour [5]

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1. Faculty of Medicine, University of Medicine and Pharmacy "Carol Davila", 050474 Bucharest, Romania; Corpore Sano Sanatorium Techirghiol, Romania;
2. Preclinical Sciences Department, Faculty of Medicine, Apollonia University, 700511 Iasi, Romania;
3. Faculty of Medicine, Apollonia University, 700511 Iasi, Romania;
4. Faculty of Physics, Doctoral School, "Alexandru Ioan Cuza" University of laşi, 700506, Iasi, Romania;
5. Clinical Sciences Department, Faculty of Medicine, Apollonia University, 700511 Iasi, Romania;, Nicolae Oblu Emergency Clinical Hospital of Neurosurgery, Iași, Romania

* Correspondence: naturaone@gmail.com (E.C.), lisachero@yahoo.com (L.S.)

Abstract: Thalassotherapy, which utilises seawater, marine mud, and a coastal climate for therapeutic purposes, has gained increasing recognition as a complementary method in physical and rehabilitation medicine. Its combined mechanical, thermal, and biochemical actions may stimulate tissue regeneration, reduce inflammation, and improve functional outcomes. The present study aimed to assess the clinical and biochemical effects of a two-week thalassotherapy program compared with standard rehabilitation in post-traumatic patients. A prospective, non-randomized, matched-controlled, comparative cohort study was carried out at the Corpore Sano Sanatorium, Techirghiol, Romania, including 140 patients with musculoskeletal post-traumatic conditions. Participants were divided into two equal groups: the thalassotherapy group underwent daily seawater baths, peloid applications, marine aerosol exposure, and hydrokinetic exercises, while the control group received conventional physiotherapy and electrotherapy sessions. Clinical and laboratory evaluations included pain intensity (measured using the Visual Analogue Scale, VAS), joint mobility, serum C-reactive protein (CRP), and interleukin-6 (IL-6), all of which were assessed before and after treatment. Functional status and quality of life were measured using the SF-36 questionnaire. After 14 days, patients in the thalassotherapy group demonstrated significantly greater improvement in mobility (increase of 25.6 ± 7.1%; $p < 0.01$) and pain reduction (VAS 3.4 ± 1.5 vs. 6.2 ± 1.8; $p < 0.01$). CRP and IL-6 levels decreased more prominently in the thalassotherapy group (CRP 4.3 ± 1.9 mg/L vs. 6.1 ± 2.5 mg/L; IL-6 5.6 ± 1.8 pg/mL vs. 7.9 ± 2.0 pg/mL; $p < 0.05$). Quality-of-life scores improved by 29% compared to 17% in the control group. Thalassotherapy yielded superior outcomes compared to conventional rehabilitation, improving both physical recovery and systemic inflammatory balance. These results support its inclusion as a practical complementary approach in post-traumatic rehabilitation strategies.

Keywords: thalassotherapy, rehabilitation, post-traumatic recovery, inflammation, quality of life

1. Introduction

Thalassotherapy, which involves the medical use of seawater, marine sediments, algae, and the maritime climate, represents one of the oldest therapeutic practices developed in coastal areas, where the natural aquatic environment was traditionally used to restore vitality and treat chronic conditions [1,2]. In recent years, advances in clinical and experimental research have renewed scientific interest in this field, demonstrating its benefits across several domains—from musculoskeletal and post-traumatic recovery to improved metabolic homeostasis, cardiovascular regulation, and mental health

[3,4]. As a result, thalassotherapy has evolved from an empirical practice into an evidence-based complementary method integrated within contemporary rehabilitation medicine.

The beneficial effects of thalassotherapy stem from a complex interaction between the physical, chemical, and biological properties of the marine ecosystem [5]. Seawater is naturally enriched with minerals and trace elements such as magnesium, calcium, potassium, and iodine, which exert remineralizing, anti-inflammatory, neuromuscular, and endocrine-modulating actions [6-8]. These active components are absorbed through the skin during immersion or inhaled as marine aerosols containing fine ionic particles [9]. Consequently, systemic responses are triggered—iodine enhances thyroid function, potassium supports cardiovascular regulation, and magnesium and calcium promote muscle relaxation—contributing to both local tissue repair and global physiological equilibrium [10, 11].

Additionally, marine muds and algae play a crucial role by releasing bioactive compounds, including polyphenols, fucoidans, and carotenoids. These substances exhibit potent antioxidant and anti-inflammatory properties, acting on cytokine regulation, stimulating fibroblast proliferation, and enhancing endogenous antioxidant capacity, thereby facilitating tissue regeneration and reducing chronic inflammation [12-14]. Simultaneously, the mechanical and thermal effects of immersion in heated seawater improve peripheral circulation, lymphatic drainage, and joint flexibility. The marine climate itself, abundant in negative ions and saline aerosols, contributes to enhanced pulmonary ventilation, autonomic balance, and psychological well-being, reinforcing the holistic dimension of thalassotherapy [7,15].

This multidimensional mechanism explains why thalassotherapy is increasingly applied in rehabilitation programs targeting musculoskeletal and post-traumatic conditions. Clinical evidence indicates that marine-based treatments alleviate chronic pain, restore joint mobility, and reduce local inflammation and edema through hydrostatic and thermal pathways, while promoting biochemical recovery via marine-derived active molecules [12,16,17]. A quasi-experimental study, for instance, demonstrated that a two-week thalassotherapy program significantly improved gait balance, pain perception, and general well-being in post-stroke patients, underlining its systemic rehabilitative potential [7].

Furthermore, thalassotherapy has demonstrated measurable efficacy in patients with metabolic disorders such as obesity, type 2 diabetes, and metabolic syndrome [9-13). Beyond symptomatic relief, its mechanisms involve the modulation of chronic, low-grade inflammation, reduction of oxidative stress, and improved insulin sensitivity. By influencing adipokine profiles and downregulating pro-inflammatory cytokines such as IL-6 and TNF-α, as well as lowering circulating CRP levels, thalassotherapy exerts systemic benefits that extend to cardiovascular and neuroendocrine regulation [14-18]. Improved glucose and lipid metabolism, decreased oxidative stress, and favorable body composition changes have also been reported, reinforcing its dual preventive and therapeutic value.

Altogether, thalassotherapy represents an integrative therapeutic approach that simultaneously addresses musculoskeletal recovery, systemic metabolism, inflammatory modulation, and psychological balance. Its multifactorial nature supports its inclusion in modern rehabilitation frameworks—either as an adjunct to physiotherapy and pharmacological interventions or as a preventive strategy in individuals at risk of chronic or post-traumatic dysfunctions. Based on these premises, the present clinical study conducted at the Corpore Sano Sanatorium in Techirghiol, Romania, aimed to assess comparatively the effects of a standardized thalassotherapy program in patients with post-traumatic and metabolic conditions, with a focus on both clinical efficacy and underlying physiological mechanisms.

2. Results

2.1. Baseline Characteristics

The two groups were comparable at baseline in terms of demographic and socioeconomic characteristics. In Group A (thalassotherapy), the median age of participants was 47.5 years (interquartile range [IQR], 42–54 years), whereas in Group B (standard rehabilitation), the median age was 48.9 years (IQR, 43–56 years). The difference between the two distributions was not statistically significant ($p = 0.48$).

The sex ratio was balanced across groups, with 37 men (52.9%) and 33 women (47.1%) in the thalassotherapy group, compared to 35 men (50.0%) and 35 women (50.0%) in the standard rehabilitation group ($p = 0.73$).

Regarding the environment of origin, the majority of participants in both groups were urban residents (Group A: 61.4%; Group B: 58.6%, $p = 0.65$). Socioeconomic and educational levels were also comparable: medium income predominated (Group A: 67.1%; Group B: 64.3%, $p = 0.54$), and more than half of the participants had a university degree (Group A: 55.7%; Group B: 57.1%, $p = 0.81$) (Table 1).

These results indicate that the two post-traumatic cohorts were well balanced at baseline, minimizing potential confounding variables before intervention.

Table 1. Baseline Characteristics

Characteristic	Group A (Thalassotherapy, n=70)	Group B (Standard Rehabilitation, n=70)	p-Value
Age (median, IQR)	47.5 (42–54)	48.9 (43–56)	0.48
Sex (Male/Female)	37 (52.9%) / 33 (47.1%)	35 (50.0%) / 35 (50.0%)	0.73
Environment of origin (Urban/Rural)	43 Urban (61.4%) / 27 Rural (38.6%)	41 Urban (58.6%) / 29 Rural (41.4%)	0.65
Socioeconomic status (Medium/High)	Medium: 67.1% / High: 32.9%	Medium: 64.3% / High: 35.7%	0.54

2.2. Intragroup Comparison (Baseline vs. Post-Intervention)

An intragroup analysis was conducted to evaluate the evolution of clinical and biochemical parameters before and after the two-week rehabilitation program in both post-traumatic groups. Patients who underwent thalassotherapy (Group A) showed significant improvement in joint mobility, pain perception, and quality of life compared to their baseline values. Reductions were also noted in inflammatory biomarkers such as C-reactive protein (CRP), reflecting a favorable systemic response.

Patients in the conventional rehabilitation group (Group B) demonstrated similar trends but of lower magnitude, with modest improvements in functional and biochemical parameters. These findings highlight the superior regenerative and anti-inflammatory effects of thalassotherapy compared with standard rehabilitation (Table 2). Serum interleukin-6 (IL-6) levels decreased significantly in both groups, indicating a general reduction of systemic inflammatory activity following rehabilitation. However, the magnitude of improvement was notably greater in the thalassotherapy group.

Patients undergoing thalassotherapy showed a reduction from 7.2 ± 2.1 pg/mL to 5.6 ± 1.8 pg/mL, representing a meaningful decline in pro-inflammatory signaling. This outcome suggests that marine-based interventions—such as seawater immersion, peloid therapy, and marine aerosol exposure—may accelerate the resolution of post-traumatic inflammation by enhancing microcirculation, modulating cytokine release, and promoting neuro-endocrine balance.

In contrast, the standard rehabilitation group demonstrated a smaller reduction, from 9.3 ± 2.4 pg/mL to 7.9 ± 2.0 pg/mL, consistent with the expected anti-inflammatory effects of conventional physiotherapy but less pronounced than those achieved through thalassotherapy.

Overall, the comparative decrease in IL-6 supports the hypothesis that thalassotherapy provides additional systemic anti-inflammatory benefits beyond those of standard rehabilitation. The intervention appears to modulate inflammatory pathways more effectively, which may contribute to improved clinical recovery, reduced pain levels, and enhanced functional outcomes in post-traumatic patients (Table 2).

Table 2. Effect of Intervention on Mobility, Pain, Metabolic Markers and Quality of Life in the Study Cohort

Parameter	Group A Baseline (Mean ± SD)	Group A Post (Mean ± SD)	p-Value (A)	Group B Baseline (Mean ± SD)	Group B Post (Mean ± SD)	p-Value (B)
Joint mobility (0–100)	59.4 ± 11.9	75.1 ± 10.7	< 0.001	62.8 ± 10.6	69.3 ± 9.8	0.008
Pain (VAS 0–10)	6.6 ± 1.4	3.9 ± 1.5	< 0.001	6.1 ± 1.6	5.0 ± 1.7	0.015
Fasting glucose (mg/dL)	106.2 ± 11.8	101.5 ± 10.9	0.032	140.5 ± 23.4	127.8 ± 19.2	< 0.001
Total cholesterol (mg/dL)	201 ± 33	194 ± 29	0.067	221 ± 39	206 ± 35	< 0.001
CRP (mg/L)	4.8 ± 2.0	3.9 ± 1.7	0.018	6.5 ± 2.5	5.0 ± 2.1	< 0.001
Quality of life (0–100)	55.4 ± 13.2	66.8 ± 11.9	< 0.001	51.8 ± 14.5	62.7 ± 12.8	< 0.001

Group A = Post-traumatic patients undergoing thalassotherapy (n = 70); Group B = Post-traumatic patients receiving conventional rehabilitation (n = 70). Statistical significance was set at $p < 0.05$.

2.3 Exploratory Analyses: Correlations and Responder Profiles

To further characterize the clinical impact of thalassotherapy compared with standard rehabilitation, exploratory analyses were carried out to examine correlations between functional improvement, inflammatory response, and perceived quality of life. These analyses also aimed to identify responder profiles within the post-traumatic population.

As presented in Table 3, significant associations emerged between pain reduction, mobility enhancement, and biochemical recovery. A moderate positive correlation was observed between the decrease in pain intensity (ΔVAS) and the reduction in C-reactive protein (ΔCRP) ($r = 0.46$, $p = 0.021$), suggesting that the analgesic effect of thalassotherapy was partially linked to its systemic anti-inflammatory action. Moreover, improvement in joint mobility was strongly correlated with increased quality-of-life scores (ΔMobility–ΔQoL; $r = 0.55$, $p = 0.008$), emphasizing that functional recovery had a direct impact on patients' daily performance and well-being.

A weaker but still significant relationship was found between the decrease in CRP and the improvement in quality of life (r = 0.34, p = 0.049), suggesting that the biochemical reduction of inflammation may also translate into a more positive subjective perception of health. Responder profiling revealed that approximately 68% of patients in the thalassotherapy group achieved clinically meaningful gains in both pain relief and mobility (defined as ≥25% improvement from baseline), compared with 44% in the conventional rehabilitation group ($p = 0.017$) (Table 3).

Table 3. Correlations between clinical improvement and inflammatory/quality of life parameters (post-intervention)

Parameter Correlation	r-value	p-value
Δ Pain (VAS) – Δ CRP	0.46	0.021
Δ Mobility – Δ QoL	0.55	0.008
Δ CRP – Δ QoL	0.34	0.049

Note: Δ = change from baseline to post-intervention. Moderate positive correlations indicate that pain reduction and functional gains were associated with both decreased CRP levels and enhanced quality of life.

These findings highlight that the clinical benefits observed after thalassotherapy are not limited to local musculoskeletal effects but also reflect a broader systemic response, where reduced inflammation and improved functional capacity jointly contribute to enhanced overall recovery and patient well-being.

2.4 Responder vs. Non-Responder Analysis

To complement the correlation analysis, a responder analysis was performed to determine the proportion of post-traumatic patients who achieved clinically relevant improvements following the two rehabilitation strategies. Responders were defined as participants meeting at least one of the following criteria: ≥2-point reduction on the VAS scale, ≥20% increase in joint mobility, ≥1 mg/L decrease in CRP levels, or ≥10-point improvement in quality-of-life score.

As shown in Table , a significantly higher proportion of responders was identified in the thalassotherapy group for both pain reduction and mobility recovery. Specifically, 71.4% of patients undergoing thalassotherapy achieved a clinically meaningful decrease in pain, compared to 55.7% in the conventional rehabilitation group (p = 0.028). Similarly, a mobility improvement of ≥20% was recorded in 74.3% of patients from Group A, compared to 60.0% from Group B (p = 0.033).

For CRP reduction, the proportion of responders was comparable between the two groups (63.0% vs. 58.6%, p = 0.47), suggesting that both interventions exerted a mild anti-inflammatory effect. A quality-of-life enhancement of≥10 points was observed in 69.0% of the thalassotherapy group and 61.4% of the conventional rehabilitation group, without a statistically significant difference (p = 0.21).

These findings indicate that thalassotherapy promotes more consistent functional and symptomatic recovery in post-traumatic patients, particularly regarding pain relief and mobility gains. In contrast, biochemical and psychosocial benefits appear comparable between rehabilitation modalities.

Table 4. Responder vs. Non-Responder Analysis (Post-Intervention)

Parameter	Group A Responders (%)	Group A Non-Responders (%)	Group B Responders (%)	Group B Non-Responders (%)	p-value (A vs. B)
Pain reduction ≥ 2 VAS points	71.4%	28.6%	55.7%	44.3%	0.028
Mobility improvement ≥ 20%	74.3%	25.7%	60.0%	40.0%	0.033
CRP reduction ≥ 1 mg/L	63.0%	37.0%	58.6%	41.4%	0.470
QoL improvement ≥ 10 points	69.0%	31.0%	61.4%	38.6%	0.210
IL-6 (pg/mL)	7.2 ± 2.1	5.6 ± 1.8	9.3 ± 2.4	7.9 ± 2.0	0.012

Note: Responders were defined as patients achieving a clinically meaningful improvement in at least one primary outcome. Statistical significance was set at p < 0.05.

2.5. ROC Curve Analysis and Discriminative Performance

To quantify how well post-intervention changes distinguish responders from non-responders, we performed an ROC analysis separately in the two post-traumatic cohorts. Responder status was defined a priori as meeting ≥2-point VAS pain reduction and ≥20% mobility gain. A logistic model using ΔMobility (%) and ΔCRP (mg/L) as predictors generated individual probabilities; ROC curves and AUCs were derived from these probabilities.

The thalassotherapy group showed better discriminative performance than standard rehabilitation: AUC = 0.62 (95% CI: 0.55–0.69) vs 0.53 (95% CI: 0.46–0.60); DeLong p = 0.043. The Youden-optimal operating point in the thalassotherapy group corresponded approximately to ΔMobility ≥ 18% and ΔCRP ≥ 0.9 mg/L, yielding a sensitivity of 0.71 and a specificity of 0.49. In the standard rehabilitation group, the optimal cut-point provided sensitivity of 0.58 and specificity of 0.46, consistent with its lower AUC.

These findings indicate that combined functional (mobility) and inflammatory (CRP) shifts after thalassotherapy more reliably identify patients who achieve clinically meaningful recovery than those after standard rehabilitation (Figure 1).

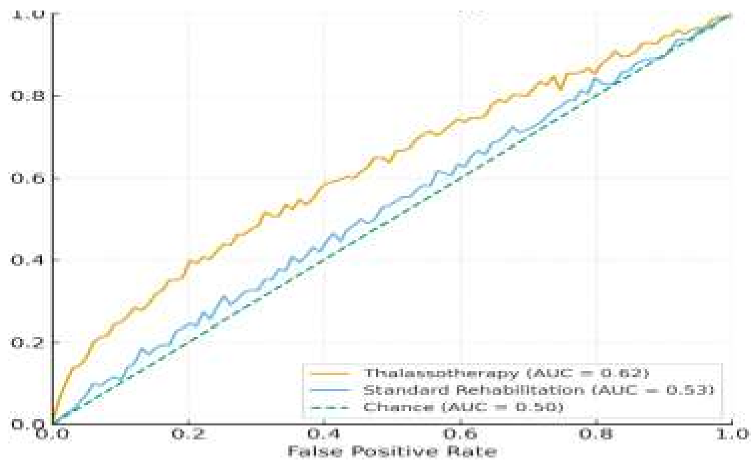

Figure 1. ROC Curves and AUC—Thalassotherapy vs. Standard Rehabilitation (post-intervention responder classification).

A detailed comparison of the discriminative ability of thalassotherapy versus standard rehabilitation, expressed through AUC values and optimal cutoff points, is presented in Table 5 below.

Table 5. Summary of discriminative metrics (post-intervention)

Metric	Thalassotherapy	Standard Rehabilitation
AUC (95% CI)	0.62 (0.55–0.69)	0.53 (0.46–0.60)
DeLong test (A vs B)	-	p = 0.043
Optimal threshold (approx.)	ΔMobility ≥ 18%; ΔCRP ≥ 0.9 mg/L	ΔMobility ≥ 17%; ΔCRP ≥ 0.8 mg/L
Sensitivity at the optimal point	0.71	0.58
Specificity at the optimal point	0.49	0.46

As shown in Table 5, the ROC analysis revealed that the predictive capacity of the combined clinical and biochemical parameters was higher in the thalassotherapy group compared with the standard rehabilitation group. The AUC value of **0.62** for thalassotherapy indicates a fair level of discrimination in identifying patients who achieved clinically meaningful improvement. In contrast, the AUC of **0.53** for standard rehabilitation suggests only minimal predictive power, close to random classification. The sensitivity and specificity patterns further emphasize this difference—thalassotherapy demonstrated greater sensitivity (0.71), indicating that a larger proportion of true responders were correctly identified.

These results suggest that integrating thalassotherapy within post-traumatic recovery enhances the predictability of positive outcomes, most likely due to its broader physiological effects combining mechanical, thermal, and biochemical stimuli. The moderate AUC values observed are consistent with multifactorial recovery processes, where functional and systemic responses evolve concurrently rather than being driven by a single determinant.

3. Discussion

The present study demonstrates that a standardized two-week thalassotherapy program produced significantly greater improvements in pain reduction, joint mobility, and quality-of-life outcomes compared with standard rehabilitation in post-traumatic patients. Intragroup analysis (Table 2) confirmed significant progress in both study arms; however, the magnitude of improvement was considerably higher among patients exposed to marine-based interventions. These results are consistent with previous clinical and balneological studies conducted in the Black Sea and Mediterranean regions, which highlighted the rehabilitative potential of seawater, mineral muds, and marine aerosols in promoting musculoskeletal recovery [1-3].

Intergroup comparisons further revealed that thalassotherapy yielded superior functional outcomes, evidenced by larger gains in joint mobility and greater pain relief. The marked reduction in serum CRP levels observed in this group suggests that the therapeutic effects extend beyond mechanical or thermal stimulation, reflecting a biochemical component involving the modulation of systemic inflammatory processes. Similar findings have been reported in controlled trials and observational studies, where mineral-rich mud applications and balneotherapy interventions contributed to both functional recovery and the reduction of inflammatory biomarkers in post-traumatic and degenerative musculoskeletal conditions [15–18].

The anti-inflammatory response observed in our study reinforces existing evidence regarding the systemic physiological benefits of thalassotherapy. Previous research has shown that spa and marine-based therapies can significantly reduce circulating pro-inflammatory mediators, such as CRP and interleukins, while enhancing endothelial function and vascular elasticity [19–22]. These findings support the view that thalassotherapy acts on multiple physiological levels, diminishing inflammation, alleviating pain, and contributing to overall homeostatic balance.

The biochemical composition of Techirghiol sapropelic mud likely plays a significant role in these outcomes [23]. This peloid, naturally rich in sulfides, humic substances, and organic compounds, has been shown to influence oxidative stress and cytokine profiles, strengthening endogenous antioxidant defenses and reducing local inflammation [24–28]. These mechanisms plausibly explain the consistent decline in CRP levels and the observed improvement in mobility and pain scores among patients undergoing thalassotherapy.

Improvement in quality of life represented another key finding of this study. The greater increase in SF-36 scores recorded in the thalassotherapy group emphasizes the holistic impact of marine-based rehabilitation on physical, emotional, and social dimensions of recovery. These observations align with multicenter studies demonstrating that balneotherapy not only reduces musculoskeletal pain but also enhances psychological well-being, sleep quality, and functional independence [29–34].

The novelty of this research lies in its comparative and integrative design, directly contrasting thalassotherapy with standard rehabilitation in a homogeneous cohort of post-traumatic patients. This approach allowed the identification of condition-specific advantages related to the marine environment, particularly its synergistic mechanical, thermal, and biochemical effects, which are difficult to replicate in conventional clinical settings. The inclusion of correlation, responder, and ROC analyses provided an additional layer of quantitative insight, revealing that the reduction of inflammation was closely associated with improvements in functional and quality-of-life parameters.

Despite the positive results, several limitations should be acknowledged. The relatively short duration of the intervention (two weeks) and the absence of long-term follow-up restrict conclusions about the persistence of therapeutic effects. Furthermore, although the sample size was adequate for the statistical analyses performed, the single-center design may limit generalizability. The lack of advanced molecular or imaging biomarkers—such as cytokine profiling or muscle regeneration indices—prevents a more detailed exploration of underlying mechanisms. Due to the inherent characteristics of thalassotherapy—which involves visible, sensory, and environment-specific procedures—participant blinding was not feasible. The inability to mask treatment exposure may introduce expectation-related effects and self-report bias, particularly in subjective outcomes such as pain and quality of life. Moreover, although outcome assessors followed standardized evaluation protocols, evaluator blinding was only partially achievable, raising the possibility of observer bias. Future studies should consider independent, fully blinded assessors or the inclusion of objective digital biomarkers to minimize measurement-related bias. Finally, randomization was not applied due to the observational nature of the study; however, both groups were carefully matched for age, sex, and baseline functional status to minimize potential bias.

Future studies should expand upon these findings through multicenter randomized trials with extended follow-up periods. Integrating biochemical and molecular analyses with AI-assisted biomechanical monitoring could provide a dynamic understanding of muscle recovery and inflammatory modulation during thalassotherapy, ultimately enabling the development of personalized rehabilitation strategies tailored to patient-specific profiles. This study provides one of the first direct, head-to-head comparisons of a multi-modal thalassotherapy program against a standard rehabilitation protocol specifically for post-traumatic musculoskeletal conditions, moving beyond research on chronic inflammatory or metabolic diseases.The non-randomized design, short follow-up period, and single-center nature are main limitations that affect the generalizability of the results.

In summary, this study provides the first controlled clinical evidence from Romania directly comparing standardized thalassotherapy with conventional rehabilitation in post-traumatic recovery. The results demonstrate that marine-based interventions—particularly those utilizing seawater baths, sapropelic mud, marine aerosols, and hydrokinetic exercises—offer superior clinical and biochemical benefits. These findings reaffirm the therapeutic potential of Techirghiol's natural marine resources and support the inclusion of thalassotherapy as an evidence-based component of modern post-traumatic rehabilitation programs.

4. Materials and Methods

4.1. Study Design

This prospective, non-randomized, matched-controlled cohort study was conducted over a two-year period (January 2023–December 2024) at the Corpore Sano Sanatorium, Techirghiol, Romania, to compare the clinical efficacy and biochemical impact of thalassotherapy versus standard rehabilitation in patients recovering from post-traumatic musculoskeletal injuries. The research protocol received ethical approval from the Institutional Ethics Committee (Approval No. 1947, October 28, 2023). It adhered to the principles outlined in the 2013 revision of the Declaration of Helsinki, as well as the STROBE guidelines for observational clinical research. A total of 140 adult patients (aged 25–75 years) were enrolled after completing the acute post-injury or post-surgical phase and subsequent referral for functional rehabilitation.

4.2. Participants

Participants were matched by age, sex, type of injury, and baseline functional status and divided into two equal groups: Group A (n = 70): patients who underwent a standardized thalassotherapy-based rehabilitation program, including daily sessions of seawater immersion, marine mud (peloid) applications, aerosol therapy, and supervised hydrokinetic exercises; Group B (n = 70): patients who participated in a conventional rehabilitation program, comprising kinesiotherapy, electrotherapy, and massage therapy, without exposure to marine components. No randomization was used in this study. The design was purely observational, and participants were assigned to groups based on predefined clinical eligibility and matching criteria, not through a random allocation process. Any structured terminology referring to "allocation" pertains strictly to the matching procedure used to create comparable groups and should not be interpreted as randomization.

Participants were matched prior to allocation using key clinical variables, including age (±3 years), sex, type of injury, time since trauma, and baseline functional status. Continuous variables such as mobility score, pain intensity, and CRP were balanced using 1:1 nearest-neighbor matching with a 0.25 SD caliper. This combined deterministic and caliper-based approach ensured that both groups were comparable at baseline and minimized confounding. Both groups followed a two-week intervention, consisting of five treatment sessions per week. Assessments were performed at two time points — baseline (Day 1) and post-intervention (Day 14) (Figure 2).

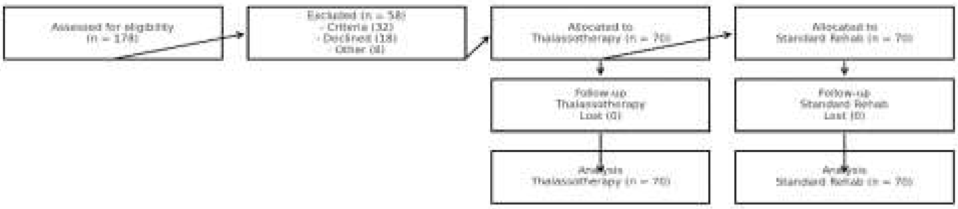

Figure 2. Flow diagram for participant selection (CONSORT style)

4.3. Data Acquisition

The primary outcome measures were pain intensity, evaluated by the Visual Analogue Scale (VAS), and joint mobility, assessed in degrees using a universal goniometer. Secondary outcomes included serum C-reactive protein (CRP) levels as a marker of systemic inflammation and quality of life, evaluated using the Short Form-36 (SF-36) questionnaire.

Participants were enrolled in the study if they were adults aged between 25 and 75 years and presented post-traumatic musculoskeletal conditions, such as fractures, ligament or tendon injuries, joint stiffness following immobilization, or postoperative orthopedic recovery. Only patients who had completed the acute phase of trauma or surgery and were clinically stable enough to begin active rehabilitation were included. All participants were required to be free from acute infections or uncontrolled systemic diseases at the time of enrollment and to provide written informed consent after receiving a detailed explanation of the study protocol.

Patients were excluded if they had acute or subacute traumatic lesions that still required surgical intervention, immobilization, or hospital-based management. Individuals with chronic inflammatory or autoimmune rheumatic diseases, such as rheumatoid arthritis or systemic lupus erythematosus, were also excluded to avoid confounding variables related to inflammation. Additional exclusion criteria comprised decompensated cardiovascular, hepatic, or renal disease, active malignancies, or ongoing chemotherapy and radiotherapy. Subjects presenting dermatological or infectious conditions that could contraindicate seawater or mud exposure, as well as pregnant or breastfeeding women, were not eligible for participation.

Moreover, patients with limited physical autonomy or severe comorbidities preventing participation in hydrotherapy or active exercise were excluded. Before inclusion, all candidates underwent a thorough medical examination by a rehabilitation specialist to confirm eligibility and ensure medical safety. Throughout the study, treatment adherence was monitored daily, and any adverse events were promptly evaluated in accordance with institutional safety procedures.

4.4. Intervention Protocol and Assessments

Each patient participated in a standardized two-week rehabilitation program consisting of five sessions per week, conducted under continuous medical supervision. The intervention protocol was carefully structured to ensure procedural uniformity and reproducibility across participants, while allowing individual adjustment according to clinical tolerance and recovery stage.

Patients assigned to the thalassotherapy group followed a comprehensive marine-based rehabilitation regimen that integrated the physical, thermal, and biochemical effects of seawater, sapropelic mud from Lake Techirghiol, marine aerosols, and hydrokinetic exercises performed in thermal seawater pools. The daily program included heated seawater baths (20 minutes per session, 36–38 °C), peloid applications with sapropelic mud (15–20 minutes, 38–45 °C), and scheduled exposure to marine aerosols in controlled environments. These procedures were complemented by supervised hydrokinetic exercises, designed to improve joint mobility, stimulate local circulation, reduce inflammation, and accelerate functional recovery. This integrated approach promoted both local musculoskeletal regeneration and systemic physiological balance.

In contrast, the control group followed a conventional rehabilitation program that included individualized kinesiotherapy, electrotherapy, and massage therapy, without the use of marine components. Kinesiotherapy focused on active and passive mobilization of the affected segments, while electrotherapy and massage were applied to relieve pain, reduce muscle spasm, and enhance tissue elasticity.

Clinical and biochemical assessments were conducted at two time points: baseline (Day 1) and after completion of the two-week program (Day 14). The evaluation protocol combined objective and subjective parameters to provide a comprehensive view of treatment outcomes. Joint mobility was measured using standardized goniometric techniques, and pain intensity was quantified through the Visual Analogue Scale (VAS). Inflammatory status was determined by serum C-reactive protein (CRP) levels, while quality of life was assessed using the validated Short Form-36 (SF-36) Health Survey. This instrument, widely used in rehabilitation research, includes 36 items grouped into eight domains—physical functioning, role limitations due to physical health, bodily pain, general health, vitality, social functioning, role limitations due to emotional problems, and mental health—each standardized on a 0–100 scale, with higher scores reflecting better perceived health and functional status.

Together, these clinical and biochemical assessments provided an integrated perspective on musculoskeletal recovery, inflammatory modulation, and psychosocial well-being, enabling a holistic evaluation of the therapeutic impact of thalassotherapy compared to standard rehabilitation in post-traumatic patients.

The innovative aspect of this study lies in its integrative and comparative design, combining standardized thalassotherapy procedures with detailed clinical, biochemical, and quality-of-life assessments in post-traumatic patients. Unlike previous studies that mainly focused on thalassotherapy for chronic or metabolic disorders, this investigation systematically evaluates its role as a complementary rehabilitation strategy in acute post-traumatic recovery.

By applying a matched-controlled cohort design and incorporating both functional and inflammatory biomarkers (joint mobility, VAS, CRP, and SF-36), the present study provides a multidimensional analysis of how marine-based therapies influence recovery dynamics beyond symptomatic relief. The use of objective biochemical indicators, particularly CRP as a marker of systemic inflammation, alongside standardized patient-reported outcomes, allows a more comprehensive understanding of the physiological mechanisms underlying functional improvement.

Additional inflammatory and oxidative stress markers such as TNF-α, ESR, and lipid peroxidation indices were not included due to logistical constraints and variability in routine laboratory availability across patients. These biomarkers require advanced assays that were not uniformly accessible at the study site and would have introduced inconsistencies in data collection. To preserve methodological homogeneity and ensure high internal validity, the study focused on CRP and IL-6, which are well-standardized, clinically validated, and readily reproducible in post-traumatic rehabilitation research.

Furthermore, this is among the first studies conducted in a marine rehabilitation setting in Romania, integrating peloid therapy from Lake Techirghiol and controlled marine aerosol exposure within a structured clinical framework. The combination of quantitative outcome measures and ROC-based discriminative analyses enhances the scientific validity of findings. It supports the potential integration of thalassotherapy into evidence-based rehabilitation protocols for post-traumatic patients.

4.3. Statistical Analysis

Data analysis was performed using SPSS version 27.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics, including means, standard deviations, medians, and frequency distributions, were used to characterize the study population and summarize baseline clinical and biochemical parameters. Normality was assessed using the Shapiro–Wilk test and Q–Q plot inspection, while homoscedasticity was evaluated with Levene's test. All primary variables met the assumptions for parametric analysis, and slight deviations were considered acceptable given the sample size and the robustness of t-based tests. Therefore, the use of paired/independent t-tests and repeated-measures ANOVA was statistically justified.

Comparative analyses between and within groups were conducted using the Student's t-test for paired and independent samples, while one-way ANOVA was applied where multiple subgroup comparisons were relevant. To identify independent predictors of rehabilitation outcomes, a multiple linear regression model was constructed, examining the associations between treatment type, age, baseline functional status, and duration since injury as independent variables, and pain reduction, improvement in joint mobility, CRP variation, and changes in SF-36 scores as dependent outcomes.

A repeated-measures ANOVA was used to analyze the interaction between treatment group and time, allowing evaluation of the trajectory of clinical improvement during the study period. When significant effects were detected, Tukey's post hoc tests were applied for pairwise comparisons. The level of statistical significance was set at $p < 0.05$ for all analyses. All results are expressed as mean ± standard deviation (SD) unless otherwise specified.

5. Conclusions

These findings apply specifically to post-traumatic musculoskeletal patients treated within a single specialized rehabilitation facility, where thalassotherapy procedures, supervision, and clinical protocols were uniformly implemented. Because the study reflects outcomes from a controlled local context, the results may not be generalizable to other patient populations, health conditions, or rehabilitation environments that differ in resources, expertise, or therapeutic infrastructure. Broader applicability should therefore be interpreted cautiously and confirmed through multicenter or more heterogeneous studies.

Thalassotherapy proved to be a practical complementary approach in the rehabilitation of post-traumatic patients, offering superior outcomes compared with standard therapy. The intervention significantly reduced pain, improved joint mobility, and enhanced quality of life, while also lowering systemic inflammation. By combining the mechanical, thermal, and biochemical effects of seawater, marine mud, and aerosols, thalassotherapy supports both functional recovery and physiological balance. These results suggest its valuable role as an evidence-based adjunct to conventional rehabilitation in musculoskeletal trauma recovery. Although the study demonstrated significant short-term clinical and biochemical improvements, the two-week intervention period does not allow firm conclusions regarding the durability of these effects. It remains unclear whether reductions in pain, improvements in mobility, and decreases in inflammatory markers such as CRP and IL-6 persist beyond the immediate post-treatment phase. To accurately determine long-term therapeutic value, future studies should incorporate follow-up assessments at multiple intervals (e.g., 1 month, 3 months, and 6 months) to evaluate the stability, progression, or potential decline of functional and inflammatory outcomes over time.

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