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Respiratory function in healthy long-term meditators: A cross-sectional comparative study

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ABSTRACT

Purpose: Respiratory function is thought to improve with long-term meditation. This study aimed to assess respiratory function in a cohort of healthy long-term meditators and non-meditators in Sri Lanka.
Methods: Respiratory function of healthy, skilled long-term meditators ($n = 20$) practicing Buddhist meditation consistently >3 years, and age-sex matched non-meditators ($n = 20$) were assessed by assessing resting respiratory rate, spirometry, breath-holding time and six-minute-walk distance. Data were analyzed with SPSS-23 statistical software.
Results: The long-term meditators; 45% male, mean (SD) total lifetime meditation experience 12.8 (6.5) years, aged 45.8 (8.74) years, BMI 23.68 (2.23) kgm^{-2}, and non-meditators; 45% male, mean (SD) age 45.3 (8.05) years, BMI 23.68 (3.28) kgm^{-2}, were comparable. Long-term meditators had slower resting respiratory rates [mean (SD); 13.35 (1.9) vs. 18.37 (2.31) breaths/minute; $p < 0.001$], higher peak expiratory flow rates [mean (SD); 9.89 (2.5) vs. 8.22 (2.3) L/s; $p = 0.03$], and higher inspiratory breath-holding times [mean (SD); 74 (29.84) vs. 53.61 (26.83) seconds, $p = 0.038$] compared to non-meditators. There was no significant difference in the six-minute-walk distance and estimated maximal oxygen consumption between the two groups.
Resting respiratory rate of long-term meditators, showed a significant negative correlation with total lifetime meditation practice in years ($r = -0.444$, $p = 0.049$), and the average length of a meditation session per day ($r = -0.65$, $p = 0.002$). The long-term meditators with longer duration of retreat participation demonstrated lower resting respiratory rate ($r = -0.522$, $p = 0.018$) and higher tidal volumes ($r = 0.474$, $p = 0.04$).
Conclusions: Long-term meditators had significantly slower resting respiratory rates and longer breath-holding times, with better spirometry parameters than non-meditators. Greater practice duration and retreat experience appear to be associated with improved resting respiratory function in long-term meditators.

1. Introduction

Meditation is an altered trait of consciousness that differs from wakefulness, relaxation at rest, and ordinary sleep state [1,2]. Buddhist meditation consists of a variety of techniques that produce heightened awareness and concentration ultimately leading to calmness in the mind and a state of complete inner peace. Sri Lankan Theravada Buddhist practitioners commonly engage in

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meditation. The two main kinds of Theravada Buddhist meditation include Samatha (concentration) and Vipassana (Insight) [3,4]. Samatha meditation involves concentration on the breath (eg: Anapanasati), repeated sounds, or objects. Vipassana meditation involves non-judgmental observation of thoughts, and sensations [4] and is further categorized according to the focus of attention; on the body, feelings and emotions, thoughts, and mental processes [5]. Focusing attention on bodily sensations is known as body-scan meditation [6]. The focus of breath is used by novice Vipassana meditators to attain shallow concentration levels [5].

Regular meditation practice induces 'state' or short-term temporary changes that arise during or immediately after meditation [7] and 'trait' or long-lasting changes [8]. State changes in respiratory parameters have been reported in many forms of meditation: such as a reduction of respiratory rate (RR) [9–12], decrease in minute ventilation [13], abrupt decrement in oxygen consumption during meditation from baseline [14], increase in tidal volume (V_T) [15], vital capacity [16], peak expiratory flow rate (PEFR), chest expansion and breath-holding time (BHT) [17]. Two Asian studies have reported increased spirometry values; increased forced vital capacity (FVC), forced expiratory volume in 1 second (FEV_1) [18,19], FEV_1/FVC [18], and PEFR [19] in Buddhist Anapanasati meditators compared to age-sex matched non-meditators. Cross-sectional studies comparing respiratory parameters in long-term meditators (LTMs) and non-meditators (NMs) have observed significantly slower baseline RR in LTMs of mindfulness meditation [20] and higher vital capacity, V_T, BHT, and expiratory pressure in short-term and long-term Raja Yoga meditators [16] compared to those of NMs. There is a paucity of data regarding respiratory function in LTMs and associations with meditation practice variables.

Buddhist meditation and mindfulness practices have thrived in Sri Lanka for over twenty centuries [21] influencing philosophy, aesthetic, and therapeutic practice [22,23]. To the best of our knowledge, no study has looked at the respiratory function in a Sri Lankan cohort of LTMs and its associations with meditation practice variables. Identifying meditation practice variables that are associated with beneficial changes in respiratory function would aid in planning therapeutic interventions for those with compromised respiratory function.

This study therefore aimed to assess respiratory function in a Sri Lankan cohort of healthy LTMs with comparable age-sex matched NMs, and assess the associations between respiratory function parameters and meditation practice variables in LTMs.

2. Materials and methods

2.1. Study design, setting, and participant recruitment

One hundred and fifty-six meditators were contacted from four different meditation centers in Sri Lanka, and a total of 71 meditators, who fulfilled the inclusion criteria of being aged between 18 and 65 years, self-reported to be healthy, and not on long-term medication, were natives of Sri Lanka and had meditated consistently for more than 3 years with a frequency of at least 6 hours per week, were selected. Smokers, pregnant/breastfeeding women, individuals engaged in extensive sports/in any form of relaxation technique and performing yoga or any kind of respiratory exercise/training were excluded. A validated interviewer-administrated intake-interview questionnaire was utilized to select "skilled" LTMs [24,25]. Of them, 3 LTMs were excluded due to elevated resting blood pressure (n = 1) and resting ECG abnormalities (n = 2) (Fig. 1), finally retaining 20 skilled LTMs for the study. Twenty age-sex matched, healthy NMs (never meditated/occasionally meditated <12 occasions per year, each occasion <20 min), who satisfied the inclusion and exclusion criteria were recruited as controls from the community using purposive sampling. All participants underwent a basic health screening by a medical officer, and those with undiagnosed elevated resting blood pressure (BP > 160/95 mmHg; n = 1 LTM), and resting ECG abnormalities (n = 2 LTMs) were excluded. Data collection for this cross-sectional comparative study was carried out from October 2021 to December 2022.

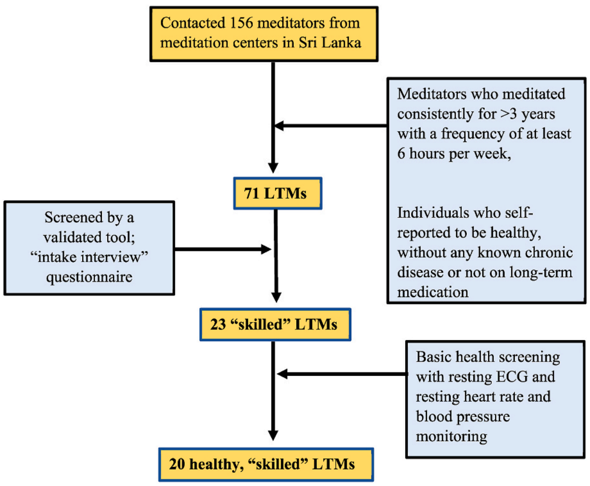

Fig. 1. Recruitment of LTMs.

2.2. Data collection procedure

Participants were asked to dress in light, comfortable clothing, abstain from vigorous exercise, and caffeine consumption, and have only a light meal 2 h before testing. A detailed history of the meditation practice of the LTMs was documented. All investigations were carried out at the Department of Physiology, Faculty of Medicine, University of Colombo, following written informed consent. This study was approved by the Ethics committee of the Faculty of Medicine, University of Colombo (Reference number for ethical approval: EC-19-117), and was carried out under the principles of the Declaration of Helsinki.

Resting respiratory rate (RR) was recorded using a respiratory belt transducer (AD Instruments, Australia) in the supine position following a 30-minutes mandatory rest period and calculated using the respiratory signals recorded for 5-minutes by the data acquisition system (Power Lab 4/26, AD Instruments, Australia) and displayed on a computer-running LabChart Pro software (version 8, AD Instruments, Australia). RR data were sampled at 1 kHz and filtered by a Mains filter to reduce electrical noise. One inspiration followed by expiration was considered as one respiratory cycle. The total number of respiratory cycles averaged for 5-minutes was taken as the resting RR in breaths/minute.

At the end of the 5-minutes data recording period, participants were asked to rate their discomfort due to positioning or instrumentation on a 0–10 (10 representing the extreme level of distraction/discomfort) scale which is very similar to the pain scale used in medical/surgical settings to record the perception of pain in patients. Ratings of 5 or above were taken as significant disturbance and the recording was repeated.

Resting spirometry was assessed using a Fitmate-Med PRO cardiopulmonary assessor (Cosmed, Rome, Italy) according to the American Thoracic Society (ATS) guidelines [26]. All measurements were recorded in the upright seated position using an antibacterial filter and a nose clip in place. Volume calibration was performed before each test using a 3L calibration syringe.

During the slow spirometry manouevre, participants took tidal breaths until a stable baseline was established at functional residual capacity (FRC), and then a maximal inhalation was followed by a complete exhalation at a sustained and steady flow rate.

During the forced spirometry manouevre, the participants took tidal breaths until the baseline was stabilized, a maximal breath was taken in and immediately exhaled forcefully. Exhalation was encouraged throughout until the end of expiration criteria were achieved or the participant terminated the test. The test was completed with forceful and maximal inspiration.

Vital capacity, V_T, FEV_1/FVC, FVC, PEFR, and MEF75, 50, 25 (Supplementary file 1; Table S1) were recorded.

Maximum BHT was measured using a respiratory belt transducer in the seated position with a nose clip in place [LabChart Pro (AD Instruments, Australia)]. The respiratory signals were inspected to prevent hyperventilation prior to BHT measurements. Inspiratory and expiratory BHT were measured in seconds and the maximum value of 3 similar trials at 5-minutes intervals was analyzed.

The physical activity level of the participants was assessed using the long form of the International Physical Activity Questionnaire (IPAQ) [27–29]. The long form of IPAQ has been translated into the Sinhala language and shows good test-retest reliability [30]. Data were processed and analyzed according to the IPAQ scoring guidelines [31]. The output from scoring the IPAQ (Total IPAQ score) was reported as a continuous variable in MET minutes a week; summation of the duration (minutes) and frequency (days) for all types of activities in all 4 domains.

Maximal oxygen consumption (VO_2max) was estimated indirectly by the 6-minute-walk test (6MWT), performed according to the ATS guidelines [32]. Baseline oxygen saturation (SPO_2), RR, blood pressure (BP), heart rate (HR), and level of exertion and dyspnoea (BORG scale) were measured before, immediately after, and 5-minutes after the 6MWT. The total distance walked was recorded as the six-minute-walk distance (6MWD) and presented as a percentage from the calculated predicted-6MWD [33] for each individual. Maximal oxygen consumption (VO_2max) was estimated using the equation below [34].

VO_2max (ml/kg/min) = 70.161 + (0.023 × 6MWD in meter) - (0.276 × weight in kilogram) – (6.79 × sex; male = 0, female = 1) – (0.193 × resting HR in beats per minute) – (0.191 × age in years).

2.3. Data analysis

Data was analyzed using SPSS-23 statistical software. The normality of the distribution of the data was tested with the Shapiro-Wilk test. Descriptive statistics were summarized as mean (SD), or median (IQR). Between-group comparisons were evaluated using the Independent sample *t*-test and Mann-Whitney U tests, and associations with Pearson or Spearman correlation.

3. Results

The socio-demographic characteristics of participants and meditation practice variables of LTMs are shown in Table 1. All meditators included in the present study were Theravada Buddhist practitioners of the same ethnicity, Sinhalese. The main meditation techniques practiced by included participants were Anapanasati, Vipassana, and body scan meditation.

The resting respiratory function parameters of the study participants are shown in Table 2.

The resting RR was significantly lower, and inspiratory BHT and PEFR were significantly higher in LTMs compared to controls. Other respiratory parameters were not significantly different between LTMs and NMs. The total IPAQ scores (Table 2, Supplementary file 2; Table S2), the RR during 6MWT, SPO_2, 6MWD, and the estimated VO_2max did not differ significantly between the 2 groups (Table 3).

The resting RR of LTMs showed a significant negative correlation with uninterrupted, continuous total lifetime meditation practice in years ($r = -0.444$, $p = 0.049$), and the average length of a meditation session per day ($r = -0.65$, $p = 0.002$). The LTMs who had a significantly longer duration of retreat participation had lower resting RR ($r = -0.522$, $p = 0.018$) and higher tidal volumes ($r = 0.474$, $p = 0.04$).

Table 1
Socio-demographic characteristics of LTMs and matched NMs and meditation practice variables of LTMs.

	LTMs (n = 20)	NMs (n = 20)	*P* value
Age (years)	45.75 (8.74)	45.25 (8.05)	.852
[a]Gender; n (%)			
Male	9/20 (45%)	9/20 (45%)	_
Female	11/20 (55%)	11/20 (55%)	_
Height (meters)	1.66 (0.09)	1.63 (0.09)	.339
Weight (kg)	65.27 (10.51)	62.83 (10.93)	.475
Body Mass Index (kg/m^2)	23.68 (2.23)	23.68 (3.28)	.997
[a]Educational level – Tertiary education (%)	14/20 (70%)	14/20 (70%)	–
[a]Educational level – Secondary education (%)	6/20 (30%)	6/20 (30%)	–
[a]Lifestyle factors - Non-vegetarian diet (%)	17/20 (85%)	18/20 (90%)	–
Meditation practice variables in LTMs			
(i). Total lifetime meditation practice experience (years)	12.8 (6.5)	–	–
(ii). Uninterrupted, continuous meditation practice experience (years)	10.15 (5.71)	–	–
(iii). Retreat participation experience (days)	207.9 (420.34)	–	–
(iv). Frequency of meditation practice (minutes per day)	91.25 (43.22)	–	–
(v). Frequency of meditation practice (days per week)	6.55 (0.83)	–	–
(vi). Self-reported length of a meditation session per day (minutes)	53.25 (16.96)	–	–

[a] Presented in (%); All other values; mean (SD); * significant at $p < 0.05$; Independent sample *t*-test.

Table 2
Resting RR, spirometry parameters, BHT, and physical activity level of study participants.

Parameter	LTMs (n = 20)	NMs (n = 20)	P value
Resting RR (breaths/min)	13.35 (1.9)	18.37 (2.31)	<.001**
Vital Capacity (l)	4.05 (0.99)	3.68 (0.94)	.228
Tidal Volume (l)	0.72 (0.76)[a]	0.8 (0.53)[a]	.818[b]
FVC (l)	3.81 (0.94)	3.47 (0.93)	.258
FEV_1 (l)	3.16 (0.84)	2.95 (0.72)	.403
FEV_1/FVC (%)	86.5 (10.75)[a]	87 (5)[a]	.946[b]
PEFR (l/s)	9.89 (2.49)	8.22 (2.28)	.033*
FEF25% -75% (l/s)	3.75 (1.58)	3.4 (0.92)	.404
MEF75% (l/s)	7.95 (2.22)	7.14 (1.7)	.207
MEF50% (l/s)	4.69 (2.16)[a]	4.1 (1.79)[a]	.409[b]
MEF25% (l/s)	1.75 (0.73)	1.58 (0.49)	.382
Calculated minute ventilation (MV) (l/min)	9.64 (9.04)[a]	18 (9.36)[a]	.028[b]*
Inspiratory BHT (seconds)	74 (29.84)	53.61 (26.83)	.038*
Expiratory BHT (seconds)	41.95 (21.66)	30.7 (18.19)	.083
Total IPAQ score	2707.5 (3746.25)[a]	3825 (3253)[a]	.219[b]

All other values, mean (SD); Independent sample *t*-test.
** Significant at $p < 0.001$; * significant at $p < 0.05$.
[a] Median (IQR),
[b] Mann Whitney *U* test significance.

Table 3
The 6MWD of the study participants and the change in respiratory parameters during 6MWT

Parameter	LTMs (n = 20)	NMs (n = 20)	P value
6MWD (meters)	577.25 (77.28)	569.95 (77.13)	.767
PREDICTED%_6MWD (%)	93.18 (9.57)	93.78 (13.15)	.871
ESTIMATED_MAXIMAL OXYGEN CONSUMPTION (VO_2max); (ml/kg/min)	41.84 (5.78)	40.77 (4.39)	.511
6MWT_PRE_RR (breaths/min)	17 (2)[a]	19 (4)[a]	.065
6MWT_PRE_ SPO_2 (%)	98 (1)[a]	98 (0)[a]	.202
6MWT_PRE_ BORG	1 (1)[a]	1.47 (1.02)[a]	.854
6MWT_POST_RR (breaths/min)	25.25 (4.87)	26.55 (3.12)	.321
6MWT_POST_ SPO_2 (%)	98 (1)[a]	98 (2)[a]	.458
6MWT_POST_ BORG	3 (1)[a]	3.16 (1.01)[a]	.045*
6MWT_RECOV_RR (breaths/min)	19.7 (4.24)	21.25 (2.79)	.18
6MWT_RECOV_ SPO_2 (%)	98 (1)[a]	98 (0)[a]	.376
6MWT_RECOV_ BORG	1 (1)[a]	2 (0.75)[a]	.027*

* Significant at $p < 0.05$.
Predicted%_6MWD = Actual 6MWD as a percentage of calculated predicted 6MWD.
[a] Median (IQR); Mann Whitney *U* test, All other values, mean (SD); Independent sample *t*-test.

4. Discussion

This is the first study in Sri Lanka to compare the respiratory function of healthy LTMs and NMs.

LTMs had significantly slower resting RR, higher PEFR, and more prolonged inspiratory BHT than NMs. Longer duration of meditation practice and retreat participation was associated with slower resting RRs and longer duration of retreat participation was associated with higher tidal volumes among LTMs. The two groups had similar physical activity (PA) scores and demonstrated similar respiratory function changes in response to submaximal exercise.

4.1. *Respiration at rest*

The RR at rest in a healthy individual is determined by active inspiration and passive expiration and is approximately 10–20 breaths per minute (BPM). Tidal breathing at rest is usually around 500 mL in an adult [35]. Controlled respiration around 6 BPM accompanied by an increase in V_T is known to improve ventilation efficiency by recruitment of alveoli and distension, reducing the alveolar dead space [35,36].

In the present study, LTMs had slower RRs, which has also been reported previously in LTMs practicing mindfulness meditation [20]. The respiratory rhythm is generated by the pre-Botzinger complex, a group of pacemaker neurons in the medulla [37–39], and is modified by inputs from the pontine pneumotaxic center, and vagal afferents from the airways and lungs [40]. During cognitive and emotional demands, respiratory rhythm is impacted by the inputs from suprapontine influences [41], shaping and adapting the breathing pattern to produce adequate alveolar ventilation with minimal cost of breathing [42]. Two studies [18,19] have previously described the possible mechanisms by which Anapanasati, a meditation form of achieving mindfulness, could affect respiratory regulation. They postulated that continued long-term practice adjusts and alters the set point of the bulbo-pontine respiratory complex setting up a new, much slower pattern of respiration. This could be a key reason for the observed slower resting RR in LTMs in the present study, as most of the LTMs included were experienced Anapanasati meditators.

4.2. *Controlled breathing*

The spontaneous RR can be changed during conscious control of breathing. During meditation, meditation practitioners of "pranayama" actively control and slow down their breathing [43] while "Anapanasati" meditators are only conscious of their breath. Body scan meditation involves neither voluntary control of breath nor being conscious of breath. The LTMs of the present study were all Theravada Buddhist practitioners, who practiced 3 meditation techniques, namely Anapanasati, Vipassana, and body scan meditation, which did not involve active control of breathing, and yet all had lower RRs compared to NMs.

The reported slower respiration in some meditation techniques which involves voluntary control of breathing during meditation (eg: pranayama, mantra-based meditation [44]) can be a result of a learning effect of this voluntarily controlled slower breathing over time. It has been found that both voluntary control of breathing and attention to spontaneous breathing modulates cortical activity [45,46]. Engagement in slow breathing during meditation has the potential to augment inherent, natural slow rhythm and activate a unique profile of neural networks to induce a functional state of "alert-relaxation" [45]. Findings of the studies on EEG (electroencephalogram) band components activity during meditation provide further granularity to understanding the impact of meditation on brain activity. A study by Park and Park, 2012 [47] found that certain meditation techniques involving voluntary control of breathing, such as paced breathing in Su-soku meditation, caused changes in the EEG, showing increased low-frequency and high-frequency alpha power and a decrease in theta power during meditation. These findings suggest that cortical activity changes that occur with meditation practice can be influenced by voluntary control of breathing during meditation. Therefore, integrating respiratory parameters with EEG measures can offer valuable insights to uncover potential relationships between respiratory function and changes in brain activity induced by the long-term practice of meditation.

The "relaxation response" could be another reason for the lower RRs in the LTMs [2,48,49]. It is also possible that meditation techniques that encourage diaphragmatic breathing which has been shown to facilitate slow respiration [35] could alter the regulation of respiration.

4.3. *Autonomic influence and hypometabolic state*

Respiration at slower rates is associated with increased vagal activation [43,50,51]. Parasympathetic dominance induced by regular practice of meditation could induce a hypometabolic state [2]. Hence, the observed slower RR at rest in LTMs could be due to heightened activation of the parasympathetic nervous system and down-regulated sympathetic activity, promoting a relaxed, stress-free resting state which developed over time with meditation practice. Future studies assessing autonomic function (in terms of cardiovascular reflex testing and heart-rate variability) in LTMs are warranted.

Minute ventilation (MV) is the total volume of air that enters the lungs per minute and is the product of RR and V_T. Therefore, with decreased RR, the V_T should be increased to maintain the MV. In our study, though LTMs had a lower RR, the V_T did not differ between LTMs and NMs, and the MV was significantly lower in LTMs than in matched NMs. A similar observation of decreased MV has been reported in experienced transcendental meditators during meditation [13]. This observation suggests that meditation induces a wakeful mental state accompanied by hypometabolism [2] with decreased metabolic rate and oxygen consumption, and therefore does not require high MV which would help to conserve energy.

4.4. Spirometry parameters

Spirometry is an effort-dependent objective measure of respiratory function that assesses airway obstruction and lung capacity. The main physiological factors that affect lung volumes and capacities include age, sex, height, weight, PA, and altitude [52]. Despite having comparable physiological parameters and similar efforts on spirometry, LTMs in the current study demonstrated significantly higher PEFR and better spirometry parameters than NMs. These findings are consistent with the Asian studies on experienced Anapanasati meditators [18,19] and Yoga and Pranayama practitioners [15–17,53]. Irrespective of the different meditation techniques and varied duration of practice, all above studies reported significantly higher FVC, FEV_1, PEFR [18,19], FEV_1/FVC [18], vital capacity, and V_T [16] in LTMs compared to NMs, though the difference in the practice duration makes difficult to distinguish state versus trait effects. Hence the wide heterogeneity in regard to the minimum duration of practice for selecting LTMs/experienced meditators appear to be the major drawback for the comparison of findings between studies.

In the present study, LTMs had higher vital capacity (both FVC and SVC) than NMs though not significant. It has been hypothesized that the increase in VC observed following a ten-week-long yoga meditation practice could be due to the efficient use of abdominal muscles and diaphragm muscles during yoga training [54]. None of the LTMs in the present study practiced yoga, and hence it is difficult to attribute the high VC in them to improved respiratory muscle function.

LTMs in our study also demonstrated a higher PEFR compared to NMs. The PEFR mainly reflects the caliber of large airways [55] and is determined by the dimensions of large intra and extra-thoracic airways, the force generated by the expiratory muscles; primarily abdominals, and the elastic properties of the lung [56]. It has also been found that psychosocial variables (PA, stress, mood) are strongly related to PEFR, with stress showing a negative correlation [57,58].

4.5. Breath-holding time

The BHT was higher in the LTMs of the present study.

During breath-holding, blood gases change with the build-up of $PaCO_2$ and/or decrease in PaO_2. The point where the build-up of these parameters causes the end of breath-holding is termed the 'physiological breaking point'. The diaphragm contracts involuntarily and the individual starts breathing again [59]. It has been described that breath-holding is easier at total lung capacity (TLC) than at functional residual capacity (FRC) and that individuals with higher vital capacities are able to hold their breath for a longer period, as with a larger lung volume it takes longer for the blood gases to reach a level that would signal the breaking point [60] and pulmonary stretch receptor afferent activity is delayed [61]. Respiration at slower rates in healthy [62], and in yoga practitioners [63] reported to be associated with reduced chemoreflex response to both hypoxic and hypercapnic states. Previous breath-holding experience or apnoea training can also prolong BHT by delaying the breaking point [64,65].

Therefore, it is possible that long-term practice of meditation with techniques that involve modulation of breathing such as slower RR, larger VC, and reduced chemoreceptor response to hypoxia and hypercapnia could be reasons for the observed prolonged BHTs in LTMs. The ability to hold their breath for a longer time and slower respiration would be beneficial to increase alveolar oxygenation.

4.6. Oxygen consumption

In this study, LTMs did not show a significantly better oxygen consumption response to submaximal exercise compared to NMs. It could be attributed to the observation that the two groups comprised healthy individuals, with comparable physique and PA profiles.

4.7. Association with meditation practice variables

LTMs of the present study with longer duration lifetime meditation practice had slower RRs similar to previous studies [20]. Further, we observed much slower RRs in LTMs with a higher average length of a meditation session per day. According to Chan and Woollacott [7], the average length of a meditation session per day could be a stronger measure of meditation expertise than lifetime measures. LTMs of the current study, with longer duration of retreat participation, had lower resting RR and higher V_T. Retreats are intensive meditation practices with concentrated periods of meditation for days, weeks, or months at a time in a more supportive environment away from distractions and obligations of ordinary day-to-day life [66]. It appears that those who practice meditation extensively and regularly for years show marked differences in physiological responses and enhanced ability to control their own physiology compared to NMs.

4.8. Limitations

This study has certain limitations. The sample size was modest due to the rigorous selection process of skilled LTMs. Regarding spirometry, small sample size and groups not prior-matched for BMI are limitations. It is possible that a larger sample might have revealed significant effects of long-term meditation on other respiratory parameters as well. Sub-analysis according to the meditation techniques was not possible due to the limited sample size. Another limitation is the absence of direct measurements of MV, oxygen consumption, and the time duration parameters of the respiratory cycle at rest. The emotional status of the participants which may have influenced the respiratory parameters during the assessment was not noted. Further, baseline information including meditation practice variables was self-reported which is a common limitation in meditation research [67]. Though meditation studies involve many confounding factors, the LTMs and controls in the current study were similar with respect to age, gender, culture of origin, PA, education level, and dietary habits which would have minimized such bias. Though PA is known to improve respiratory function, LTMs in our study did not demonstrate a higher PA level that could have positively influenced better respiratory function. As this study only included LTMs who practiced meditation that did not involve voluntary control over breathing during meditation, we could not present the reproducibility of respiratory function changes in LTMs practicing meditation techniques that involve voluntary control over breathing during meditation.

4.9. Conclusion and recommendations

This study advances meditation research in a number of ways and has several strengths. This is the first study to look at the respiratory function in a Sri Lankan cohort of LTMs compared to age-sex-matched NMs with similar PA. Years of meditation practice is the primary index used in most previous studies, which is only a crude measure of meditation proficiency in selecting LTMs. To overcome this limitation, we recruited skilled LTMs using a validated questionnaire tool [25] which would have contributed to the significance of the findings, even with limited sample size. The use of respiratory tracings recorded by a respiratory belt for RR and BHT measurements produced valid results.

The findings revealed significant positive correlations between respiratory parameters and effect modifiers (total lifetime meditation practice experience, average length of a meditation session per day, and retreat experience). The findings are encouraging in that they suggest certain long-lasting changes in the respiratory function of healthy individuals with long-term meditation practice and hold promise for further beneficial change with continued practice. Whether these findings are generalizable to less healthy individuals with compromised respiratory function awaits future research. A decrease in PEFR over 6 months is associated with mortality in idiopathic pulmonary fibrosis (IPF) patients [68] and optimal PEFR is crucial for inhalation therapy in Chronic Obstructive Pulmonary disease (COPD) patients [69]. Therefore, meditation interventions have significant potential as beneficial and non-invasive adjuvant therapy for patients with chronic pulmonary conditions such as IPF and COPD. Slower breathing reduces the sympathoexcitation in COPD [70]. Meditation techniques that set up slower breathing with practice over time may modulate the sympathovagal balance in COPD patients, which was found to be markedly altered in these patients. Future trials with meditation interventions in respiratory disease will investigate the applicability of these results. Future studies are recommended to explore the influence of meditation on neural and chemical regulation of breathing in optimizing breathing efficiency and oxygen utilization. There is also, a dire need for studying the impact of long-term meditation practice on other psychophysiological variables (cardiovascular, autonomic, cognitive function, and psychology) in healthy individuals besides respiratory function and their associations with respiratory function to understand the full underlying mechanism of action.

Ethics statement

Ethical approval for this study was obtained from the Ethics Review Committee, Faculty of Medicine, University of Colombo, Sri Lanka (EC-19-117). The study was conducted following the written informed consent of the study participants.

Author contribution statement

Karunarathne LJU: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Amarasiri WADL; Fernando ADA: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data included in article/supp. Material/referenced in article.

Additional information

Supplementary content related to this article has been published online at [URL].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e18585.

Abbreviations

LTMs	Long-term meditators
NMs	Non-meditators
RR	Respiratory rate
FEV_1	Forced expiratory volume in 1 second
FVC	Forced vital capacity
SVC	Slow vital capacity
PEFR	Peak expiratory flow rate
BHT	Breath-holding time
ATS	American Thoracic Society
FRC	Functional Residual Capacity
TLC	Total Lung Capacity
V_T	Tidal Volume
6MWT	Six-minute-walk test
6MWD	Six-minute-walk distance
VO_2max	Maximal oxygen consumption
ATS	American Thoracic Society
IQR	Interquartile range
EEG	Electroencephalogram

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