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TEAS Enhances Lung Function and Accelerates Recovery in Lung Cancer Patients Undergoing Thoracoscopic Surgery

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Abstract

This study aimed to assess the effectiveness of transcutaneous electrical acupoint stimulation (TEAS) in mitigating oxidative stress caused by one-lung ventilation, as well as its impact on pulmonary function and postoperative recovery quality among lung cancer patients. A total of 80 patients (n = 80) were randomly allocated to either the sham group or the TEAS group. In the TEAS group, stimulation was applied to bilateral Feishu (BL13), Zusanli (ST36), and Hegu (LI4) points starting 30 minutes prior to anesthesia induction and lasting throughout the surgical procedure. The sham group received placement at identical acupoints but without any electrical current. Lung function parameters, including PaO2/FiO2, intrapulmonary shunt ratio (Qs/Qt), alveolar-arterial oxygen gradient (A-aDO2), and respiratory index (RI), were assessed at baseline before one-lung ventilation (T0), 30 min into one-lung ventilation (T1), 1 h into one-lung ventilation (T2), and 10 min after returning to two-lung ventilation (T3). Oxidative stress markers, specifically malondialdehyde (MDA) levels and superoxide dismutase (SOD) activity, were measured at the same time points (T0, T1, T2, T3). Additional endpoints encompassed the time to thoracic drainage tube removal, intensive care unit (ICU) stay duration, postoperative hospital length of stay, rates of pulmonary complications after surgery, and Quality of Recovery-15 (QoR-15) scores on postoperative days 1 and 2.

Compared to the sham group, TEAS led to a notable rise in PaO2/FiO2 values at T1 and T2, accompanied by significant reductions in Qs/Qt, A-aDO2, and RI from T1 through T3 ($P < 0.05$). Additionally, MDA concentrations were markedly lowered while SOD activity was enhanced at T2 and T3 ($P < 0.05$). TEAS further reduced the duration of postoperative ICU and overall hospital stays, with substantially elevated QoR-15 scores on days 1 and 2 after surgery ($P < 0.05$). TEAS appears to attenuate oxidative damage to the lungs associated with one-lung ventilation, thereby preserving respiratory function and promoting faster postoperative recovery in lung cancer patients.

Keywords: Transcutaneous electrical acupoint stimulation, One-lung ventilation, Oxidative stress, Pulmonary function

Introduction

One-lung ventilation (OLV) has facilitated more advanced thoracic procedures and has become essential with the rise of minimally invasive approaches. However, this non-physiological ventilation strategy is recognized as a contributor to acute lung injury (ALI) and linked to higher risks of pulmonary complications following surgery [1]. Upon resumption of two-lung ventilation, the previously collapsed lung undergoes re-expansion and re-oxygenation, resulting in hypoxia-reoxygenation damage akin to ischemia-reperfusion, characterized by elevated malondialdehyde (MDA) and reactive oxygen species (ROS) generation [2]. The intensity of oxidative stress correlates directly with OLV duration and inversely with PaO2/FiO2 ratios [3]. Prolonged OLV exceeding 1 h may trigger cardiovascular issues via oxidative mechanisms [4], and such stress is central to the pathogenesis of ALI and acute respiratory distress syndrome (ARDS) [5].

Acupuncture represents a key component of traditional Chinese medicine, extensively practiced in China, Japan, and South Korea. Modern forms include manual

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acupuncture, electroacupuncture, and transcutaneous electrical acupoint stimulation (TEAS). Prior research has demonstrated that acupuncture can safeguard against myocardial ischemia-reperfusion damage by suppressing oxidative stress in animal models [6]. Other investigations have indicated that electroacupuncture mitigates cerebral ischemia-reperfusion injury through anti-inflammatory and antioxidant effects [7, 8]. Several preclinical studies have also revealed that electroacupuncture reduces pulmonary damage from limb ischemia-reperfusion [9–11]. TEAS, a non-invasive technique integrating traditional acupoint stimulation with transcutaneous electrical nerve stimulation (TENS), has proven effective for intraoperative sedation and postoperative pain management [12], while also lowering inflammatory markers and shortening hospital stays [13]. Despite these findings, the potential of TEAS to enhance lung function and postoperative recovery by modulating oxidative stress during OLV remains uncertain.
Thus, the present investigation was designed to examine the influence of TEAS on oxidative pulmonary injury, respiratory performance, and recovery quality in lung cancer patients subjected to thoracoscopic surgery under one-lung ventilation.

Materials and Methods

Study design
This was a single-blind, randomized controlled trial featuring two parallel arms. The study received approval from the Ethics Committee for Clinical Trials at Hebei General Hospital, China (approval number: 2019-48; approval date: 29/04/2019). Every participant (or their legal representative) provided written informed consent. The trial was registered under the number ChiCTR-2,000,038,243 (initial registration date: 15/09/2020).

Sample size
Sample size calculation was performed using GPower software, based on PaO_2/FiO_2 values obtained from a preliminary pilot study. With M1 = 169.25, M2 = 137.15, SD1 = 45.27, SD2 = 38.04, $\alpha = 0.05$, and power = 80%, a minimum of 28 patients per group was required. Accounting for a potential 20% dropout rate, at least 34 participants were needed in each arm. Ultimately, 85 patients were enrolled in the trial.

Participants
A total of 85 lung cancer patients scheduled for thoracoscopic lobectomy were included **(Figure 1)**. Inclusion criteria comprised American Society of Anesthesiologists (ASA) physical status II-III, age range of 30–65 years, and sufficient comprehension and cognitive abilities. Patients were excluded if they met any of the following: (1) preoperative diagnosis of moderate to severe respiratory impairment; (2) forced expiratory volume in 1 s (FEV1) < 50%, body temperature > 37.5ºC, or recent use of antioxidant medications; (3) presence of a cardiac pacemaker; (4) prior exposure to acupoint stimulation or acupuncture therapy; (5) infection or skin damage at the intended stimulation sites.

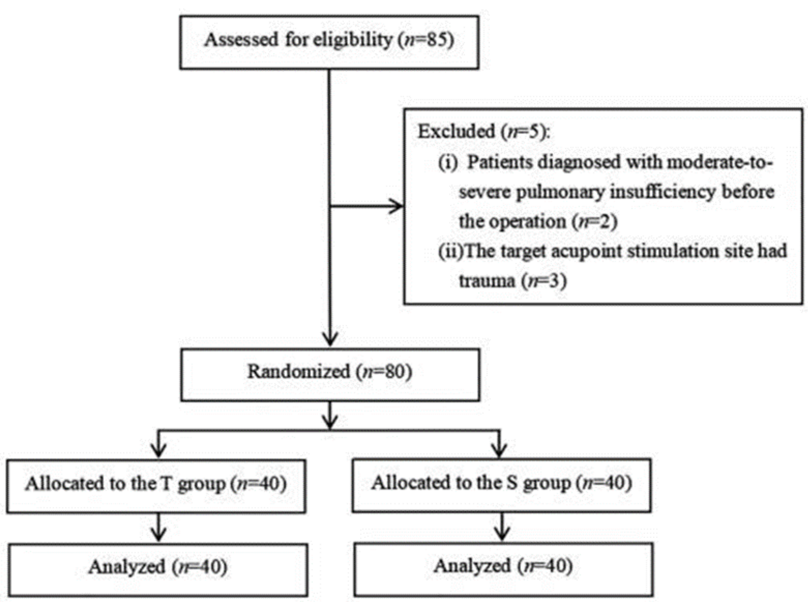

Figure 1. Study flow diagram of participants in the randomized trial

Randomization and blinding

An independent researcher (B.W) assigned patients to either the TEAS group or the sham group at a 1:1 ratio using a computer-generated randomization sequence. Enrollment was handled by M.Z, while intervention allocation was managed by two additional researchers (M.N.L and J.L.L). Allocation concealment was ensured through sequentially numbered, opaque, sealed envelopes. Attending anesthesiologists, surgeons, outcome assessors, and patients remained blinded to group assignment. Patients were informed that they might experience varying sensations—ranging from intense or mild tingling to none—during the procedure. They were also told that only one specific TEAS parameter was under investigation, making it impossible to differentiate between active and sham stimulation [14].

Anesthesia and surgery

Patients fasted for 6 h and abstained from fluids for 2 h prior to surgery. Standard monitoring included electrocardiogram, peripheral oxygen saturation (SpO2), bispectral index (BIS), heart rate (HR), and mean arterial pressure (MAP). Radial artery cannulation under ultrasound guidance and local anesthesia was performed for invasive blood pressure monitoring and arterial blood sampling.

Preoxygenation with 100% oxygen was administered for at least 3 min before induction. Anesthesia induction involved intravenous sufentanil 0.3 µg/kg, midazolam 0.05 mg/kg, etomidate 0.3 mg/kg, and rocuronium 1.0 mg/kg. An appropriately sized double-lumen tube (DLT) was placed in the left or right main bronchus, with correct positioning verified by auscultation and fiberoptic bronchoscopy. Ventilation was conducted in pressure-controlled volume-guaranteed (PCV-VG) mode for lung protection. Two-lung ventilation settings included tidal volume (VT) of 6-8 mL/kg, respiratory rate of 12 to 15 breaths/minute, inspiratory:expiratory (I:E) ratio of 1:2, and fraction of inspired oxygen (FiO2) of 100%. During one-lung ventilation, parameters were adjusted to VT of 5-6 mL/kg, FiO2 of 80%, positive end-expiratory pressure (PEEP) of 5 cmH2O, with end-tidal CO2 maintained between 35 and 45 mmHg. If arterial saturation (SaO2) fell below 92%, FiO2 was temporarily raised to 100%, DLT position was rechecked, and lung recruitment maneuvers were applied. Anesthesia maintenance utilized sevoflurane, remifentanil, and rocuronium infusions to keep BIS values between 40 and 60. At procedure completion, the collapsed lung was re-expanded using sustained positive pressure of 20 to 25 cmH2O. Hypotension (MAP < 30% of baseline) was treated with 6 mg ephedrine hydrochloride, while hypertension (MAP > 120%) was managed with urapidil hydrochloride (0.10–0.15 mg/kg). Bradycardia (< 50 beats/min) prompted administration of 0.2 mg atropine sulfate intravenously. All anesthetic agents were stopped at the end of surgery. Perioperative intravenous fluids followed a standardized protocol. Postoperatively, patients were initially observed in the postanesthesia care unit (PACU) before transfer to the thoracic surgery intensive care unit (ICU) under anesthesiologist supervision for further management.

Intervention

Prior to anesthesia induction, individuals in the TEAS group underwent 30 min of transcutaneous electrical acupoint stimulation applied bilaterally at Feishu (BL13, situated approximately 5 cm lateral to the spinous process of the third thoracic vertebra), Zusanli (ST36, positioned 5 mm below and lateral to the anterior tibial tubercle), and Hegu (LI4, located at the midpoint on the radial aspect of the second metacarpal bone, between the first and second metacarpals on the dorsal hand) using an SDZ-II device (Suzhou Medical Appliances Co. Ltd, Suzhou, China). Stimulation was sustained throughout the entire surgical procedure.

Acupoint selection followed standard traditional locations. The device was calibrated before each session. Adhesive electrodes were affixed to bilateral BL13, ST36, and LI4 sites. A dense-disperse (2/100 Hz) waveform was employed continuously, with current intensity adjusted between 5 and 15 mA. In the sham group, electrodes were attached identically, but no current was delivered. Patient blinding was maintained throughout. All procedures, whether active or sham, were carried out by one dedicated researcher, while data acquisition was handled by a separate investigator blinded to group assignment.

Measurements

The primary endpoint was the PaO2/FiO2 ratio. Secondary outcomes comprised (1) indicators of pulmonary function and oxidative stress: intrapulmonary shunt fraction (Qs/Qt), respiratory index (RI), alveolar-arterial oxygen difference (A-aDO2), malondialdehyde (MDA), and superoxide dismutase (SOD); (2) additional clinical variables: mean arterial pressure (MAP), heart rate (HR), hemoglobin (Hb), pH, PaCO2, time to thoracic drain removal, intensive care unit stay duration, postoperative hospital length of stay, Quality of Recovery-15 (QoR-15) questionnaire scores [15], and rates of postoperative pulmonary complications. Pulmonary complications were defined as pleural effusion or atelectasis [16].

Arterial blood gas sampling was conducted at baseline prior to one-lung ventilation (T0), 30 min into one-lung ventilation (T1), 1 h into one-lung ventilation (T2), and 10 min following resumption of two-lung ventilation (T3) to derive PaO2/FiO2, A-aDO2, RI, and Qs/Qt values. Central venous blood from the internal jugular vein was obtained at the same time points (T0, T1, T2, T3) for assessment of SOD activity via the xanthine oxidase technique and MDA concentration using the thiobarbituric acid reaction (kits from Nanjing Ji Sheng Medical Technology Co, Ltd, Nanjing, China), in accordance with established protocols [17, 18].

The following formulas were applied to compute these indices:

$$\mathrm{Q_s/Q_t = (PA - aDO_2 \times 0.0031) \div (PA - aDO_2 \times 0.0031 + 5)} \quad (1)$$

whereby $\mathrm{PA\text{-}aDO_2 = [FiO_2 \times (P_B\text{-}P_{H2O})]\text{-}(PaCO_2/}R\mathrm{)\text{-}PaO_2}$,

$$\mathrm{RI = PA - aDO_2/PaO_2} \quad (2)$$

The alveolar-arterial oxygen gradient is denoted as PA-aDO2; atmospheric pressure is represented by PB (760 mmHg); water vapor pressure is indicated by PH2O (47 mmHg); and the respiratory quotient is given as R (0.8).

Statistical analysis

Data processing and evaluations were performed utilizing SPSS software version 26.0 (IBM Corporation, Armonk, New York, United States). Numerical continuous outcomes were expressed as means accompanied by standard deviations, whereas categorical outcomes were displayed as frequencies or percentages. For continuous outcomes confirmed to follow a normal distribution through the Kolmogorov-Smirnov test, comparisons employed the independent samples Student's t-test. Categorical outcomes underwent examination via the Chi-square test. Variations across successive measurement points for identical parameters were assessed by applying repeated measures analysis of variance (RM-ANOVA). A two-tailed P value below 0.05 was deemed indicative of statistical significance.

Results and Discussion

Baseline patient demographics and perioperative features

This investigation took place over the period spanning September 2020 through September 2021. An initial screening involved 85 individuals, from which 5 were removed owing to the fulfillment of exclusion conditions. Specifically, two cases involved preexisting moderate-to-severe respiratory compromise before the procedure, while three exhibited injury at the designated sites for acupoint application. In the end, 80 cases proceeded to randomization, with equal distribution of 40 to the control (sham) arm and 40 to the active TEAS arm. The participant progression schematic appears in **Figure 1**. No meaningful disparities emerged in demographic profiles or operative details across the arms ($P > 0.05$) **(Table 1)**.

Table 1. Baseline demographics and perioperative details

Variable	TEAS Group (n = 40)	Sham Group (n = 40)	P-value
Age (years)	56.15 ± 9.57	56.58 ± 9.53	0.832△
Gender (Male/Female)	15/25	19/21	0.366&
Body Mass Index (kg/m²)	24.86 ± 2.33	25.21 ± 2.50	0.445△
Smoking status (No/Current)	34/6	35/5	0.745&
ASA classification (II/III)	33/7	28/12	0.189&
Comorbidities			
– Hypertension	15 (37.5%)	13 (32.5%)	0.639&
– Coronary heart disease	3 (7.5%)	2 (5%)	0.644&
– Diabetes	2 (5%)	5 (12.5%)	0.235&

Preoperative blood gas			
– pH	7.40 ± 0.12	7.40 ± 0.02	0.737△
– PaO_2 (mmHg)	88.08 ± 12.40	84.25 ± 15.06	0.990△
– $PaCO_2$ (mmHg)	41.47 ± 3.07	41.39 ± 2.90	0.979△
– Hemoglobin (g/L)	137.13 ± 14.47	137.13 ± 15.96	0.719△
Preoperative pulmonary function			
– FEV_1 (L)	2.66 ± 0.46	2.78 ± 0.46	0.251△
– FVC (L)	3.29 ± 0.54	3.44 ± 0.57	0.246△
– FEV_1/FVC (%)	80.53 ± 3.52	80.72 ± 3.31	0.799△
Preoperative cardiac function			
– LVEF (%)	64.75 ± 4.11	65.40 ± 4.74	0.385△
Type of surgery			
– Lobectomy	28 (70.0%)	30 (75.0%)	0.692&
– Wedge resection	8 (20.0%)	8 (20.0%)	
– Segmentectomy	4 (10.0%)	2 (5.0%)	
Operative site (Left/Right)	14/26	13/27	0.813&
Operation duration (min)	140.75 ± 47.21	153.50 ± 53.32	0.261△
Anesthesia duration (min)	182.88 ± 46.20	196.38 ± 52.78	0.227△
One-lung ventilation time (min)	120.38 ± 45.64	133.25 ± 50.17	0.234△
Intraoperative fluid volume (L)	1.32 ± 0.20	1.34 ± 0.16	0.642△
Intraoperative urine output (L)	0.35 ± 0.03	0.35 ± 0.02	0.973△

Outcomes are displayed as means ± standard deviations or case numbers. △Student's t-test, &Chi-square test. ASA: American Society of Anesthesiologists classification; BMI: body mass index (derived from weight in kilograms over height in meters squared); FEV1: forced expiratory volume during the first second; FVC: forced vital capacity; LVEF: left ventricular ejection fraction; TEAS: transcutaneous electrical acupoint stimulation.

Variations in hemodynamic stability, arterial blood gases, and respiratory performance

Inter-arm comparisons revealed no noteworthy variances in heart rate (HR), mean arterial pressure (MAP), pH levels, hemoglobin concentrations (Hb), or partial pressure of carbon dioxide in arterial blood (PaCO2) ($P > 0.05$). Prior to initiating one-lung ventilation (T0), values for PaO2/FiO2, intrapulmonary shunt fraction (Qs/Qt), alveolar-arterial oxygen gradient (A-aDO2), and respiratory index (RI) exhibited comparability between arms ($P > 0.05$). Within each arm, PaO2/FiO2 demonstrated a clear decline across T1 to T3 relative to baseline T0 ($P < 0.05$). Conversely, elevations were evident in Qs/Qt, A-aDO2, and RI over the interval from T1 to T3 in relation to T0 ($P < 0.05$). In contrast to the sham arm, application of TEAS yielded markedly higher PaO2/FiO2 readings specifically at T1 and T2 ($P < 0.001$). Furthermore, the TEAS arm displayed pronounced attenuations in Qs/Qt, A-aDO2, and RI levels spanning T1 to T3 ($P < 0.05$) **(Table 2)**.

Table 2. Perioperative hemodynamics, arterial gases, and respiratory parameters

Parameter	Sham Group (n = 40)	TEAS Group (n = 40)	P-value
Heart Rate (beats/min)			
– T0	74.00 ± 10.12	76.03 ± 13.40	0.448△
– T1	71.85 ± 8.76	72.10 ± 9.34	0.902△
– T2	68.97 ± 8.06	70.43 ± 10.12	0.481△
– T3	71.79 ± 9.68	72.75 ± 11.13	0.741△
Mean Arterial Pressure (mmHg)			
– T0	98.38 ± 10.28	99.33 ± 9.16	0.664△
– T1	92.78 ± 7.35	93.28 ± 5.67	0.734△

– T2	92.80 ± 7.39	94.10 ± 6.23	0.398△
– T3	94.48 ± 7.81	95.23 ± 6.50	0.642△
Hemoglobin (mg/L)			
– T0	136.03 ± 14.50	135.51 ± 13.40	0.868△
– T1	135.48 ± 13.90	134.78 ± 12.61	0.815△
– T2	135.08 ± 13.50	134.28 ± 12.35	0.784△
– T3	134.40 ± 12.87	133.66 ± 11.71	0.787△
pH			
– T0	7.42 ± 0.04	7.41 ± 0.04	0.317△
– T1	7.41 ± 0.05	7.40 ± 0.04	0.228△
– T2	7.40 ± 0.05	7.40 ± 0.04	0.908△
– T3	7.38 ± 0.04	7.38 ± 0.04	0.956△
$PaCO_2$ (mmHg)			
– T0	40.79 ± 5.68	40.58 ± 4.91	0.862△
– T1	41.95 ± 5.51	41.10 ± 5.35	0.486△
– T2	41.83 ± 5.95	40.23 ± 4.41	0.176△
– T3	42.40 ± 5.12	42.90 ± 4.42	0.643△
PaO_2/FiO_2 (mmHg)			
– T0	297.75 ± 66.89	304.32 ± 52.42	0.626△
– T1	105.15 ± 30.70*†	180.43 ± 47.51*#†	0.001△
– T2	128.18 ± 47.75*†	184.93 ± 33.93*#†	<0.001△
– T3	221.53 ± 58.53*†	245.13 ± 48.84*†	0.056△
Qs/Qt (%)			
– T0	18.34 ± 2.68	18.10 ± 2.23	0.341△
– T1	25.60 ± 1.09*†	22.94 ± 1.73*#†	<0.001△
– T2	24.79 ± 1.70*†	22.83 ± 1.25*#†	<0.001△
– T3	21.32 ± 2.19*†	20.39 ± 1.95*#†	0.026△
$A\text{-}aDO_2$ (mmHg)			
– T0	364.26 ± 65.63	357.95 ± 53.83	0.596△
– T1	555.41 ± 31.38*†	481.20 ± 46.80*#†	<0.001△
– T2	532.54 ± 47.61*†	477.79 ± 33.30*#†	<0.001△
– T3	438.47 ± 57.01*†	412.25 ± 49.77*#†	0.022△
Respiratory Index (RI)			
– T0	1.36 ± 0.63	1.25 ± 0.43	0.353△
– T1	5.78 ± 1.81*†	2.94 ± 1.11*#†	<0.001△
– T2	4.90 ± 2.27*†	2.69 ± 0.62*#†	<0.001△
– T3	2.24 ± 1.08*†	1.81 ± 0.62*#†	0.023△

Outcomes are reported as means ± standard deviations. $P < 0.05$ relative to T0; $P < 0.05$ relative to sham arm. △Student's t-test, †RM-ANOVA. HR: heart rate; MAP: mean arterial pressure; PaCO2: arterial carbon dioxide partial pressure; A-aDO2: alveolar-arterial oxygen difference; RI: respiratory index; Qs/Qt: shunt fraction within the lungs; TEAS: transcutaneous electrical acupoint stimulation; RM-ANOVA: repeated measures analysis of variance. T0: prior to one-lung ventilation; T1: 30 min following one-lung ventilation onset; T2: 1 h following one-lung ventilation onset; T3: 10 min after restoration of two-lung ventilation.

Levels of MDA in serum and activity of SOD

At baseline (T0) and T1, no meaningful variations existed in MDA concentrations or SOD activity across the groups ($P > 0.05$). From T1 to T3, both groups showed elevated MDA values compared to T0, alongside decreased SOD activity at T2 and T3 ($P < 0.05$). During T2 and T3, the TEAS group exhibited notably lower serum MDA contents and higher SOD activity relative to the sham group ($P < 0.05$) **(Table 3)**.

Table 3. Changes in MDA level and SOD activity

Parameter	Sham Group (n = 40)	TEAS Group (n = 40)	P-value
Malondialdehyde (MDA, nmol/mL)			
– T0	4.46 ± 0.61	4.39 ± 0.63	0.584△
– T1	5.01 ± 0.35*†	4.94 ± 0.74*†	0.584△
– T2	5.66 ± 0.81*†	5.27 ± 0.83*#†	0.036△
– T3	7.10 ± 0.49*†	6.21 ± 0.89*#†	<0.001△
Superoxide Dismutase (SOD, U/mL)			
– T0	464.51 ± 30.90	463.26 ± 26.98	0.848△
– T1	457.76 ± 22.19	458.01 ± 18.86	0.957△
– T2	412.80 ± 13.50*†	423.80 ± 16.85*#†	0.002△
– T3	387.22 ± 24.35*†	405.79 ± 27.25*#†	0.002△

Data are expressed as mean ± standard deviation. P < 0.05 versus T0; P < 0.05 versus sham group. △Student's t-test, †RM-ANOVA. MDA: malondialdehyde; SOD: superoxide dismutase; TEAS: transcutaneous electrical acupoint stimulation; RM-ANOVA: repeated measures analysis of variance. T0: before one-lung ventilation; T1: 30 min after one-lung ventilation; T2: 1 h after one-lung ventilation; T3: 10 min after resuming two-lung ventilation.

Additional clinical outcomes

The groups displayed comparable results regarding thoracic drainage tube removal duration, as well as occurrence rates of pleural effusion and lung collapse (P > 0.05). However, patients receiving TEAS had considerably reduced postoperative stays in the ICU and overall hospital duration (P < 0.05). QoR-15 scores on the first and second days post-operation were markedly elevated in the TEAS cohort versus the sham cohort (P < 0.05) **(Table 4)**.

Table 4. Other clinical endpoints

Outcome	TEAS Group (n = 40)	Sham Group (n = 40)	P-value
Pleural effusion	11 (27.5%)	13 (32.5%)	0.626&
Atelectasis	2 (5%)	7 (17.5%)	0.157&
ICU stay duration (hours)	21.03 ± 6.92*	27.93 ± 12.42	0.003△
Thoracic drainage tube removal time (days)	3.44 ± 1.31	3.29 ± 1.21	0.597△
Postoperative hospital stay (days)	5.76 ± 1.35*	6.45 ± 1.66	0.046△
QoR-15 score on postoperative day 1	114.33 ± 4.55*	111.70 ± 3.00	0.003△
QoR-15 score on postoperative day 2	130.05 ± 3.88*	126.85 ± 4.25	0.001△

Data are expressed as mean ± standard deviation or number of patients. P < 0.05 versus the sham group. △Student's t-test, &Chi-square test. ICU: intensive care unit; QoR-15: Quality of Recovery-15; TEAS: transcutaneous electrical acupoint stimulation.

Safety profile

TEAS might cause lingering sensations from stimulation or temporary skin insensitivity. All such incidents were planned for documentation. Severe or urgent issues would prompt immediate trial withdrawal and medical intervention, with mandatory reporting to the ethics body. In this investigation, no such incidents occurred.

The present randomized trial indicated that TEAS application mitigated oxidative stress associated with one-lung ventilation (OLV) among individuals with lung cancer, resulting in better oxygenation parameters and lung diffusion capabilities. Moreover, it led to briefer ICU and hospital durations post-surgery, alongside superior QoR-15 ratings. Such outcomes highlight potential advantages of incorporating TEAS in OLV for thoracic operations in lung cancer cases.

OLV represents a routine approach in thoracic anesthesia to secure airways, blocking transfer of fluids or blood from the surgical side while providing unobstructed visibility for procedures. Yet, combining OLV with lung resection introduces risks from elements like ventilation-related lung damage (VILI), low-oxygen vasoconstriction in lungs (HPV), reperfusion after ischemia, and operative injury, causing structural and molecular harm to lung tissue. Extensive prior research has pinpointed oxidative stress as a primary driver of lung damage in OLV scenarios during chest surgery [19, 20]. Hence, strategies to curb oxidative stress hold promise for lowering post-surgical lung issues and optimizing recovery.

TEAS, a contemporary acupuncture modality, applies targeted low-frequency electrical impulses via skin electrodes, mimicking electroacupuncture benefits. Animal studies have implied that electroacupuncture counters lung oxidative harm and inflammation by limiting p38 activation and caspase-3 pathways [21]. TEAS offers advantages over needle-based electroacupuncture, including reduced discomfort, trauma, and infection risks. Various reports confirm that acupoint activation substantially boosts respiratory performance and patient well-being [22–24]. The BL13 (Feishu) point traditionally aids pulmonary conditions, addressing symptoms like coughing, breathing difficulties, and thoracic discomfort [25, 26]. Lung innervation involves T1-T5 segments, aligning BL13 with T3. Earlier findings showed that electroacupuncture at ST16 and BL13 lessens inflammatory responses after lung cancer surgery in seniors, cutting complication risks [27]. Separate work demonstrated protection from remote ischemia-reperfusion lung effects via cytokine and oxidative suppression using these points [28]. Further data indicated that preemptive electroacupuncture at LI4 (Hegu) eases endotoxin-triggered lung distress by influencing PPARγ/NF-κB signals [29]. Thus, BL13, LI4, and ST36 were designated as intervention sites here.

Mechanisms of lung injury during OLV

In the course of one-lung ventilation, the non-ventilated lung experiences alveolar collapse and a roughly 50% reduction in blood flow attributable to hypoxic pulmonary vasoconstriction (HPV) and gravitational effects, resulting in direct vascular damage and heightened reactive oxygen species (ROS) generation [30, 31]. Earlier work indicated that suppressing ROS generation supports HPV function, whereas reduced SOD activity intensifies oxidative stress and diminishes HPV efficacy [32]. Additionally, circulating leukocytes and activated resident microglia contribute to elevated oxygen free radical production during ischemia-reperfusion phases, triggering cellular necrosis, amplified inflammatory cascades, and excessive release of proinflammatory cytokines, including IL-1, IL-6, IL-8, and TNF-α [33, 34]. Consequently, both oxidative damage and inflammation can harm healthy tissue. Hypoxia-related cellular injury follows a two-phase pattern: initial onset during oxygen deprivation, followed by worsening upon reoxygenation. Research has established that massive free radical release causes reoxygenation injury in lungs following thoracic procedures [35]. Aligning with prior reports, our data revealed substantial rises in serum MDA concentrations, notable drops in SOD activity during OLV relative to baseline, and elevated shunt fractions, implying that oxidative stress might compromise HPV's protective role [32, 36]. Supporting this, another investigation reported elevated 8-iso-PGF2α, nitrite/nitrate levels, and hydrogen peroxide in blood and exhaled condensates during OLV [37], reinforcing evidence of oxidative pulmonary damage in lobectomy patients. Here, the TEAS cohort displayed markedly lower MDA values and higher SOD activity, suggesting that TEAS modulates oxidative stress in thoracic surgical settings.

Assessment of pulmonary function

The PaO2/FiO2 ratio serves as a standard measure for evaluating gas exchange and oxygenation, while also acting as a key criterion for ARDS diagnosis. OLV often induces ventilation-perfusion mismatch, leading to greater intrapulmonary shunting (Qs/Qt) and lower arterial oxygen levels [38]. Parameters such as alveolar-arterial oxygen difference (A-aDO2) and respiratory index (RI) indicate diffusion capacity and correlate positively with injury severity [39]. Accordingly, this trial assessed TEAS lung-protective effects via PaO2/FiO2, Qs/Qt, A-aDO2, and RI. Prior evidence notes that lung resection partially disrupts ventilation-to-perfusion ratios, contributing to hypoxemia and impaired respiratory performance [39, 40]. Consistent with this, both groups in our trial showed rises in Qs/Qt, A-aDO2, and RI alongside declines in PaO2/FiO2 during OLV, confirming functional impairment from the technique. However, the TEAS group achieved better PaO2/FiO2 at T1 and T2, with reduced Qs/Qt, A-aDO2, and RI across T1 to T3, indicating that TEAS alleviates ventilation-perfusion disparities and enhances oxygenation and diffusion. Existing literature supports these observations by demonstrating TEAS-related gains in PaO2 and reductions in A-aDO2 during OLV [41, 42]. Other reports link pulmonary improvements to control of oxidative injury [43, 44]. Additionally, work by Pen *et al*. proposed that electroacupuncture enhances regional circulation through balancing endothelial vasoactive factors [45]. Taken together, our results point to oxidative stress suppression as a core pathway by which TEAS preserves lung function during OLV in lung cancer cases.

Secondary outcomes and recovery

Rates of pleural effusion and atelectasis showed no intergroup differences. By contrast, postoperative ICU and total hospital durations were substantially shorter in the TEAS arm, likely linked to lessened oxidative burden [46]. The QoR-15 questionnaire reliably gauges postoperative recovery quality and is frequently applied in trials. In this work, TEAS patients recorded higher QoR-15 scores on days 1 and 2 after surgery, reflecting superior recovery.

Study limitations

Key constraints include the modest sample size, which introduces potential sampling bias and necessitates validation in larger cohorts. Additional investigations should examine alternative protective pathways of TEAS.

Conclusion

In summary, TEAS appears capable of lessening oxidative pulmonary damage during OLV, thereby safeguarding respiratory function and accelerating early postoperative recovery in lung cancer patients.

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