Technology to enhance physical rehabilitation of critically ill patients

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Background: **Neuromuscular complications after critical illness are common and can be severe and persistent. To ameliorate complications, there is growing interest in starting physical medicine and rehabilitation therapy immediately after physiologic stabilization. The introduction of physical medicine and rehabilitation-related technology into the intensive care unit may help facilitate delivery of this therapy.**

Discussion: **Neuromuscular electrical stimulation therapy creates passive contraction of muscles through low-voltage electrical impulses delivered through skin electrodes placed over target muscles. Although neuromuscular electrical stimulation has not been studied in patients with acute critical illness, published guidelines based on available evidence suggest that neuromuscular electrical stimulation may be considered in intensive care unit patients who are at high risk of developing muscle weakness. Bedside cycle ergometry can provide range of motion and muscle strength training for intensive care unit patients who are either sedated or awake, and may help preserve muscle architecture and improve strength and function. Finally, custom-designed technological aids to assist with ambulating mechanically ventilated patients may reduce the human resource requirements and improve the safety and effectiveness of early mobilization in the intensive care unit.**

Conclusion: **Physical medicine and rehabilitation-related technologies may play an important role in preventing and treating intensive care unit-acquired neuromuscular complications. Future studies are needed to evaluate their efficacy in intensive care unit patients. (Crit Care Med 2009; 37[Suppl.]:S000–S000)**

Key Words: electric stimulation therapy; ergometry; physical therapy modalities; physical medicine; rehabilitation; early ambulation; exercise therapy; muscle weakness; respiration; artificial; critical care; intensive care units

Neuromuscular complications after critical illness are common and can be severe and long lasting (1–5). Patients in the intensive care unit (ICU) are exposed frequently to prolonged immobilization (6–8), which plays an important role in ICU-acquired neuromuscular complications (9). Since World War II, the harms of bed rest and the benefits of early mobilization of hospitalized patients have been recognized (10–12). More recently, a meta-analysis of 39 randomized trials examining the effect of bed rest on 15 medical conditions and procedures demonstrated that bed rest did not have benefit and may be harmful (13). As a consequence of these developments, there is growing interest in physical medicine and rehabilitation for critically ill patients with early introduction of therapies immediately after physiologic stabilization, typically within days of ICU admission (14). To facilitate the delivery of these therapies, it is important to understand the potential benefits of introducing physical medicine and rehabilitation-related technology into the ICU setting including both standard equipment used for physical medicine and rehabilitation outside of the ICU, and technology custom-designed for the unique requirements of the ICU patient and environment. Our objective is to describe three technologies relevant to early physical medicine and rehabilitation in critically ill patients: neuromuscular electrical stimulation, cycle ergometry, and technological aids and equipment for ambulating mechanically ventilated patients.

Neuromuscular Electrical Stimulation

Neuromuscular electrical stimulation (NMES) therapy creates passive contraction of skeletal muscles through use of a low-voltage electrical impulse delivered through electrodes placed on the skin over the target muscle groups (Fig. 1). F1 NMES is capable of increasing muscle oxidative capabilities and is thought to mimic the effects of repetitive muscle contractions during mild exercise, with improvement in intramuscular blood flow, maximal muscle force output, and force endurance (15, 16). NMES is used routinely within physical medicine and rehabilitation (17, 18) and has been evaluated in healthy adults with injury or immobilization to an extremity and in patients with chronic disease.

Healthy Adults

In healthy adults, NMES improves or preserves muscle strength through a reduction in disuse atrophy (15, 19). A meta-analysis of 35 randomized trials of NMES in healthy adults (n = 1345) concluded that, during immobilization, NMES is effective at increasing quadriceps strength. Furthermore, when combined with volitional exercise, electrical stimulation is more effective than exercise alone (15). The mechanism for prevention of muscle atrophy may be related to maintenance of muscle protein synthe-

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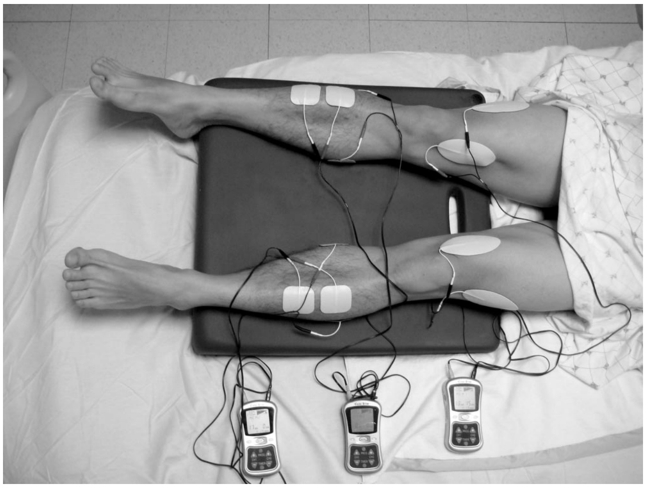

Figure 1. Neuromuscular electrical stimulation on healthy volunteer. Neuromuscular electrical stimulation allows for passive muscle contraction via electrodes placed on the skin over the target muscle groups. In the photograph, electrodes are placed over the quadriceps, tibialis anterior, and gastrocnemous muscle groups.

sis that would otherwise decline with immobility (20). Only a small number of studies have reported no strength gain with NMES therapy. In all cases, this lack of benefit has been attributed to a very short duration of the stimulation pulse (e.g., 45–100 μsec) or the limited numbers of treatment sessions (e.g., 15 sessions) delivered to patients (21–24). With NMES, larger gains in muscle strength have been observed in weaker muscles, disused muscles, and nondominant limbs (24).

Chronic Disease

In patients with chronic illness, NMES is safe and effective at improving muscle strength, physical function, and quality of life (16, 25–27). Two small, randomized controlled trials in patients with moderate-to-severe chronic obstructive pulmonary disease (COPD) ($n = 15$ and $n = 18$) found that NMES resulted in a significant increase in knee extension strength from baseline (24%–43%) (28, 29). When NMES is combined with routine physical therapy, patients had a significant increase in muscle strength from baseline vs. those who received physical therapy alone (97 ± 71 vs. 36 ± 34 Newton, $p = .03$) (30). Furthermore, gains in muscle strength translated into improved physical function and endurance with an increase in 6-min walk distance, shuttle walk test, and performance on cycle ergometry (28–30). Finally, patients with COPD who received NMES reported an improvement in their sensation of dyspnea (29, 30).

In three studies (total $n = 63$) of patients with severe congestive heart failure, daily NMES resulted in decreased muscle atrophy with a concomitant increase in muscle strength and function. When applied to knee extensor muscles, NMES resulted in a 13% to 23% increase in strength (25, 26). In this population, NMES also seems to increase muscle cross-sectional area (16, 25) and improve patient endurance and measures of activities of daily living (16, 25, 26). In refractory heart failure, a randomized trial ($n = 42$) demonstrated that NMES significantly improved patients' functional status, as measured by the New York Heart Association heart failure classification system (25).

Mechanically Ventilated Patients

There is one trial of NMES therapy in mechanically ventilated patients (27). This unmasked, randomized, controlled trial was performed in 24 bed-bound patients in a high-dependency unit. The study subjects, who had COPD requiring mechanical ventilation, were assigned randomly to either mobilization therapy alone or to mobilization plus twice-daily, 30-min NMES for 28 days. Patients randomized to the NMES therapy group had significantly improved muscle strength on physical examination as compared with those who received mobilization therapy alone (mean Medical Research Council muscle strength score = 2.2 ± 1.0 vs. 1.3 ± 0.8, $p = .02$) and a significant decrease in the number of days required to transfer from bed to chair (11 ± 2 vs. 14 ± 2 days, $p = .001$) (27).

Clinical Practice Guidelines

NMES is well tolerated in the chronically ill, with few adverse effects (25, 29, 30). The majority of studies have not found any significant change in heart rate or blood pressure (16, 27), although one small study found a statistically significant but clinically unimportant increase in heart rate (4 ± 3 beats/min) (25). However, NMES has not been studied in patients with acute critical illness. Based on the existing evidence, guidelines from the American Thoracic Society, European Respiratory Society, and European Society of Intensive Care Medicine state that NMES therapy may be considered as an adjunctive therapy in critically ill patients who are bed-bound and at high risk of developing skeletal muscle weakness (31, 32).

Cycle Ergometry

A cycle ergometer is a stationary cycling apparatus with built-in mechanisms that can alter the work done by the person who is exercising. Among healthy subjects, exercise with a cycle ergometer preserved anterior thigh muscle thickness during prolonged immobilization (33). With bedside cycle ergometers, patients can exercise through passive, active-assisted, or active training (Fig. 2). Consequently, cycle ergometry may be feasible for sedated, immobile patients with severe critical illness where even passive range of motion may play a role in preserving muscle architecture (34). Despite its potential benefits, rigorous evaluation of cycle ergometry as a rehabilitation therapy for hospitalized patients has been limited. An observational study of cycle ergometry during hemodialysis for 22 outpatients demonstrated its safety and feasibility in this patient population (35). Similarly, safety and feasibility were demonstrated in another study of nine bed-bound patients with severe COPD (36). Cycle ergometry has also been evaluated in ambulatory patients with COPD, where it is frequently combined with inspiratory muscle training (37, 38).

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The safety, feasibility, and efficacy of cycle ergometry in the ICU setting have been evaluated in a recently randomized, controlled trial of 90 medical and surgical ICU patients (39). Patients were eligible for the study if: 1) on or after ICU day 5,

Figure 2. Bedside cycle ergometry on healthy volunteer. Bedside cycle ergometry allows for passive, active-assisted and active movement of lower extremities as a patient remains in bed, thus providing range of motion and muscle strength training for critically ill patients who are either sedated or awake.

they achieved cardiorespiratory stability (e.g., fraction of inspired oxygen ≤55% and noradrenaline ≤0.2 μg/kg/min) and 2) they had an anticipated ICU length of stay of at least 7 additional days after meeting the prior criterion. The trial evaluated the potential benefit of cycle ergometry, using 6-min walk distance at hospital discharge as the primary outcome measure. Both the intervention and control groups received standard physical therapy, with the intervention group also receiving passive or active cycling for 20 mins daily, 5 days per week, using a bedside ergometer. Physical therapists on the hospital ward who treated study patients after discharge from the ICU were unaware of the patients' randomized allocation in the ICU, and were instructed to provide usual care to all patients.

During the trial, the average ICU length of stay before cardiorespiratory stability and initiation of cycling in the control and treatment groups was 10 and 14 days, respectively. The median number of cycling sessions completed per week and by ICU discharge was 4 and 7, respectively. The total treatment time including set-up and clean-up was 30 mins to 40 mins. From a total of 425 cycling sessions, 16 (4%) were stopped early due to predefined changes in cardiorespiratory status. However, all of these changes resolved within 2 mins of stopping cycling, and no serious adverse events were reported.

At ICU discharge, there were no significant differences in the secondary outcome measures between the two randomized groups. Specifically, at ICU discharge, the majority of survivors were unable to stand independently (66% vs. 77% in treatment vs. control groups, $p = .40$) or to walk independently (86% vs. 90%, $p = .72$). However, at hospital discharge, patients in the intervention group had improved isometric quadriceps force (2.37 vs. 2.03 Newton/kg, $p < .05$), handgrip force (59% vs. 51% of predicted, $p = .15$), median 6-min walk distance (196 vs. 143 meters, $p < .05$), and physical function (measured by the self-reported Short-Form 36 quality of life survey) (21 vs. 15, $p < .01$). There were no differences in ventilator weaning duration, length of stay, or 1-yr mortality. Because patients randomized to cycle ergometry received an additional 20 mins of therapy per day, the trial cannot determine whether cycling, specifically, would have an incremental benefit over providing patients a longer daily duration of usual care physical therapy in the ICU.

Technological Aids for Ambulation of Mechanically Ventilated Patients

"Early mobilization" is a common component of patient care in ICUs that emphasize early physical medicine and rehabilitation. Early mobilization is initiated when patients are first physiologically stable, and includes progressive therapeutic activities, such as bed mobility exercises, sitting on the edge of the bed, standing, transferring to a chair, and ambulation. For ambulation, especially with mechanically ventilated patients, issues regarding equipment and specialized technological aids are important to maximize the safety, efficiency, and effectiveness of early mobilization. Standard medical equipment, frequently used for intrahospital transport of critically ill patients, may assist with ambulation therapy. Such equipment includes a portable cardiac monitor and pulse oximeter to allow continuous vital sign monitoring during ambulation, and a wheeled pole with infusion pumps for intravenous medications that cannot be temporarily stopped during mobilization. Standard physical medicine and rehabilitation equipment relevant to ambulation of mechanically ventilated patients are also important. A walker, in addition to hands-on assistance from a physical therapist, provides balance and support during ambulation. A wheelchair is generally pushed behind an ambulating ICU patient to permit the patient to immediately sit and rest when necessary, and to transport patients to their room if they become physically incapable of walking due to weakness, fatigue, or medical complications.

Technological considerations for early mobilization must also include evaluation of options for providing ventilatory support during ambulation. Relevant options include use of: 1) the patient's own ICU ventilator under battery power; 2) a portable or transport ventilator; or 3) a bag-valve mask with oxygen supply. In our experience, a portable ventilator can be convenient and offers the advantage of allowing a longer duration of therapy for patients who require moderate levels of ventilatory support.

F3 Figure 3 illustrates how various equipment and personnel are involved in ambulating a mechanically ventilated patient in the ICU setting. In this figure, the patient is using a walker and being stabilized from behind by a physical therapist as the patient's bedside ICU nurse participates and pushes a wheeled pole with infusion pumps. A technician follows immediately behind the physical therapist with a wheelchair. Finally, the patient is receiving mechanical ventilation via a wheeled portable ventilator, which is being directly supervised and pushed by a respiratory therapist. A cardiac monitor is hanging from the handle of wheeled stand, which supports the portable mechanical ventilator.

Clearly, ambulating mechanically ventilated patients have significant equipment-related issues and frequently may require the assistance of four staff members. The latter staffing issue may have significant resource implications in the ICU and may limit the number of patients

Figure 3. A mechanically ventilated patient ambulating in the medical intensive care unit. Photograph of a 56-yr-old man during his fourth day in the intensive care unit. The patient is being ambulated while receiving mechanical ventilation via an oral endotracheal tube, with the assistance of a physical therapist, respiratory therapist, intensive care nurse, and a rehabilitation technician. The associated equipment includes a portable ventilator with attached oxygen tanks, a portable cardiac monitor, a wheeled pole with intravenous infusion pumps, and a wheeled walker. A wheelchair (not seen) is being pushed behind the patient by the rehabilitation technician. Reproduced with permission from Korupolu et al (46).

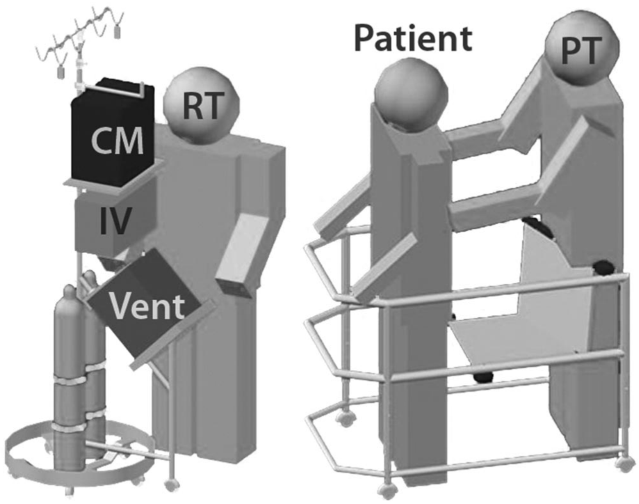

Figure 4. Schematic illustrating the two components of the MOVER Aid to assist with mobilizing a mechanically ventilated patient: a wheeled walker with a safety seat and an equipment tower housing the cardiac monitor (*CM*), intravenous infusion pump (*IV*), portable ventilator (*Vent*), and oxygen tanks. With the MOVER Aid, only two staff members are required to ambulate a mechanically ventilated patient: a physical therapist (*PT*) and a respiratory therapist (*RT*).

who can be mobilized each day. Furthermore, despite the demonstrated safety of early mobilization (40–42), staff must exercise significant care to ensure that that catheters, tubes, and wires are secured adequately before starting ambulation and do not get tangled or removed during mobilization. As a consequence of these factors, technological aids may assist with reducing the human resource requirements and improving the safety and effectiveness of ambulating a mechanically ventilated patient. Review of the historical literature has revealed that such aids for ambulation of mechanically ventilated ICU patients have been identified as early as 1965. One report described the use of a self-inflating bag with supplemental oxygen to ambulate ICU patients requiring mechanical ventilation (43). A second report illustrated customization of a commercially available walker to include a ventilator, oxygen tanks, intravenous pole, and a seat that could swing out of the way when not in use (44, 45). With this latter device, only a single staff member accompanied the patient during ambulation.

In our own critical care physical medicine and rehabilitation program at the Johns Hopkins Hospital (14, 46), we wanted to improve the safety, efficiency, and effectiveness of ambulating mechanically ventilated patients in the ICU. Because the previously described devices had not been commercialized, we collaborated with the Department of Biomedical Engineering at the Johns Hopkins University to custom-design a new biomedical device, known as the *M*oving *O*ur Patients for *V*ery *E*arly *R*ehabilitation (MOVER) Aid, for this purpose (47). The MOVER Aid, as illustrated in a Web-based video (48), demonstrates the challenges and potential technological solutions for assisting with ambulation of mechanically ventilated patients in the ICU. The MOVER Aid has two components: a walker and an equipment tower (Fig. 4). The custom-designed walker has a built-in emergency seat which eliminates the need for a staff member dedicated to pushing a wheelchair behind the patient. The equipment tower consolidates all the medical supplies and equipment required by an ICU patient (i.e., intravenous fluids and medications, infusion pumps, cardiac monitor, portable mechanical ventilator, and two oxygen tanks) into a single wheeled tower. The tower accommodates standard medical equipment, is specially designed to allow adequate viewing of the equipment display screens, and has improved stability (to prevent tipping) over traditional methods described above. With consolidation of all equipment onto a single wheeled tower (rather than separate wheeled devices for a ventilator and an intravenous pole), only one staff member is required to manage the medical equipment and push the wheeled tower. Through this technological aid, the number of staff required to ambulate a mechanically ventilated patient can be reduced from four to two.

CONCLUSIONS

Strategies aimed at minimizing prolonged immobilization during critical illness may prevent the development of neuromuscular complications after critical illness. The introduction of physical medicine and rehabilitation-related technologies, such as NMES, cycle ergometry, and customized mobility aids, may play an important role for improving muscle strength and physical function in ICU patients. NMES and cycle ergometry may be especially valuable as a component of early rehabilitation during the acute phase of critical illness, where sedation and immobilization may limit patients' ability to participate in active rehabilitation interventions. Given the unique challenges presented by critically ill patients and the ICU environment, the novel application of these technologies in the ICU requires further evaluation to confirm safety, feasibility, and efficacy.

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