

Repetitive Bilateral Arm Training With Rhythmic Auditory Cueing Improves Motor Function in Chronic Hemiparetic Stroke

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Background and Purpose—Chronic upper extremity hemiparesis is a leading cause of functional disability after stroke. We investigated the hypothesis that bilateral arm training with rhythmic auditory cueing (BATRAC) will improve motor function in the hemiparetic arm of stroke patients.

Methods—In this single group pilot study we determined the effects of 6 weeks of BATRAC on 14 patients with chronic hemiparetic stroke (median time after stroke, 30 months) immediately after training and at 2 months after training. Four 5-minute periods per session (3 times per week) of BATRAC were performed with the use of a custom-designed arm training machine.

Results—The patients showed significant and potentially durable increases in the following: Fugl-Meyer Upper Extremity Motor Performance Test of impairment ($P < 0.0004$), Wolf Motor Function Test (performance time measure, $P < 0.02$), and University of Maryland Arm Questionnaire for Stroke measuring daily use of the hemiparetic arm ($P < 0.002$). Isometric strength improved in elbow flexion ($P < 0.05$) and wrist flexion ($P < 0.02$) for the paretic arm and in elbow flexion ($P < 0.02$) and wrist extension ($P < 0.02$) for the nonparetic arm. Active range of motion improved for paretic-side shoulder extension ($P < 0.01$), wrist flexion ($P < 0.004$), and thumb opposition ($P < 0.002$), and passive range of motion improved for paretic wrist flexion ($P < 0.03$).

Conclusions—Six weeks of BATRAC improves functional motor performance of the paretic upper extremity as well as a few changes in isometric strength and range of motion. These benefits are largely sustained at 8 weeks after training cessation. (*Stroke*. 2000;31:2390-2395.)

Key Words: hemiplegia ■ motor activity ■ physical function ■ rehabilitation

Stroke is the third leading cause of death in the United States and the leading cause of adult disability.¹ Annually, approximately 750 000 Americans suffer a stroke.² Although incidence rates have remained constant over the last 3 decades, mortality has declined, leaving an increasing number of patients requiring rehabilitation.³ Approximately two thirds of stroke survivors have residual neurological deficits that persistently impair function.⁴ Specifically, dysfunction from upper extremity (UE) hemiparesis impairs performance of many daily activities such as dressing, bathing, self-care, and writing, thus reducing functional independence. In fact, only 5% of adults regain full arm function after stroke, and 20% regain no functional use.⁵ Hence, alternative strategies are needed to reduce the long-term disability and functional impairment from UE hemiparesis.

Traditionally, methods of stroke rehabilitation have been focused on the first 3 months after stroke and consist largely of passive (nonspecific) movement approaches⁶ or compen-

satory training of the nonparetic arm.⁷ This time window is consistent with natural history studies of stroke recovery that show a plateau after 3 months. Recently, both the paradigms for rehabilitation interventions and the time frame for possible UE motor recovery have been challenged. Experiments demonstrate that functional gains and possible neural plasticity can occur, via active practice, long after spontaneous recovery would be expected to end.⁸ For example, monkey models of chronic stroke demonstrate functional recovery as well as cortical reorganization after being forced to use their paretic limb.⁹⁻¹¹ On the basis of this “forced-use” paradigm, Taub, Wolf, and colleagues constrained the nonparetic arm of patients with chronic stroke and forced the use of the paretic arm in task-specific activities in an intensive 2-week protocol.¹²⁻¹⁶ In general, patients made significant functional gains as measured by tests of functional ability and daily use. These findings support a hypothesis that patients have “learned nonuse” of their paretic limb and that the forced use,

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particularly with intensive training techniques, unmask the dormant neuromuscular pathways.¹⁴ Clearly, forced-use or “constraint-induced” training, in general, has major implications for stroke rehabilitation. Indeed, principles of forced use and “task specificity” combined with repetition have supported a rationale for treadmill training studies in chronic hemiparetic stroke patients that demonstrate improvements in functional mobility and motor strength.^{17–19}

In the present study we extend the forced-use paradigm in the form of a repetitive bilateral arm training with rhythmic cueing (BATRAC) protocol. The principles of forced use and task specificity are retained, but the concept of constraining the nonparetic arm is not. Specifically, we force the use of rhythmic reaching and retrieving actions using a metronome to cue the patients. Auditory cueing has been used successfully to promote immediate and posttraining gait changes over and above those produced by gait training alone in subacute stroke patients.^{20,21} Indeed, the BATRAC has more in common with current gait (leg) rather than arm training paradigms except for one important feature. Gait training paradigms^{17,21} typically have some element of physical conditioning that may produce exercise-mediated cardiovascular or musculoskeletal adaptations that could contribute to improved functional mobility and endurance. The BATRAC is designed to reduce, although it cannot eliminate, conditioning to better isolate the effects of motor training as an independent variable.

This initial single group design study examines the efficacy and potential durability of a novel training protocol in patients with chronic stroke. We hypothesized that BATRAC would result in significant improvements in sensorimotor impairments, functional ability, and daily use of the paretic arm. Because of the nature of the training, we also hypothesized that few significant changes would be found in strength or range of motion (ROM) outcome measures.

Subjects and Methods

Patients

Sixteen patients, consisting of 8 men and 8 women with chronic hemiparetic arm dysfunction, were recruited from the Baltimore Veterans Affairs Medical Center and the James Lawrence Kernan Rehabilitation Center at the University of Maryland. Informed consent approved by the joint Veterans Affairs–University of Maryland Institutional Review Board was obtained from all patients before inclusion in the study. At the time of recruitment, all patients had long been discharged from conventional poststroke rehabilitation and had experienced their stroke at least 12 months (median, 30 months) previously. Baseline evaluations included a medical history, the Folstein Mini-Mental State Examination, and the Orpington Prognostic Scale.

Inclusion criteria were as follows: at least 6 months since a unilateral stroke, ability to follow simple instructions and 2 step commands, volitional control of the nonparetic arm, and at least minimal antigravity movement in the shoulder of the paretic arm. Exclusion criteria were as follows: symptomatic cardiac failure or unstable angina, uncontrolled hypertension (>190/110 mm Hg), significant orthopedic or chronic pain conditions, major poststroke depression, active neoplastic disease, severe obstructive pulmonary disease, dementia (Mini-Mental State Examination score <22), aphasia with inability to follow 2 step commands, or severe elbow or finger contractures that would preclude passive ROM of the arm.



Figure 1. Bilateral arm trainer in use.

Training

Training consisted of 20 minutes of BATRAC 3 times per week for 6 weeks (18 sessions). In each session, patients were seated comfortably at a table in front of a custom-designed bilateral arm trainer in the following limb positions: ankles in neutral dorsiflexion, knees and hips placed at 90°, shoulders in 0° flexion, elbows in 60° flexion, and wrists in neutral position of flexion/extension. The apparatus (see Figure 1) consists of 2 independent T-bar handles that can move, nearly friction free, in the transverse plane (perpendicular to the patient). The patient grasps the handles or the affected hand is strapped to the handle, depending on the severity of the deficits. By using shoulder flexion/protraction and elbow extension, the patient pushes the handles away and then (using shoulder extension/retraction and elbow flexion) pulls them toward the body. This action mimics the behavior of reaching and bringing an object to oneself. When necessary, the trainer provided minimal assistance for the affected arm, sometimes to help with the arm extension and at other times to keep the elbow from striking the table. In these cases, patients were encouraged to provide the active pushing and pulling. The handles of the apparatus were positioned at shoulder width for each patient, and a padded chest guard was adjusted to rest against the patient. The chest guard was used to prevent the patient from using the trunk while reaching forward. Recently, Levin et al²² confirmed that patients with chronic hemiplegia have a significant tendency to use trunk flexion to reach compared with nonhemiplegic controls.

The training itself consisted of the following parameters: four 5-minute periods of BATRAC interspersed with 10-minute rest periods. By having rest periods that were twice as long as the exercise periods, conditioning effects might be reduced.²³ Heart rate and blood pressure measurements were taken before and after each 5-minute training period to check for adverse cardiovascular reaction and to assess for aerobic conditioning. Four active training periods enabled the session to be completed in 1 hour, a typical treatment time for outpatient-based occupational therapy. Periods consisted of bilateral repetitive pushing/pulling movements that were simultaneous (inphase) for periods 1 and 3 and alternating (antiphase) for periods 2 and 4. Movements were timed to an auditory metronome set at the participant's preferred speed that was established at the first session by asking patients to assume a comfortable speed that they could continue for 5 minutes. This frequency remained constant across the entire 6 weeks of training, with no increase in workload, again in an attempt to reduce specific conditioning effects.

Retention was assessed during an 8-week period after the cessation of training. During this time patients were asked to do no special training but to continue to use their paretic arm on activities that they had identified on the daily use scale (see below).

Testing

A pretest, posttest, and retention test consisted of the following items: (1) The Fugl-Meyer Upper Extremity Motor Performance

TABLE 1. Characteristics of Subject Population

Subject	Age, y	Sex	Months Since CVA	Side of CVA	Hand Dominance	Orpington Category	MMSE Score
1	62	F	26	Left	Right	Moderate	15*
2	60	M	29	Right	Right	Minimal	28
3	44	F	30	Right	Right	Moderate	23
4	60	M	40	Right	Left	Minimal	26
5	89	M	192	Left	Right	Minimal	27
6	68	M	204 (1st) 39 (2nd)	Left	Left	Moderate	21
7	80	F	18	Right	Right	Severe	30
8	70	M	59	Right	Right	Minimal	28
9	67	M	360	Right	Right	Moderate	26
10	49	F	29	Left	Right	Moderate	29
11	62	F	31	Left	Left	Minimal	30
12	44	F	23	Left	Right	Minimal	28
13	65	M	46	Right	Right	Moderate	30
14	73	M	14	Left	Right	Minimal	22

CVA indicates cerebrovascular accident; MMSE, Mini-Mental State Examination.

*Secondary to expressive aphasia, but subject could follow 2 step commands.

Section Test was selected because it assesses impairments in sensorimotor function. This test has been shown to be valid and reliable,^{24,25} and it correlates well with interjoint UE coordination measures in the upper extremity of patients after stroke.²⁶ It has a top score of 66. (2) The Wolf Motor Function Test was selected because it reliably measures functional ability in a variety of activities and appears to be more sensitive than other UE tools.^{14,16} On this test, timed items assess speed of performance. The ability to lift a weight assesses functional strength, and quality of motor function is assessed by a 5-step ordinal scale. (3) A custom-designed questionnaire, the University of Maryland Arm Questionnaire for Stroke (UMAQS), has been developed to assess daily use of the paretic arm in accomplishing activities of daily living on the basis of a 5-point ordinal scale that grades degree of independence. The top score is 50. This questionnaire differs from the Functional Independence Measure²⁷ by measuring daily use rather than level of assistance, and it differs from the Motor Activity Log¹⁴ in that it accounts for unilateral and bilateral tasks as well as considering handedness. Types of activities include typical activities of daily living as well as lifting, carrying, and pulling a 2-handled drawer. Activities that are hand specific and complementary (eg, eating with a fork in the dominant hand and supporting a plate with the nondominant hand) are on separate but equivalent questionnaires that are administered according to whether the affected hand was dominant or nondominant before the stroke. We also graded patient satisfaction and perceived improvement on the basis of 5-point scales to provide patient self-report of the effectiveness of the BATRAC intervention. The UMAQS is currently being tested for reliability and validity, including caregiver confirmation regarding the accuracy of the responses. (4) Isometric strength of the shoulder (flexion/extension/abduction), elbow (flexion/extension), wrist (flexion/extension), and thumb opposition was assessed with the Chatillon Force Dynamometer and grip strength with the BASELINE Hydraulic Hand Dynamometer.²⁸ (5) Active/passive ROM of the UE was assessed by standard goniometry, which has been demonstrated to be reliable and sensitive (within 5°).²⁹

Data Reduction and Analysis

The initial analyses were 1-way repeated-measures ANOVAs to compare the pretest, posttest (at 6 weeks of training), and retention test (8 weeks after the cessation of training) measures on the dependent variables. Significant results were further investigated

with post hoc (Tukey honestly significant difference) comparisons. Subjects 1 to 3 did not undergo retention testing or the Wolf and UMAQS tests because these were added to the protocol later. Therefore, nonsignificant results were duplicated with a 1-way repeated-measures analysis to compare pretest and posttest results on all 14 subjects. The α level was set at 0.05.

Results

Of the 16 patients, 14 completed the protocol, with 1 woman dropping out after the pretest and another after 2 training sessions, both because of transportation problems. The remaining 14 completed all 18 training sessions within a 6- to 9-week period. The characteristics of the final subject pool are presented in Table 1. All but 1 subject (subject 7) had more than trace movement at the shoulder, but only 3 subjects could extend the finger joints by at least 10° or the wrist joint by at least 20°. The group mean increase in training heart rate summed across sessions 1, 6, 12, and 18 was unchanged at 2.7 beats (± 3.1). Notwithstanding the fact that some patients were on medications that would influence these results, there was no indication of an aerobic training adaptation.

The Fugl-Meyer Upper Extremity Motor Performance Section Test scores showed significant improvements ($P < 0.004$). Post hoc analysis revealed that both the posttest and retention test scores were higher than the pretest score (reflecting 18% and 26% increases, respectively, and effect sizes of 0.41 and 0.66) (Figure 2A). The Wolf Motor Function Test scores for performance time showed significant improvements over the 3 testing periods ($P < 0.02$). Post hoc analysis revealed that both the posttest and retention test scores were significantly higher than the pretest score (reflecting 12% and 13% increases, respectively, and effect sizes of 0.20 and 0.20) (Figure 2B). Neither the weight nor the quality of function aspects of the Wolf test revealed significant differences, although both showed a trend for improvement. The UMAQS questionnaire section on daily use

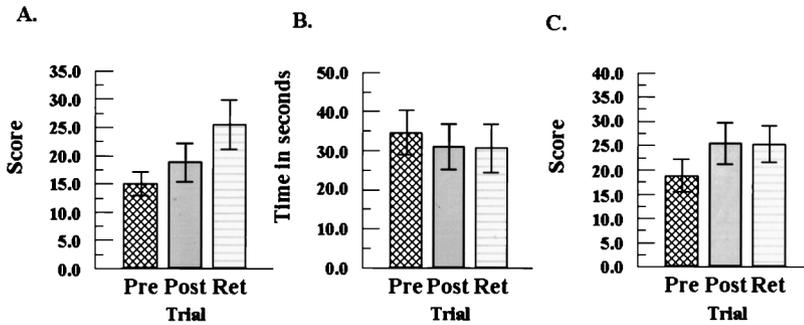


Figure 2. A, Fugl-Meyer Upper Extremity Motor Performance Section Test mean scores. B, Wolf Motor Function Test of performance time mean scores. C, UMAQS mean scores. Error bars indicate SEM. Significant differences ($P < 0.05$) pretest (Pre) vs posttest (Post) and pretest vs retention test (Ret) for each measure.

showed significant improvements over the 3 testing periods ($P < 0.002$). Post hoc analysis revealed again that posttest and retention test scores were significantly higher than the pretest score (reflecting 42% and 43% increases, respectively, and effect sizes of 0.52 and 0.55) (Figure 2C). The relatively small sample size precludes drawing any conclusions concerning the effect of premorbid handedness and side of cerebrovascular accident.

The patient satisfaction section of the UMAQS revealed that all but 1 subject (subject 7) reported that they were either satisfied or very satisfied with the training. Similarly, all but subject 7 reported that they had improved a little or to a great extent after training. These ratings were maintained at the retention period. Subject 7 was the only subject who made no improvement throughout the training. She was also the only subject with a severe categorization from the Orpington Prognostic Scale and with barely trace movement. Patients also reported the following: “I can use my arm more”; “I can feel my arm more”; “I can hold onto things now”; “I can do things with 2 hands”; and “I feel like I have 2 arms again.”

Four of 16 strength measures revealed significant improvements. For the paretic arm, elbow flexion ($P < 0.05$, but no post hoc differences) and wrist flexion ($P < 0.02$, pretest versus posttest) were significant. For the nonparetic arm,

elbow flexion ($P < 0.02$, pretest versus retention test) and wrist extension ($P < 0.02$, pretest versus retention test) were significant. Four of 28 active and passive ROM measures revealed significant improvements. For the paretic arm, active ROM for shoulder extension ($P < 0.01$, pretest versus posttest), wrist flexion ($P < 0.004$, pretest versus posttest), and thumb opposition ($P < 0.002$, pretest versus posttest/pretest versus retention test) were significant. For the paretic arm, passive ROM for wrist flexion ($P < 0.03$, pretest versus posttest) was also significant. Table 2 displays the mean values of these significant changes in strength and ROM.

Discussion

In this single group design study, we found that 6 weeks of BATRAC improved several key measures of sensorimotor impairments, functional ability (performance time), and functional use in patients with chronic UE hemiparesis. Furthermore, these improvements were maintained at 2 months after patients stopped training, suggesting that the motor improvements were potentially durable. This supports the hypothesis that forced use in a repetitive stereotypical training program, in this case bilaterally, improves motor function in chronic hemiparetic stroke patients who have long since completed conventional training. The effect sizes of our major depen-

TABLE 2. Significant Changes in Mean Strength and ROM Measures

Measure	Pretest (n=14)	Posttest (n=14)	Pretest (n=11)	Posttest (n=11)	Retention Test (n=11)
Strength*					
Paretic arm					
Wrist flexion	4.58	6.35	...	...	...
Elbow flexion	...	...	7.93	9.28	9.77
Nonparetic arm					
Wrist extension	...	...	9.40	10.45	11.84
Elbow flexion	...	...	12.95	14.17	16.55
ROM†					
Paretic arm, active					
Shoulder extension	...	...	39.55	48.45	44.10
Wrist flexion	...	...	23.27	36.36	27.91
Thumb opposition‡	...	...	0.91	1.36	1.45
Paretic arm, passive					
Wrist flexion	71.21	75.57	...	...	...

*Strength measured in kg force.

†ROM measured in degrees.

‡Three-point ordinal scale.

dent variables are modest compared with those reported for the constraint-induced studies.¹² In cases in which direct comparison can be made with the Wolf Motor Function Test for performance time, our results are more comparable for some studies^{12,16} but less comparable for others.¹⁵

A rationale regarding the reason why active bilateral UE training in the present study is effective can be found in the motor behavior and neurophysiology literature. Practicing bilateral movements in synchrony (and in alternation) may result in a facilitation effect from the nonparetic arm to the paretic arm. For example, when bimanual movements are initiated simultaneously, the arms act as a unit that supersedes individual arm action,^{30,31} indicating that both arms are strongly linked as a coordinated unit in the brain. In addition, it is well known that even if one arm or hand is activated with moderate force, this can produce motor overflow in the other such that both arms are engaged in the same or opposite muscle contractions although at different levels of force.^{32,33} Furthermore, studies have shown that learning a novel motor skill with one arm will result in a subsequent bilateral transfer of skill to the other arm.³⁴ Taken together, these experiments suggest a strong neurophysiological linkage in the central nervous system that explains how bilateral (simultaneous and perhaps alternating) movements may benefit motor learning.

A second important aspect of the BATRAC is the rhythmic repetition of an action via auditory cueing. Repetition, or "time on task," is a well-known motor learning principle,³⁵ and recent animal studies have demonstrated that forced use involving a repetitive motor task rather than forced use alone may best promote central neural plasticity.³⁶ Rhythmic auditory cueing has 3 advantages. First, by holding frequency constant it ensures that the same movement is actually repeated. In effect, the auditory cueing may entrain the motor system to its beat.²⁰ Second, trying to match the sound with full extension or flexion provides an attentional goal for the patient. Goal setting is also known to promote motor learning.³⁷ One recent study demonstrated the efficacy of having a real object (goal) to reach for in patients with hemiparetic arms.³⁸ Third, receiving feedback has been shown to be fundamental to motor learning.³⁹ In this experiment, sensory information from the audio cues, as well as that from visual and somatosensory sources, provided intrinsic feedback to the patient regarding the movement goal.²¹ Collectively, it is plausible that the techniques employed that involved repetition and cueing, based as they are on motor learning principles in nonhemiparetic persons, may also contribute to motor relearning in the hemiparetic case.

Our initial findings suggest that even patients with quite severe UE hemiparesis can benefit from the BATRAC program. Constraint-induced protocols require subjects to have a fair degree of voluntary movement. For example, in the studies of Taub et al,^{12,14} patients were excluded if they could not achieve at least 10° of active extension at the metacarpophalangeal and interphalangeal joints of the hand and 20° of active extension at the wrist of the affected limb. Wolf et al¹⁶ required subjects to actively initiate wrist and finger extension on the hemiparetic side. Similar criteria applied to our pretest active ROM measures would have excluded 11 of our 14 subjects. Although it is not yet

established whether the constraint-induced paradigm may be beneficial to patients who are not highly functioning, our results suggest that the BATRAC protocol improves motor function in patients with much denser UE hemiparesis. This expands the applicability of forced-use, task-oriented training across a broader deficit severity spectrum in chronic stroke.

Our training protocol demonstrates that gains can be attained over a relatively brief training period. The time spent training the arms, 6 hours, is approximately one tenth of the intervention time used in the constraint-induced paradigm, although the treatment time period of the latter is shorter (2 versus 6 weeks). Conceivably, the distributed practice in the present study (72 periods of 5 minutes) versus the massed nature of the constraint-induced paradigm (10 periods of 360 minutes) contributed to the success of the former over a shorter exercise time.⁴⁰ Regardless, the present study demonstrates that functional gains in a chronic paretic arm can be achieved after a total of only 6 hours of training; it is possible that longer training periods or other variations of BATRAC, including progressive or incremental resistive components, could result in greater motor and functional gains.

As Taub et al¹⁴ have argued, changes that occur quickly after practice more likely represent an "unmasking" of dormant neuromuscular pathways rather than neural reorganization or plasticity. The veracity of this argument requires a direct investigation of underlying mechanisms. In addition, reconditioning of the neuromuscular system by reversing disuse atrophy may contribute to functional gain. Although no direct measures of conditioning were taken, physiological changes at the level of skeletal muscle such as hypertrophy and change in fiber type are not expected within this time frame and at such low-intensity training. Indeed, we observed only a few changes in strength measures after training or at retention testing. For example, in the paretic arm, wrist flexion improved after training but was not retained. Evidently the action of pulling the handle toward the body produced this temporary gain. Temporary gains were also seen in the active ROM of shoulder extension and wrist flexion of the paretic arm. Only active ROM for paretic thumb opposition was a retained gain. In the nonparetic arm, elbow flexion and wrist extension were strengthened, but not significantly so until after the training had finished, which made these data hard to interpret. Overall, the few, largely temporary, strength and ROM changes are not supportive of large muscular conditioning effects, as expected given the training protocol.

In conclusion, this study suggests that the BATRAC regimen based on motor learning principles leads to significant and potentially durable functional gains in the paretic UE of chronic hemiparetic patients. The BATRAC is appropriate for patients with greater baseline severity motor deficits than are amenable to constraint-induced treatments. Moreover, the intervention is not prohibitively complex and hence may be feasible for home use by many patients. Although we cannot determine precisely which parameters of the training are most useful, a future goal is to systematically determine the most efficacious and user-friendly protocol for each patient. We can only speculate that bilateral training per se may be more useful than unilateral training of the same kind (ie, unilateral

training on our machine). In the future, a direct comparison of methods could be made to test this effect on the paretic arm. Finally, randomized studies are needed to establish whether this bilateral arm training protocol durably improves UE motor function in chronic hemiparetic stroke and whether these functional motor adaptations are mediated by central neural plasticity.

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