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Review

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Review of outcomes measures used to evaluate upper extremity surgical treatment of cervical spinal cord injury with recommendations for the future

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Abstract

Cervical spinal cord injury is a life-altering event that profoundly affects an individual's upper extremity function. Nerve transfer surgeries have been shown to restore more natural movement and fine motor control in this population. At present, there is no consensus on how to evaluate the efficacy of these restorative surgeries. The purpose of this work was to perform a comprehensive review of the existing literature and describe the outcome measures used. We hypothesized that the assessments will be heterogeneous across studies and will incompletely capture the effect of nerve transfers on upper extremity motion in cervical spinal cord injury. A search strategy was designed and a review of multiple databases (Embase.com, Ovid-Medline All, and Scopus) yielded 481 articles; 26 unique studies met inclusion criteria and underwent analysis. Both manual muscle strength testing and video content were presented in the majority of studies. Outcome assessments including myometry, functional outcomes measures (such as the grasp and release test), patient-reported outcomes (including generic, extremity, and disease-specific types), and custom *de novo* questionnaires were used variably across studies. Future work should focus on standardizing outcomes measures in the field and developing and incorporating kinematic analysis to quantify the intricate, coordinated, and precise movement attained after nerve transfer surgery in the setting of cervical spinal cord injury.

Keywords: Nerve transfer surgery, upper extremity function, cervical spinal cord injury, tetraplegia, outcome assessments, kinematic analysis

INTRODUCTION

Over a quarter million individuals are living with spinal cord injury (SCI) and approximately 18,000 new SCI cases occur in the United States alone each year[1,2]. Over half of these are at the cervical level and profoundly affect the individual's upper extremity (UE) movement and function[3]. Restoring UE function is essential to performing basic activities of daily living (ADLs) and can improve independence in this setting[4,5].

Spontaneous recovery with standard rehabilitation and UE surgery can both lead to gains in UE movement; devices such as neuroprostheses may be useful but are not currently commercially available[5-7]. Both traditional tendon transfer (TT)[8-10] and newer nerve transfer (NT)[11-19] surgeries can restore key movements such as elbow and wrist extension and hand opening and closing. Reports of TT surgeries in the setting of cervical SCI appeared in the literature in the 1940s and 50s[10]. The first reports of NT surgery in this setting were in the 1960s and 80s[20,21], but these predated the extensive use of NT techniques in peripheral nerve and brachial plexus injury, which has added immensely to surgeons' understanding of the detailed intraneural anatomy that allows for successful surgery. Thus, it is only in the last decade that NT surgery has been more widely used in people with cervical SCI.

Historically, outcome measures used in studies of TT surgery have been comprised of manual muscle strength testing, myometry (pinch and grip), and measures of range of motion. In 2007, Mulcahey and Kozin described some of tools for evaluation of the UE in cervical SCI, and made recommendations for continued attention to developing, validating, and using better tools to measure outcomes in this setting[22]. Reports on NT surgery have used a variety of outcomes measures that have differed from those reported in the TT surgery literature. For example, a prospective study of NT in SCI reported changes in manual muscle testing and results for the following: (1) the action research arm test (ARAT); (2) the grasp and release test (GRT); and (3) the spinal cord independence measure (SCIM)[23].

The purpose of this study was to provide a broad overview of the assessment measures and outcomes tools reported in the NT surgery in cervical SCI literature. We hypothesize that the measures are heterogeneous across studies and limit our understanding of the effect of NT surgery on UE function in cervical SCI.

METHODS

We performed a comprehensive review of assessment measures and outcomes tools used in articles reporting clinical results after NT surgery in people with cervical SCI. The preferred reporting items for systematic reviews and meta-analysis (PRISMA) statement guidelines were followed as the subject matter and content of articles permitted.

Eligibility, information sources, and search strategy

First, the senior author shared a working list of pertinent articles with the co-author and a health sciences librarian. Articles were reviewed for relevance and key words. Using this information, the literature search strategies were designed by the health sciences librarian for the concepts of NT surgery and spinal cord injury or quadriplegia, with related synonyms. The strategies were created using a combination of controlled vocabulary terms and keywords including NT, nerve transplant, nerve crossover, SCI, spinal cord trauma, quadriplegia, and tetraplegia. The search strategy was executed in Embase.com, Ovid-Medline All, and Scopus. A filter for human studieswas utilized to exclude animal studies. All database searches were completed on April 27, 2023. See [Figure 1] for the detailed search strategy information. Finally, after the search strategy was completed, the results were cross-referenced back to the senior author's list of pertinent articles.

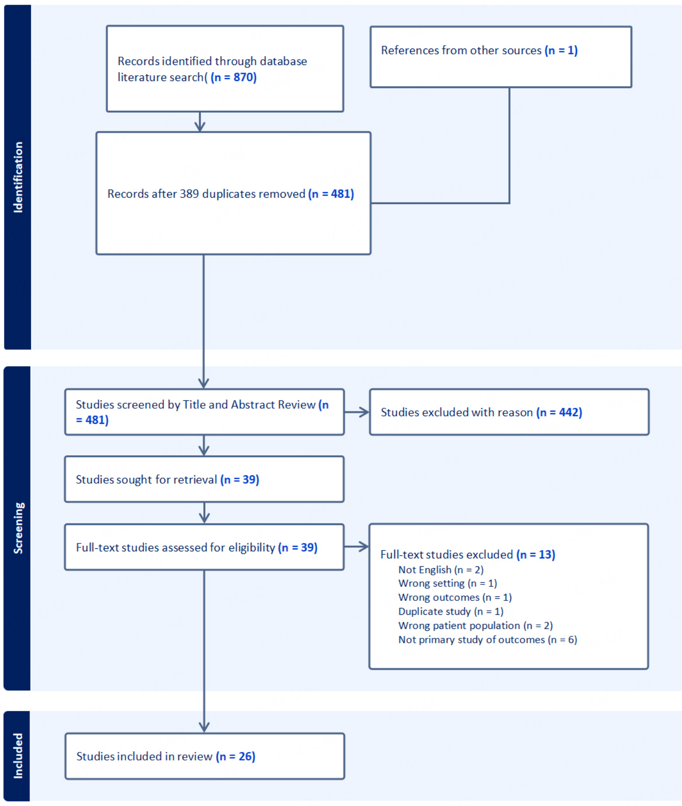

Figure 1. Flow diagram outlining the review process. Reasons for exclusion of full-text studies are listed above. Covidence systematic review software, Veritas Health Innovation, Melbourne, Australia.

Selection process, inclusion and exclusion criteria

Studies that provided original data, including prospective studies, retrospective studies, and clinical trials, were included for analysis. Studies were excluded if the primary language was not English. Studies of NT surgery in peripheral nerve and brachial plexus injuries were also excluded.

Data collection and synthesis

From the included studies, information on operative details, clinical assessments including hand function tests, strength measurements and patient-reported outcomes were extracted. A review and summary of all relevant studies was performed. Assessment tools and outcomes measures were described for each study and categorized based on previously reported methodology[24]. The first author performed the initial article reviews and compiled a list of assessments used. Both authors reviewed and categorized the measures and organized them for presentation in the results section.

RESULTS

A total of 870 results were retrieved from the database literature search and imported to Endnote. This was cross-referenced to the senior author's list of relevant articles and only one additional reference was added. There were 389 duplicate citations that were identified and removed, and the remaining 481 citations were included for further title and abstract screening analysis. A total of 39 full-text studies were extracted and 13 were excluded with reasons [Figure 1]. A total of 26 unique studies that met inclusion criteria were published between 1966 and 2022. The findings are summarized in Tables 1 and 2.

Table 1. Included studies in the nerve transfer surgery in cervical spinal cord injury review

Author, year	N	ASIA	ICSHT	Cervical Levels	Goals of Surgery
Benassy 1965[20]	1	n/a	n/a	C5 and C6	Wrist/digit flexion
Kiwerski 1982[21]	20	n/a	n/a	C6 and C7	Hand flexion (grasp)
Krasuski & Kiwerski 1991[63]	42	n/a	n/a	C6 and C7	Wrist/digit flexion
Bertelli 2010[27]	1	n/a	ICSHT Group 2	n/a	Digit extension
Bertelli *et al.* 2011[26]	1	n/a	ICSHT Group 2	n/a	Elbow extension
Bertelli *et al.* 2012[28]	1	n/a	n/a	n/a	Digit flexion
Friden & Gohritz 2012[13]	1	n/a	ICSHT Group 0	C5	Wrist extension
Mackinnon *et al.* 2012[14]	1	A	ICSHT Group 5	C7	Digit flexion
Bertelli & Ghizoni 2013[29]	1	n/a	ICSHT Group 2	n/a	Elbow extension, digit flexion/extension
van Zyl *et al.* 2014[15]	1		n/a	C6	Elbow extension, wrist ulnar deviation, digit flexion / extension, thumb abduction
Bertelli & Ghizoni 2015[17]	7	n/a	n/a	C6	Elbow extension, digit extension
Fox *et al.* 2015[12]	9	A-C	ICSHT Groups 1-4	C4-C6	Elbow extension, wrist extension, digit flexion/extension
Hawasli *et al.* 2015[30]	1	A	n/a	C7	Digit flexion
Bertelli & Ghizoni 2016[31]	7	n/a	ICSHT Groups 3-5	C6-C7	Wrist extension, digit extension
Bertelli & Ghizoni 2017[18]	9	A	ICSHT Groups 1-4	C5-C7	Elbow extension, digit flexion/extension
Emamhadi & Andalib 2018[32]	1	n/a	ICSHT Group 4-5	n/a	Finger flexion extension
Fox *et al.* 2018[33]	1	B	n/a	C5	Digit flexion
Dibble *et al.* 2019[34]	2	A	n/a	C4	Elbow extension
Khalifeh *et al.* 2019[16]	21	A-C	ICSHT Groups 0-4	C2-C7	Elbow extension, digit flexion/extension
van Zyl *et al.* 2019[23]	16	A-B	ICSHT Groups 2-5	C5-C7	Elbow extension, digit flexion/extension
Biondi *et al.* 2020[35]	1	A	ICSHT Group 3, 5	C6	Elbow/digit extension
van Zyl *et al.* 2021[36]	26	A-B	n/a	n/a	Wrist/digit extension
Waris *et al.* 2021[37]	1	n/a	ICSHT Group 0	C5	Wrist extension, digit flexion
Waris *et al.* 2022[43]	6	A	ICSHT Group 2-5	C4-C7	Finger flexion and extension, thumb flexion
Javeed *et al.* 2022[47]	22	A-C	ICSHT Groups 0-4	C1-C8	Elbow extension, digit flexion/extension
Sacco *et al.* 2022[50]	11	A-B	ICSHT Groups 0-5	C4-C7	Elbow extension, digit flexion/extension

ASIA: American Spinal Injury Association Impairment Scale (range A-D); ICSHT: the International Classification for Surgery of the Hand in Tetraplegia group, N-number of patients; C5: cervical spinal cord level 5; C6: cervical spinal cord level 6; C7: cervical spinal cord level 7.

Description of injury characteristics and overview

The American Spinal Injury Association (ASIA) Impairment scale, as well as the corresponding level of SCI for study participants, were reported. The International Classification for Surgery of the Hand in Tetraplegia (ICSHT) is a detailed classification of UE motor function specific to planning reconstructive surgery[25] and was also reported for each study. Outcome measures were divided broadly into the following categories for reporting purposes: (1) strength/movement; (2) functional; (3) patient-reported; and (4) other. The strength/movement category measured changes in pinch and grip, UE muscle strength, and range of motion. The functional measures category included a variety of assessments that graded the ability and quality of UE movement. The patient-reported outcomes category included self-report across several

Table 2. Outcome measures reported in nerve transfer surgery in cervical spinal cord injury articles

Author, Year	Outcome measures						
	Strength / Movement	F(x)-al test	PROM			Others	Video
			General	*Systemic*	*Disease*		
Benassy 1965[20]	MMT (custom)					Custom observational reports	yes
Kiwerski 1982[21]						Custom grasp rating	no
Krasuski & Kiwerski 1991[63]						Custom hand function rating	no
Bertelli 2010[27]	MMT (MRC)						yes
Bertelli *et al.* 2011[26]	MMT (MRC)						no
Bertelli *et al.* 2012[28]	MMT (MRC) Dynamometry						yes
Friden & Gohritz 2012[13]	MMT (MRC)						no
Mackinnon *et al.* 2012[14]	MMT (MRC)					Custom observational reports	yes
Bertelli & Ghizoni 2013[29]	MMT (MRC) Dynamometry						yes
van Zyl *et al.* 2014[15]	MMT (MRC) Custom measurementsDynamometry		COPM				yes
Bertelli & Ghizoni 2015[17]	MMT (MRC)					Custom observational reports	yes
Fox *et al.* 2015[12]	MMT (MRC)					Custom patient-reported functional results	no
Hawasli *et al.* 2015[30]	MMT (MRC)						no
Bertelli & Ghizoni 2016[31]	MMT (MRC)						yes
Bertelli & Ghizoni 2017[18]	MMT (MRC)						yes
Emamhadi & Andalib 2018[32]	MMT (MRC)					Custom observational reports (ADLs)	yes
Fox *et al.* 2018[33]	MMT (MRC) Dynamometry					Custom patient-reported functional results	no
Dibble *et al.* 2019[34]	MMT (MRC)					Semmes-Weinstein - sensory	no
Khalifeh *et al.* 2019[16]	MMT (MRC) Donor muscle (MRC)	SHFT	SF36	MHQDASH			no
van Zyl *et al.* 2019[23]	MMT (MRC) Dynamometry	ARATGRT	COPM		SCIM	Sensation, proprioception, and pain Custom satisfaction scale (Likert scale)	yes
Biondi *et al.* 2020[35]	MMT (MRC) Custom measurements						no
van Zyl *et al.* 2021[36]	MMT (MRC) Goniometer					Custom patient satisfaction - 5 pt Likert scale	yes
Waris *et al.* 2021[37]	MMT (MRC)						no
Waris *et al.* 2022[43]	MMT (MRC) Dynamometry						no
Javeed *et al.* 2022[47]	MMT (MRC)	SHFT	SF36	MHQDASH			yes
Sacco *et al.* 2022[50]	MMT (MRC)	GRASSP			SCIM		no

N: number of study participants; F(x)-al: functional; PRO: patient-reported outcome measures; MMT: manual muscle testing; MRC: medical research council; ROM: range of motion; SHFT: Sollerman Hand Function Test; ARAT: Action Research Arm Test; GRT: Grasp and Release Test; SF36: short form-36; COPM: Canadian Occupational Performance Measure; MHQ: Michigan Hand Questionnaire; DASH: Disabilities of Arm, Shoulder, and Hand; SCIM: Spinal Cord Independence Measure.

validated questionnaires about quality of life, independence, and ability to perform ADLs. Finally, additional customized questionnaires, assessment tools and the inclusion of visual content (such as videography) were reported under the other category.

Strength/movement outcomes

Manual muscle testing (MMT) was the most widely used assessment measure; 24/26 studies used MMT as their primary outcome to measure gains in strength following NT surgery[11,13-18,20,26-37]. Results were graded using the Medical Research Council (MRC) scale (range of 0-5). The MRC scale is the most widely accepted[38] and was designed for the examination of the peripheral nervous system[39,40]. Strength is graded as follows: (1) 0/5 - no movement; (2) 1/5 - flicker of movement (3) 2/5 - movement with gravity eliminated; (4) 3/5 - antigravity movement; (5) 4/5 - strong movement; and (6) 5/5 - normal power[39]. Myometry is a more quantitative and objective measure of strength. It is commonly used to assess pinch and grip strength in pounds or kilograms. If measurable, myometry can provide continuous data, which may show changes not detectable with standard MMT[41,42]. In our review, 6/26 studies included myometric measurements[15,23,28,29,33,43].

Functional outcomes

Several studies describe the use of tests that measure UE and hand movement and/or functional limitations[44-46]. Some were originally developed to be disease-specific, while others were developed to measure changes after certain therapeutic interventions.

The Sollerman Hand Function Test (SHFT) was developed to measure the common hand grips used by people with cervical SCI when performing ADLs[44] and was measured in 2/26 studies[16,47]. ARAT was originally used to assess UE function in people recovering from stroke and brain injury[48]. It grades coordination, dexterity, and function based on the performance of a specific series of tasks. This was used in 1/26 studies[23]. The Graded Redefined Assessment of Strength, Sensibility and Prehension (GRASSP) Test is a valid and reliable test that was designed to measure functional outcomes in complete and incomplete cervical SCI[45]. The GRASSP has been shown to be predictive of overall UE and self-care function[49] and was used in 1/26 studies[50]. GRT was originally developed to assess outcomes after neuroprosthesis implantation in people with SCI[46]. Further studies have demonstrated that GRT can reliably detect hand function changes before and after TT surgery as well[51]. The GRT was used in 1/26 studies[23].

Patient-reported outcomes

In this review, we categorized patient-reported outcome (PRO) questionnaires into three groups - general, system-specific, and disease-specific - based on the classifications described by Alderman and Chung[24,52]. General PROs evaluate general well-being and do not focus on a specific disease process or organ system. System-specific PROs focus on an organ system or functional body unit and assess how it is impacted by disease processes and improvements after surgical intervention. Lastly, disease-specific PROs are designed for populations affected by certain pathologies. These instruments focus on evaluating the efficacies of treatments for particular diseases.

The Short Form 36 (SF-36) survey is widely used to assess general health-related function and well-being[53]. It was originally designed as a generic health measure to compare health at the population level but has been applied to specific groups such as people living with schizophrenia and stroke[54]. This assessment was used in 2/26 studies[16,47]. The SF-36 walk-wheel modification version was used to maintain appropriate content validity in the physical domain section since wheelchairs (not walking/climbing) are the main mode of locomotion for people with cervical SCI[55].

The Michigan Hand Questionnaire (MHQ) was developed using psychometric principles to measure different health state domains for patients with hand disorders[56]. The questionnaire consists of 37 items broken into six main categories, which include overall hand function, ADLs (e.g., holding glass, turning door knobs, tying shoelaces), satisfaction with hand function, pain, work performance, and aesthetics. A systematic review of the MHQ demonstrated high re-test reliability and internal consistency[57]. The MHQ was used in 2/26 studies[16,47].

The Disabilities of Arm, Shoulder, and Hand (DASH) questionnaire was a joint initiative of the American Academy of Orthopedic Surgeons and several other organizations and measures patient-rated UE disability and symptoms[58]. It consists of a 30-item disability scale with questions focusing on the degree of difficulty of performing physical tasks (e.g., gardening, changing lightbulb overhead, making bed, washing back); severity of associated pain, weakness, and stiffness; and negative impact on social activities, self-perception, and sleep. The DASH was used in 2/26 studies[16,47].

SCIM evaluates disability and function that are affected by SCI, including self-care (feeding, grooming, bathing, dressing), respiration and sphincter management, and mobility (including transfers to chair/bed). The SCIM was developed and validated for use in people with SCI and multiple iterations have been refined, with the latest available version being the SCIM III[59-61]. The SCIM was used in 2/26 studies[23,50].

The Canadian occupational performance measure (COPM) was designed for use by occupational therapists to assess outcomes in the areas of self-care, productivity, and leisure. It is based on a semi-structured interview and measures patient-designated goals for daily function[62]. It comes in digital or paper forms that must be purchased prior to use. The COPM was used in 2/26 studies[15,23].

Other reports

In 10 of the 26 studies, *de novo* satisfaction scales, semi-structured interview qualitative measures, and other subjective descriptions of participants' abilities to perform ADLs were reported[11,14,17,20,21,23,32,33,36,63]. In 13 of 26 studies, some pre- and post-operative video content of UE movement was included to enhance visualization of the outcomes[14,15,17,18,20,23,27-29,31,32,36,47].

DISCUSSION

Summary of the current literature and findings

In people with cervical SCI, gaining UE function is a top priority[64,65]. NT surgery expands eligibility for surgical reconstruction and improves function and independence[17]. In the current SCI literature, there is a lack of consensus regarding which clinical assessments and outcome measures are most useful[22]. In this comprehensive literature review, we found that MMT was the most widely used post-operative outcome measure. While many studies included functional and patient-reported outcome measures, only 19% of the studies used standardized assessments and 38% included subjective *de novo* questionnaires and observational reports.

While strength assessment with MMT is useful, it has high interrater variability and provides ordinal non-continuous data[66]. Additionally, an increase in strength does not necessarily translate into useful UE function or improved performance of ADLs[66]. Nevertheless, MMT remains the most widely used outcome measure in this setting. Another commonly used assessment is myometry, which has been shown to be more sensitive than MMT[67,68]. However, similar to MMT, myometry may not correlate with useful function. Standard dynamometers for pinch and grip measurement can also require more force than some people with cervical SCI are able to produce[41].

While physical tests and biomechanical measurements may demonstrate gains in UE strength and movement following surgery, the clinical significance is unclear. These outcomes may not reflect the patient perception or experience of change[69,70]. For example, what a surgeon may view as considerable improvement in grip may not correspond to improved hand function from the patient's perspective. In light of this, PROs were developed. PROs allow for the assessment of function, satisfaction, and quality of life from the patient's perspective[24,71].

General PROs such as the SF-36 may demonstrate change for reasons unrelated to hand and UE function and may be less useful in this field. System-specific PROs that evaluate generic UE function such as the DASH and MHQ may not account for the nuances of hand and UE function in cervical SCI[72]. For example, questions in the DASH such as "making a bed" or "changing a lightbulb overhead" may not capture important gains in function experienced after surgery[58]. Disease-specific PROs such as the FIM, SCIM, and CUE were developed to assess UE disability in the setting of cervical SCI. In particular, the SCIM has been validated and found to be highly reproducible and a good predictor for ADL attainment[60,73]. However, in this review, we found that these measures were rarely used.

The reviewed literature rarely included measures for UE movement quality and precision during task execution. This is a critical deficit in NT surgery outcome studies in the current cervical SCI literature. One of the purported advantages of NT over TT surgery is the ability to regain coordinated, natural and smooth UE movements when performing tasks[23].

Future directions

By contrast, kinematic or motion analysis can provide objective and quantifiable measurement of hand dexterity and smoothness of motion[74]. Kinematic analysis is the study of the motion of the human body, limbs, and joints through three-dimensional space and time. It often utilizes an optoelectronic system built from multiple high-speed cameras and infrared diodes to capture bodily movements using active markers. Kinematic measures of UE function have been investigated in the stroke population and have been shown to detect minute changes that augment traditional clinical assessments[74,75]. For example, Lili *et al.* used a 5-camera optoelectronic system to capture movement time, smoothness, and other kinematics findings that correlated with the ARAT and SHFT assessments[76].

Capturing the smoothness and fluidity of UE motion using more complex visual imagery makes inherent sense. In many studies investigating NT or TT surgery outcomes, post-operative videos were often included in the online supplemental sections. In this review, 13/26 (50%) studies included post-operative video content. Kinematic analysis extracts the intuitive visual success of this video content into quantifiable metrics. Metrics such as hand trajectory variability, velocity, acceleration, and grip aperture have previously been demonstrated to have excellent repeatability for the assessment of ADL performance in able-bodied subjects[77].

Using kinematic analysis in the field of NT surgery in cervical SCI could improve pre-operative counseling, surgical decision-making, and post-surgery rehabilitation. However, current kinematic analysis requires a special set-up with multiple cameras and physical markers that are placed on the UE. Simpler methods need to be developed. The ultimate goal for performing kinematic analysis in this population would be to capture UE movement during ADLs and other activities outside of a research environment.

Recent work has focused on gaining an understanding of movement and its effect on independence. Future work should compare the assessment of kinematics, strength, movement, function, and independence, as well as patient and caretaker perceptions of those changes before and after NT surgery. We must more comprehensively capture outcomes across treatment strategies to allow for better comparison to non-surgical rehabilitation, tendon transfer surgery, and other as yet unimagined curative treatment strategies.

CONCLUSION

The use of NT surgery to restore UE function in SCI is rapidly expanding and numerous reports in the literature show gains across outcomes measures. However, the heterogeneity across studies is quite remarkable. There is also an absence of standardized assessments that measure dexterity, precision, coordination, and natural motion. Future work should focus on standardizing outcomes measures and developing and incorporating kinematic analysis to more comprehensively capture the effect of these newer, relatively rare surgeries in unique populations such as those living with cervical SCI.

DECLARATIONS

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Authors' contributions

Made substantial contributions to the conception and design of the study and performed data analysis and interpretation: Lin J, Fox I

Availability of data and materials

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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