



# Effects of a cyborg-type robot suit HAL on cardiopulmonary burden during exercise in normal subjects

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## Abstract

**Background** The hybrid assistive limb (HAL) is the world's first cyborg-type robot suit that provides motion assistance to physically challenged patients. HAL is expected to expand the possibilities of exercise therapy for severe cardiac patients who have difficulty in moving on their own legs. As a first step, we examined whether or not the motion assistance provided by HAL during exercise could effectively reduce the cardiopulmonary burden in healthy subjects.

**Methods** A total of ten healthy male adults ( $35 \pm 12$  years) underwent cardiopulmonary exercise testing (CPX) on a cycle ergometer with or without assistance from HAL. The CPX protocol consisted of four 3-min stages performed in a continuous sequence: rest, 0 W, 40 W, and 80 W. The heart rate (HR), blood pressure, oxygen uptake ( $VO_2$ ), minute ventilation (VE), and gas exchange ratio ( $R$ ) were monitored during the CPX.

**Results** At 0 W, the HR,  $VO_2$ , and VE were significantly higher when HAL was used. At 80 W, however, the HR ( $107 \pm 14$  vs  $114 \pm 14$  beats/min,  $p < 0.01$ ), systolic blood pressure ( $141 \pm 15$  vs  $155 \pm 20$  mmHg,  $p < 0.01$ ),  $VO_2$  ( $17.6 \pm 2.4$  vs  $19.0 \pm 2.5$  mL/min/kg,  $p < 0.05$ ), and  $R$  ( $0.88 \pm 0.04$  vs  $0.95 \pm 0.09$ ,  $p < 0.05$ ) were significantly lower when HAL was used.

**Conclusions** HAL has the potential to reduce cardiopulmonary burden during moderate-intensity exercise and can, therefore, be used as a support for exercise therapy. Further studies on cardiac patients are expected to contribute to the establishment of a new exercise therapy program using HAL.

**Keywords** Hybrid assistive limb · Exercise testing · Cardiopulmonary burden

## Introduction

Cardiac rehabilitation is a safe and low-cost therapy for improving exercise tolerance and quality of life in patients with heart failure (Neto et al. 2016). Cardiac rehabilitation

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has numerous benefits, including established effects in modifying risk factors and preventing future cardiovascular events (Nishitani et al. 2013). The improved survival attained by cardiac rehabilitation in cardiac patients (Kureshi et al. 2016) has prompted the expanded use of the therapy all over the world in recent years.

Cardiac rehabilitation is a comprehensive program consisting of exercise therapy, diet therapy, daily life guidance, and so on. The exercise component of the therapy improves weakened muscles and reduces respiratory discomfort and fatigue during physical exertion in cardiac patients, providing benefits that can tangibly enhance quality of life. Yet in many patients, cardiac functions are too severely compromised to endure the demands of the current cardiac rehabilitation programs.

The hybrid assistive limb (HAL) is the world's first cyborg-type robot suit designed to provide motion assistance to physically challenged patients. HAL has been reported to improve walking functions in patients with chronic myelopathy (Kubota et al. 2017) and muscular dystrophy (Sczensy-Kaiser et al. 2017), and to reduce the level of disability in acute stroke patients (Ogata et al. 2015). No earlier reports have been published, however, on the efficacy of HAL in cardiac patients. HAL is expected to promote exercise therapy for severe cardiac patients who have difficulty in moving on their own legs.

Cardiopulmonary exercise testing (CPX) is one of the most useful clinical tools for evaluating the severity of disease and the limitations of physical activities in cardiac patients (Takayanagi et al. 2017). Gas exchange indices such as oxygen uptake ( $VO_2$ ), minute ventilation (VE), and the gas exchange ratio ( $R$ :  $CO_2$  output ( $VCO_2$ )/ $VO_2$ ) can be measured through respiratory measurement system during CPX. The increase in cardiac output during exercise facilitates the increase in  $VO_2$  by the working muscles (Balady et al. 2010). VE also increases in proportion to the increase in the work rate in normal subjects (Balady et al. 2010). The gas exchange ratio is reported to be a reliable gauge in assessing a subject's effort. With the progression to higher exercise intensities, lactic acid buffering contributes to the rise in  $VCO_2$ , which in turn increases the gas exchange ratio (Balady et al. 2010). As a first step to establish a new exercise therapy program in cardiac patients, we performed a respiratory gas analysis to examine whether or not motion assistance by HAL during bicycle exercise could lead to an effective reduction of cardiopulmonary burden in healthy subjects.

## Methods

### Study subjects

A total of ten healthy male subjects ranging in age from 22 to 60 years underwent CPX on a cycle ergometer with

or without motion assistance from HAL at the University of Tsukuba Hospital. The mean height  $\pm$  SD and mean weight  $\pm$  SD of the ten subjects were  $176.1 \pm 6.5$  cm and  $66.4 \pm 11.5$  kg, respectively. The subjects were defined as healthy when cardiac disease was ruled out by medical history, electrocardiogram, and other standard examinations. All of the subjects included in the study were volunteers recruited through poster advertisements at the University of Tsukuba Hospital. All of them provided written, informed consent to participate in the study after learning about the aim and design of the study. The protocol of this study was approved by the Institutional Review Board of the University of Tsukuba Hospital and registered with the UMIN Clinical Trials Registry (UMIN000026713).

### Cardiopulmonary exercise testing (CPX) and respiratory gas analysis

The CPX was performed on an upright, electromagnetically braked cycle ergometer (Strength Ergo 8; Mitsubishi Electric Engineering Co., Ltd., Tokyo, Japan) using a protocol consisting of four stages: rest, 0 W, 40 W, and 80 W. The exercise test consisted of a 3-min rest period in a seated position on the ergometer followed by three 3-min periods of exercise at successively higher intensities: 0 W at 50 rpm, followed by 40 W at 50 rpm, followed by 80 W at 50 rpm. Each participant performed two CPX sessions: one using HAL (HAL-FL05, CYBERDYNE, Inc.) (Fig. 1) and one without HAL.

Faint signals from the brain to muscle leaked to the surface of the participant's skin were detected by electrodes of HAL placed on the skin over the rectus femoris, gluteus maximus, vastus lateralis, and biceps femoris. The first CPX session was performed with motion assistance from HAL by five participants and without assistance by five participants. An interval of  $7.4 \pm 4.8$  days was scheduled between the two CPX sessions.

The heart rate was continuously monitored and measured using an electrocardiogram (exercise stress test electrocardiograph, STS-2100, Nihon Kohden Corporation, Japan) and blood pressure was measured every minute using an electric upper-arm type sphygmomanometer equipped with a cuff device (Tango M2, 99-0088-01, Sun Tech Medical, Inc., United States). After finishing the CPX, the participant was asked to subjectively rate the exercise intensity using the 6–20 Borg scale, an index demonstrated to be useful in quantifying a participant's relative fatigue (Balady et al. 2010).

We also measured and analyzed the  $VO_2$ , VE, and gas exchange ratio throughout the test using an Aeromonitor AE-300 s (Minato Medical Science, Osaka, Japan). The average values of these gas exchange indices were calculated during the last minute of each 3-min stage. The Aeromonitor AE-300 s consists of a microcomputer, a hot wire flowmeter,



**Fig. 1** CPX using an upright, electromagnetically braked cycle ergometer while wearing HAL

and a gas analyzer containing a sampling tube, filter, suction pump, infrared CO<sub>2</sub> analyzer, and O<sub>2</sub> analyzer composed of a paramagnetic oxygen cell (Takayanagi et al. 2017). The VO<sub>2</sub> was calculated breath-by-breath based on the mathematical analysis described by Beaver et al. (1973). The concentration and flow were aligned synchronously by compensating for the time delays of the O<sub>2</sub> and CO<sub>2</sub> analyzers (the flow delay from the sampling site to the analyzer plus the response time of the analyzer) with respect to the flow signal (Sue et al. 1980). Before the parameters from the respiratory gas analysis were calculated, breath-by-breath data were interpolated to give second-by-second values. These second-by-second values were then calculated as successive 3-s averages and the averages were translated into a 5-point moving average.

### Statistical analysis

Data are presented as the mean  $\pm$  SD. Differences for variables between CPX using HAL and CPX without HAL were compared by the paired *t* test. All analyses were performed using SPSS version 22.0 software (SPSS Inc., Chicago,

Illinois). A *p* value of less than 0.05 was considered statistically significant for all comparisons.

### Results

Table 1 shows the heart rate, systolic blood pressure, diastolic blood pressure, VO<sub>2</sub>, VE, gas exchange ratio, and Borg scale measured during the CPX. Figure 2 compares the heart rate and blood pressure between the CPX tests performed with and without motion assistance from HAL. The heart rate at 0 W was  $81 \pm 11$  beats/min with assistance from HAL, which was significantly higher than that without assistance from HAL ( $78 \pm 11$  beats/min,  $p=0.03$ ). The heart rate at 80 W, however, was  $107 \pm 14$  beats/min in the CPX performed with assistance from HAL, which was significantly lower than that without assistance ( $114 \pm 14$  beats/min,  $p=0.004$ ). The systolic blood pressure at 80 W was  $141 \pm 15$  mmHg with assistance from HAL, which was significantly lower than that without assistance ( $155 \pm 20$  mmHg,  $p=0.007$ ). Figure 3 compares the VO<sub>2</sub> and VE between the CPX with and without motion assistance from HAL. VE at 0 W was  $16.4 \pm 2.3$  mL/min with assistance from HAL, which was significantly higher than that without assistance ( $13.7 \pm 1.8$  mL/min,  $p=0.008$ ). The VO<sub>2</sub> at 0 W was  $7.6 \pm 1.2$  mL/min/kg with assistance from HAL, which was significantly higher than that without assistance ( $5.8 \pm 0.8$  mL/min/kg,  $p=0.002$ ). The VO<sub>2</sub> at 80 W, on the other hand, was  $17.6 \pm 2.4$  mL/min/kg with motion assistance from HAL, which was significantly lower than that without assistance ( $19.0 \pm 2.5$  mL/min/kg,  $p=0.030$ ). Figure 4 compares the gas exchange ratio and Borg scale between the CPX with and without motion assistance from HAL. The gas exchange ratio at 80 W was  $0.88 \pm 0.04$  with motion assistance from HAL, which was significantly lower than that without assistance ( $0.95 \pm 0.09$ ,  $p=0.016$ ). The Borg scale at 80 W exercise was also significantly lower when the participants wore HAL ( $12.4 \pm 1.3$  vs  $13.8 \pm 1.1$ ,  $p=0.015$ ).

### Discussion

The findings from the present study demonstrated that motion assistance from HAL during moderate-intensity exercise, i.e., 80 W, effectively reduced cardiopulmonary burden in healthy subjects. At 80 W exercise, HAL decreased not only the heart rate, systolic blood pressure, VO<sub>2</sub>, and gas exchange ratio, but also the participants' subjective rating of exercise intensity on the Borg scale.

Brain signals sent to the contracting muscles leak to the skin surface as very faint electrical charges. HAL can read these signals from detectors attached to the surface of the

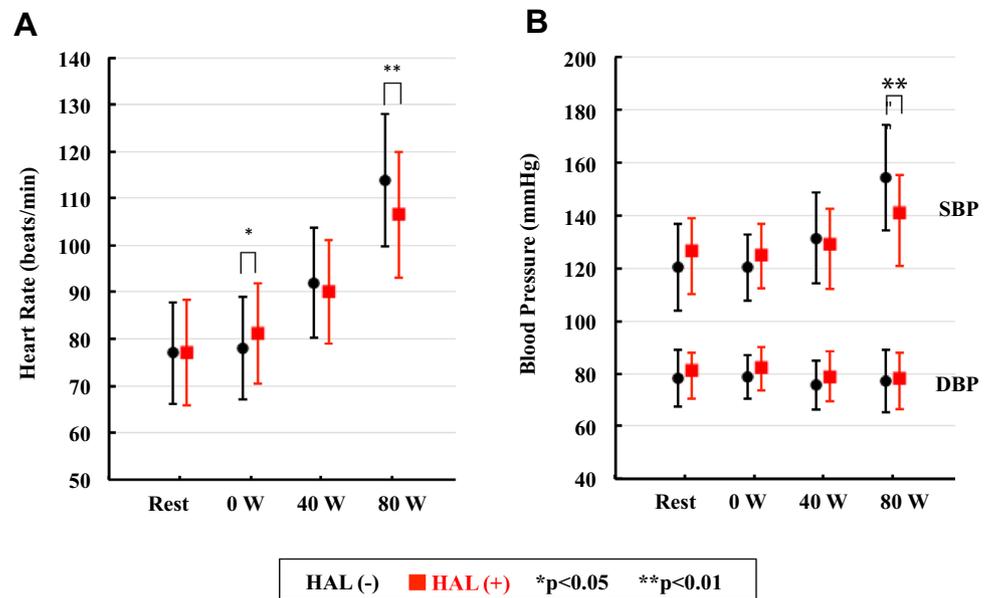
**Table 1** Cardiopulmonary indices of the study subjects during CPX

Indices	Stage	HAL (-)	HAL (+)	<i>p</i> value
Heart rate (bpm)	Rest	77.0 ± 10.9	77.1 ± 11.4	NS
	0 W	78.1 ± 11.0	81.2 ± 10.7	0.030
	40 W	92.0 ± 11.8	90.0 ± 11.0	NS
	80 W	113.9 ± 14.1	106.5 ± 13.6	0.004
Systolic blood pressure (mmHg)	Rest	120.4 ± 16.4	126.4 ± 12.7	NS
	0 W	120.2 ± 12.6	125.0 ± 11.7	NS
	40 W	131.3 ± 17.2	129.4 ± 13.3	NS
	80 W	154.5 ± 20.1	140.8 ± 14.5	0.007
Diastolic blood pressure (mmHg)	Rest	78.3 ± 10.8	81.2 ± 7.0	NS
	0 W	78.8 ± 8.4	82.1 ± 8.1	NS
	40 W	75.7 ± 9.5	79.0 ± 9.7	NS
	80 W	77.2 ± 11.9	78.4 ± 9.4	NS
VO <sub>2</sub> (mL/min/kg)	Rest	4.2 ± 0.4	4.4 ± 0.6	NS
	0 W	5.8 ± 0.8	7.6 ± 1.2	0.002
	40 W	11.9 ± 1.6	11.5 ± 1.8	NS
	80 W	19.0 ± 2.5	17.6 ± 2.4	0.030
VE (L/min)	Rest	10.0 ± 1.2	10.4 ± 0.9	NS
	0 W	13.7 ± 1.8	16.4 ± 2.3	0.008
	40 W	19.2 ± 2.8	20.4 ± 2.5	NS
	80 W	31.1 ± 4.0	29.7 ± 3.3	NS
<i>R</i>	Rest	0.81 ± 0.08	0.81 ± 0.07	NS
	0 W	0.86 ± 0.07	0.86 ± 0.04	NS
	40 W	0.79 ± 0.08	0.80 ± 0.05	NS
	80 W	0.95 ± 0.09	0.88 ± 0.04	0.016
Borg scale	80 W	13.8 ± 1.1	12.4 ± 1.3	0.015

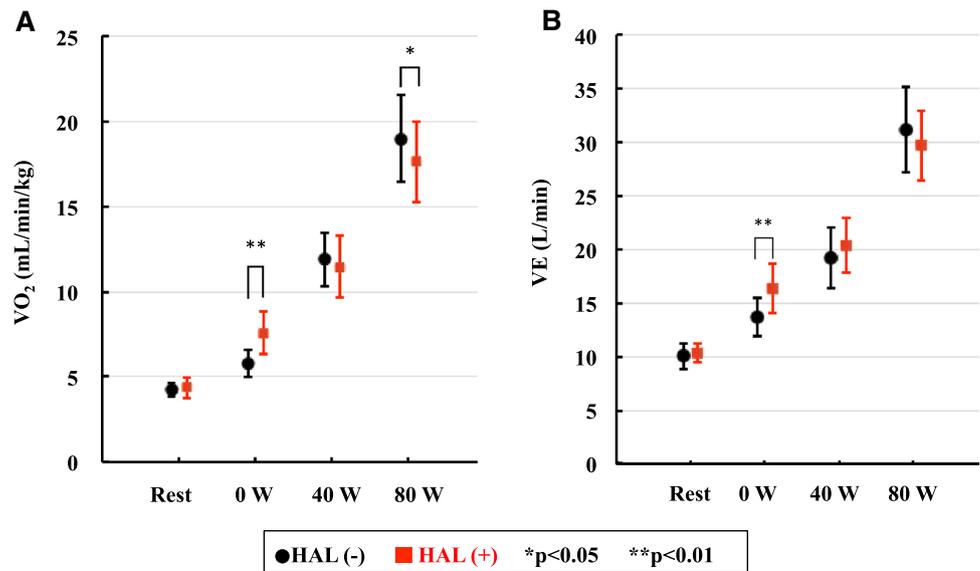
Data are presented as the mean ± SD

VE minute ventilation, VO<sub>2</sub> O<sub>2</sub> uptake, *R* gas exchange ratio, HAL hybrid assistive limb, NS not significant

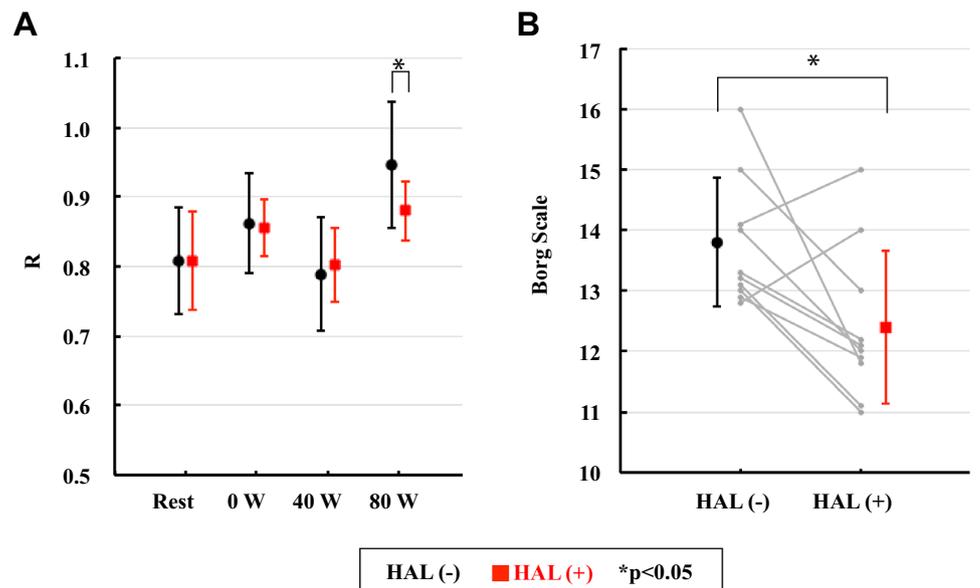
**Fig. 2** Comparisons of heart rate (a) and blood pressure (b) during exercise between CPX with and without motion assistance from HAL. SBP systolic blood pressure and DBP diastolic blood pressure



**Fig. 3** Comparisons of O<sub>2</sub> uptake (VO<sub>2</sub>) (a) and minute ventilation (VE) (b) during exercise between CPX with and without motion assistance from HAL



**Fig. 4** Comparisons of the gas exchange ratio (*R*) during exercise (a) and the Borg scale at 80 W (b) between CPX with and without motion assistance from HAL



wearer’s skin. By consolidating information from these signals together with various physiological variables, HAL recognizes the types of motions intended by the brain and controls its power units to assist the recognized motions. Through this approach, HAL assists the intended motions of the wearer, enabling them to exert greater power than they would exert ordinarily.

The total weight of HAL used in this study, about 14 kg, was likely to impose some degree of cardiopulmonary burden constantly throughout the exercise. Because HAL delivers a constant level of assistance to the muscles irrespective of the exercise intensity, the participant can be expected to reach a threshold beyond which the reduction in cardiopulmonary burden by HAL outbalances the burden of

the weight of HAL itself. During exercise at 80 W in the present study, the reduction in cardiopulmonary burden by HAL probably outbalanced the burden of HAL’s weight and consequently reduced the cardiopulmonary burden. In the healthy subjects, however, the exercising muscles demanded only low to moderate levels of O<sub>2</sub> during exercise at 0 W or 40 W. As such, the weight of HAL itself probably offsets the reduction of the cardiopulmonary burden provided by the motion assistance. At 0 W, the additional effort required to move the 14 kg HAL almost certainly exceeded the support from HAL. We can reasonably assume, therefore, that the intensity of 0 W was too low to obtain a benefit from HAL in healthy subjects. In cardiac patients with severe left ventricular dysfunction, on the other hand, cycling at 0 W

sometimes pushes them past their anaerobic (lactic acidosis) threshold. For this reason, HAL is expected to decrease the cardiopulmonary burden on these patients even during exercise at an intensity corresponding to low exercise intensity in healthy subjects.

The gas exchange ratio at 80W in our study participants was  $0.95 \pm 0.09$  in the exercise without motion assistance from HAL and  $0.88 \pm 0.04$  in the exercise with assistance. We can, therefore, assume that the intensity of these exercises was probably near or slightly below the anaerobic threshold in our healthy subjects. In patients with heart failure, the prescribed exercise intensity should ideally be set at or slightly below the anaerobic threshold (Tan et al. 2017). Hence, a cardiac patient can be expected to benefit from the use of HAL during exercise therapy set at an intensity appropriate for the patient's exercise capacity.

As an alternative treatment for chronic heart failure patients who cannot engage in conventional exercise training programs, electrical muscle stimulation has been reported to show potential beneficial effects. One group has reported, for instance, that electrical muscle stimulation increases muscle mass and improves peak  $VO_2$  and quality of life (Neil et al. 2013). Electrical muscle stimulation is, therefore, expected to serve as an effective therapy for chronic heart failure patients (Neil et al. 2013). In exercise supported by HAL, muscle action potentials are detected through the electrodes attached to the anterior and posterior surfaces of the wearer's thigh. Based on these potential signals, HAL can support the wearer's motion by adjusting the level and timing of the assistive torque provided to each joint (Kubota et al. 2013). Hence, HAL can be expected to support the wearer's motions more naturally and improve the wearer's muscle performance more precisely than electrical muscle stimulation. By doing exercise with the motion assistance from HAL, chronic heart failure patients with limited mobility can become better able to perform the necessary motions more steadily, obtain more natural and precise muscle performances and lower their psychological distress, and continue their exercise therapy. By undergoing such exercise therapy, they can improve their quality of life, and enjoy the benefits of shortened periods of hospitalization, prevention of future cardiovascular events, and a lower risk of readmission owing to their improvements of heart failure and the level of exercise capacity.

### Study limitations

This study was subject to several limitations. To begin, the study was performed at only one center with a small number of participants. A study with a larger sample size to confirm the findings would have been ideal. We also focused on bicycle exercise rather than walking exercise, as the former is more widespread in the field of cardiac rehabilitation for

patients with advanced heart failure. Further investigation will be necessary to clarify the efficacy of HAL during walking exercise on a treadmill. In that case, consideration of weight reduction of HAL might be necessary, such as using a device which enables to pull up HAL. Development of lightweight HAL is also expected. The HAL used in this study was developed for medical use, not for subjects with normal cardiac and physical function. When normal subjects with sufficient muscles wear HAL for medical use, the motion assistance provided by the suit may be inconsistent in anticipating the movements intended by the brain or in achieving sufficient effects in assisting the wearer's motions. Finally, to establish a new exercise therapy program using HAL in cardiac patients, we may have to take some measures to minimize the influence of the weight of HAL on circulatory dynamics at the beginning of exercise, considering the individual severity of cardiac function and types of exercise such as treadmill and ergometer.

### Conclusions

We found that HAL reduces cardiopulmonary burden during moderate-intensity exercise (80 W stage) in healthy subjects. HAL might have the potential to benefit cardiac patients whose cardiac functions are too severe to permit full compliance with a cardiac rehabilitation program.

**Author contributions** AK contributed to the conception or design of the work. YP, HW, TT, HK, MT, and HK contributed to the acquisition, analysis, or interpretation of data for the work. YP drafted the manuscript. AK critically revised the manuscript. JK, IN, AS, HK, KA, MI, and YS provided technical help with the design of the study. All gave final approval and agree to be accountable for all aspects of work ensuring integrity and accuracy.

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### Compliance with ethical standards

**Conflict of interest** Hiroaki Kawamoto and Yoshiyuki Sankai are stockholders in, and the CEO of, Cyberdyne Inc. (Ibaraki, Japan), the manufacturer of the robot suit HAL. This study was proposed by the authors, and Cyberdyne was not directly involved in the study design, in the collection, analysis, and interpretation of data, in the writing of the report, or in the decision to submit the paper for publication.

**Statement of human rights** All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

**Informed consent** Informed consent was obtained from all individual participants included in the study.

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