Human Movement Sciences: Sport, Exercise and Health

Research Internship
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The effect of Electrostimulation on upper leg blood flow

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Abstract

The purpose of this study was to determine whether Electrostimulation (sensory level stimulation) increases blood flow compared to rest. Twenty healthy subjects (14 men and 6 women) participated in this study. The areas of interest were m. vastus lateralis and m. vastus medialis. Light exercise was also performed to provide insight in the clinical relevance. A wireless continuous-wave near-infrared spectrophotometer was used to measure blood flow to the upper leg during venous occlusion. No overall differences in blood flow were found. A significant difference was found between the two muscles, both in rest and during electrical stimulation ($p < .001$). After light exercise subjects had a significantly higher blood flow when compared to Electrostimulation ($p < .001$). We conclude that Electrostimulation does not provide an increase in blood flow to the treated area.

Introduction

At the highest levels, sport requires a lot of high-volume and high-intensity training. This brings a lot of stress to the body. During intensive exercise, fuel sources such as creatine phosphate and carbohydrates are consumed rapidly and metabolic byproducts, especially lactic acid, are made and are harmful for performance. Elite athletes often have multiple training sessions per day. Fast and proper recovery is vital in order to maintain these intensive training schedules. There are multiple types of recovery, as defined by Bishop et al. [1]: immediate recovery (e.g. between strides while walking), short-term recovery (e.g. between exercise sets), and training recovery (e.g. between work-outs or bouts).

There are not many ways to influence immediate recovery and short-term recovery. For training recovery, however, athletes use a wide variety of strategies. Active recovery (e.g. cooling-down) and passive recovery (PR, e.g. massage, sauna, ice baths, electrical stimulation (ES), and compression garments) are two types of strategies that athletes use to accelerate recovery [2, 3]. As compared with rest, these strategies might enhance recovery through an increase in blood flow or pain management [4, 5]. The increase in blood flow observed with active recovery enhances the supply of fuel back into the exercised skeletal muscle and the clearance of metabolic byproducts from the muscle and blood [6]. The removal of these byproducts, such as lactate, is crucial for restoring or maintaining athletic performance.

Alternatives to active recovery that can reach similar results (i.e. an increase in blood flow) should definitely be explored and researched. One of these alternatives is ES. ES has certainly garnered plenty of interest among physical therapists the last decades. Clinical research has provided mixed results, with some researchers reporting an increase in blood flow with electrical stimulation [7-11], other researchers reporting a decrease [12-14], and others reporting that electrical stimulation has no effect on blood flow [15-18]. However, most studies investigated cutaneous blood flow, and not muscle blood flow. In addition, some researchers used electrical stimulations with intensities high enough to evoke muscle contractions.

Electrical stimulation (specifically transcutaneous electrical nerve stimulation (TENS)) is also used in clinical settings as a method for pain relief [19]. For this goal, mostly high-frequency (~100 Hz), low intensity (sensory stimulation that does not cause muscle contractions) stimulations are used, with electrodes placed at the injured site. In contrast, low-frequency (< 10 Hz), high-intensity stimulations are often used to evoke muscle contractions, with electrodes placed at muscle motor points. Various forms of TENS have been shown to be effective methods for pain relief, either via stimulation of group II myelinated afferent fibers [20], or via stimulation of group III and IV afferent fibers [21].

The 10 kHz electrical current is part of a fairly new device in the field of electrical stimulation and is mainly used for rehabilitation of skeletal muscle. It has found its use in physical therapy and various forms of sports (e.g. football, volleyball). This devices produces direct current (main signal) compounded with a high frequency background waveform (a patented modified form of Russian current)[22]. Russian current can be defined as time-modulated alternating current [23]. It allows current to flow and cease for a few milliseconds in a repeated cycle. The high frequency (10 kHz) background signal is provided to counter the negative side effects of direct current, such as pain and skin burns. According to the manufacturer, this background signal has two uses: in combination with the main signal (acting as a pain modulator), or by itself (to enhance blood flow and provide muscle relaxation) [24]. In the latter case the signal is called ES-10kHz. It should be noted that this signal operates at a much higher frequency (10kHz) than any of the devices used in previous studies, and is used for sensory stimulation [22].

The aim of this study was to determine the effect of ES-10KHZ on blood flow to the treated area. Two muscles were studied: m. vastus lateralis (VL) and m. vastus medialis (VM). These muscles were chosen because they are easily accessible and because the upper leg is large enough for all the equipment to fit on. An exercise condition in the form of knee extensions was added to give insight in the clinical relevance of ES-10KHZ. This exercise was chosen since VM and VL are both knee extensors.

The following research questions were formulated:

1. Does ES-10KHZ provide an increase in blood flow in the treated area compared to rest?
    1.1. Is the effect of ES-10KHZ the same for the m. vastus medialis and the m. vastus lateralis?
    1.2. How does the effect of ES-10KHZ compare to the effect of light exercise?

No overall increase in blood flow to the treated area was expected. No difference in effect was expected for the two studied muscles. Finally, it was expected that the effect of light exercise would be larger than the potential effect of ES-10KHZ.

Method and materials

Study design

The study was conducted at the Amsterdam Rehabilitation Research Center (Reade Center for Rehabilitation and Rheumatology, Amsterdam). All subjects were tested once. The subjects were subjected to ES-10KHZ twice for 5 minutes, and had to perform 30 knee extensions once. The experiment lasted approximately one hour per subject. An overview of the study design is given in figure 1. The Faculty Ethics Committee approved the study and all subjects gave their written informed consent.

Figure 1. Overview of the study design. All blocks are drawn at scale. VMR: Vastus Medialis Rest, VMES: Vastus Medialis ES-10KHZ, VLR: Vastus Lateralis Rest, VLES: Vastus Lateralis ES, VLEX: Vastus Lateralis Exercise.

Subjects

Twenty healthy subjects (14 men and 6 women) participated in this study. They were recruited from the VU University Amsterdam, the Reade Rehabilitation Center, and our friend circles. Demographic information about the subjects can be found in table 1.

Table 1. Demographic information about subjects. BMI: body mass index.

Height (cm)	180.3	± 8.2
Body mass (kg)	69.5	± 10.6
BMI	21.3	± 2.3
Age (years)	22.8	± 3.0
Sport (hours/week)	4.8	± 2.8

Preparation

The subject was placed supine on a physical therapy table in a comfortable position prior to the test. The backrest had an upward angle of 30°. The right leg was supported underneath the knee with a knee cushion. Two self-adhesive electrodes (9 x 5 cm) were placed on the distal side of the muscle bellies of the VM and VL. A wireless continuous-wave near-infrared spectrophotometer (Portamon, Artinis Medical System, Zetten, The Netherlands) was placed in between the electrodes (figure 2). A pneumatic cuff was placed proximal to the pads (not visible in figure 2).


Figure 2. Electrodes and NIRS placement.

Protocol

The experiment started with a 15-minute rest period after placement of the instruments. This was done to make sure the subject was fully rested before any measurements were made. After the initial rest period, blood flow measurements were made during passive rest and during electrical stimulation on the VM, using venous occlusion (50 mmHg). This was followed by a 5-minute recovery period. During this period, the NIRS device was placed on the VL. After the recovery period, measurements were again made during passive rest and during electrical stimulation. This was followed by another 5-minute recovery period.

In the final measurement, subjects were asked to perform 30 knee extensions in 2-second cycles (figure 3). Measurements were made directly following the exercise. This was necessary because it is difficult to measure blood flow with NIRS during rhythmic contractions [25]. All venous occlusions lasted 20 seconds, and were separated by 40 seconds of recovery. An overview of the protocol is given in figure 4.


Figure 3. Knee extension exercise.

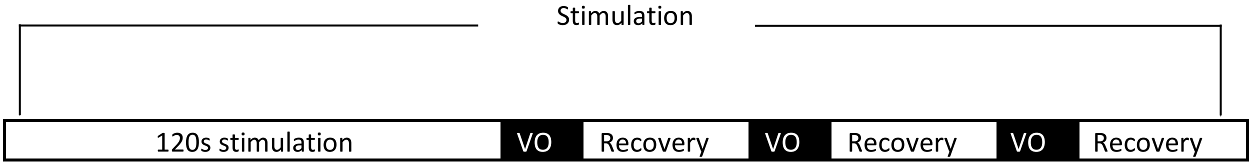

Figure 4. Overview of the protocol used in this study. All blocks are drawn at scale. Blood flow measurements were made during VO (venous occlusion).

ES-10KHZ

An electrical stimulation device was used for electrical stimulation. The recovery signal was used for this study, which produces sensory level stimulation. This means that no muscle contractions were evoked due to electrical stimulation. The low intensity of the recovery signal means that the sensation is quite similar to tickling.

The ES-10kHz mode produces a constant amplitude sine-wave signal with a frequency of 10,000 Hz and pulse duration of 25 µs. These parameters cannot be changed. The intensity was set at maximum, according to the manufacturer's recommendation. Subjects received electrical stimulation for 5 minutes at a time, followed by a 5-minute rest period. Two sets of self-adhesive electrodes were used: one set for each muscle. The electrodes were placed on the distal side of the muscle belly.

Blood flow measurements

NIRS (near-infrared spectroscopy) in combination with venous occlusion was used to measure blood flow. This method was chosen because it is a non-invasive method to directly measure blood volume changes by monitoring the hemoglobin/myoglobin content within the muscle. An example of such a measurement is depicted in figure 5. This technique is widely used in research settings and has been validated as a method for blood flow measurement [26-28].

Venous occlusion was applied by inflating a cuff to a pressure of approximately 50mmHg, blocking the venous outflow but not the arterial inflow. This resulted in an increase of blood volume in the part of the limb distal from the cuff. Blood flow was calculated from the increase in total hemoglobin (tHb) after venous occlusion [26, 29]. The sum of oxyhemoglobin (O_2Hb) and deoxyhemoglobin (HHb) concentrations ([O_2Hb] and [HHb]) reflects the total hemoglobin concentration ([tHb]) and changes in [tHb] can be interpreted as changes in blood volume in the tissue. Changes in [tHb] are expressed in µM/s and were converted to milliliters blood per minute per 100 milliliters tissue (ml/min/100ml). Male and female hemoglobin concentrations were derived from literature [30]. For males 15.5 g/dL was used, for females 14.5 g/dL. The molecular weight of hemoglobin (64.458 g/M) and the molecular ratio between Hb and O_2 (1:4) were also taken into account. Blood flow was calculated using the following formula [26]:

$$BF = (((\,tHb \times 60) / (([Hb] \times 1000) / 4)) \times 1000) / 10$$

in ml/min/100ml.

For the analysis, the change in [tHb] during the VO was calculated and divided by the time ([tHb-max] – [tHb-min] / t), to obtain tHb (figure 5). The calculated tHb was used in the above formula to calculate blood flow in ml/min/100ml tissue.

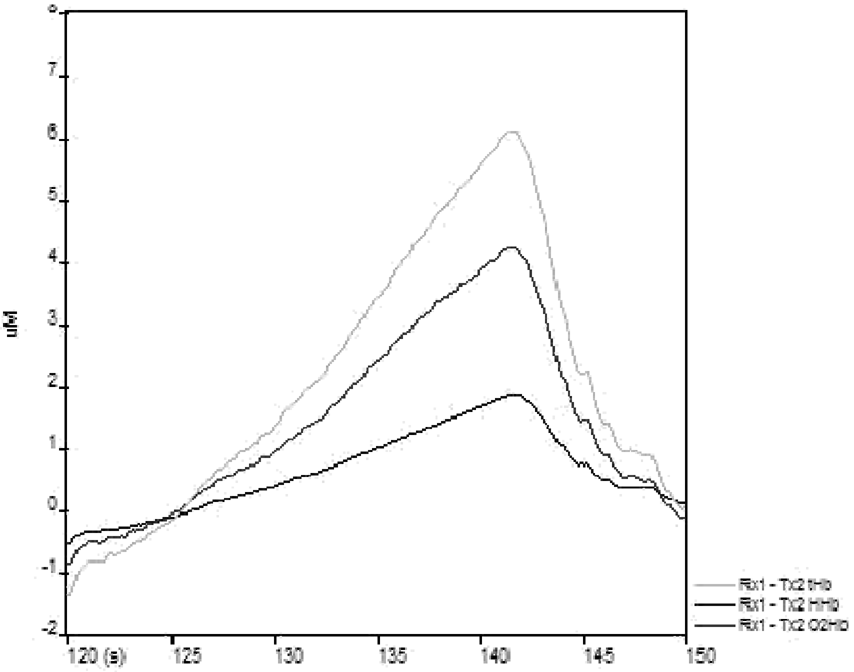

Figure 5. NIRS measurement during venous occlusion. The lines from top to bottom: [tHb], [O_2Hb], [HHb]. For the data-analysis the change in [tHb] was divided by the time to obtain the slope that was used in the formula.

Statistics

A Shapiro-Wilk test was used to check all variables for normality ($p < 0.05$). Square root transformations were performed on variables that failed the normality test. A repeated measures within-subjects ANOVA was performed to test the reproducibility of the three measurements per condition. Average blood flow was calculated for every condition and occlusion, and a coefficient of variation (CV) was also calculated to give more insight in the reproducibility. Since the measurements did not statistically differ from each other and the coefficient of variation was low, they were considered reproducible.

A 2 x 2 x 3 [Muscle (VM, VL) x Condition (Rest, ES) x Occlusion (first, second, third VO)] repeated measures within-subjects ANOVA was performed to test the effect of ES-10KHZ on the blood flow of the upper leg. Follow-up paired t-tests were performed if significant main effects were found. The assumption of sphericity was checked [31]. If the assumption was violated and the Greenhouse-Geisser epsilon was > 0.75, the Huynh-Feldt correction was used. If the assumption was violated and the Greenhouse-Geisser epsilon was < 0.75, the Greenhouse-Geisser correction was used. Partial eta^2 was also calculated to determine the effect size. All tests were performed with an alpha of 0.05. Follow up tests were performed one-tailed.

Results

The reproducibility of the three consecutive NIRS measurements was checked by means of four repeated measures ANOVAs combined with the coefficient of variation. Since the measurements did not statistically differ from each other, and the CV's were low, they were considered reproducible. All values of the measurements, as well as a coefficient of variation, are presented in table 2. The pooled data of the measurements can be found in table 3, as well as the average differences between resting and ES-10KHZ condition for both muscles.

Blood flow was not higher for the ES-10KHZ condition (M = 0.797, SD = 0.61) compared to the resting condition (M = 0.757, SD = 0.54) (*p* = .234). In figure 6, individual differences between both muscles and conditions are plotted. In general, higher blood flow values and bigger differences between conditions were found for the VM (blacked dots). However, a decrease in blood flow was found in ~40% of the subjects. For the VL not only were the values lower, but the differences between conditions were also markedly smaller. Most of the time the resting values were higher than the ES-10KHZ values.

Table 2. Reproducibility of NIRS blood flow measurements during three consecutive venous occlusions (VO). Values are mean ± SD, and the coefficient of variation is given for each variable.

	VO I	**VO II**	**VO III**	**CV (%)**	**Significance**
VM Rest (ml/min/100ml)	0.97 ± 0.66	0.93 ± 0.61	0.96 ± 0.68	7.7	*p* = .716
VM ES (ml/min/100ml)	1.00 ± 0.65	1.08 ± 0.72	1.08 ± 0.76	6.3	*p* = .122
VL Rest (ml/min/100ml)	0.56 ± 0.33	0.59 ± 0.40	0.53 ± 0.28	6.9	*p* = .121
VL ES (ml/min/100ml)	0.52 ± 0.36	0.53 ± 0.29	0.56 ± 0.39	10.7	*p* = .604

Table 3. Effect of ES-10KHZ and light exercise on upper leg blood flow. Values are mean ± SD. * Significantly higher than rest, *p* < 0.001.

	VM	**VL**	**Effect**	**Significance**
Rest BF (ml/min/100ml)	0.96 ± 0.64	0.56 ± 0.33	Muscle	*p* < .001
ES BF (ml/min/100ml)	1.06 ± 0.70	0.54 ± 0.33	Condition	*p* = .234
-BF (Rest-ES) (ml/min/100ml)	0.10 ± 0.19	-0.02 ± 0.08	Muscle x Condition	*p* < .05
Exercise (ml/min/100ml)		1.07 ± 0.58*		

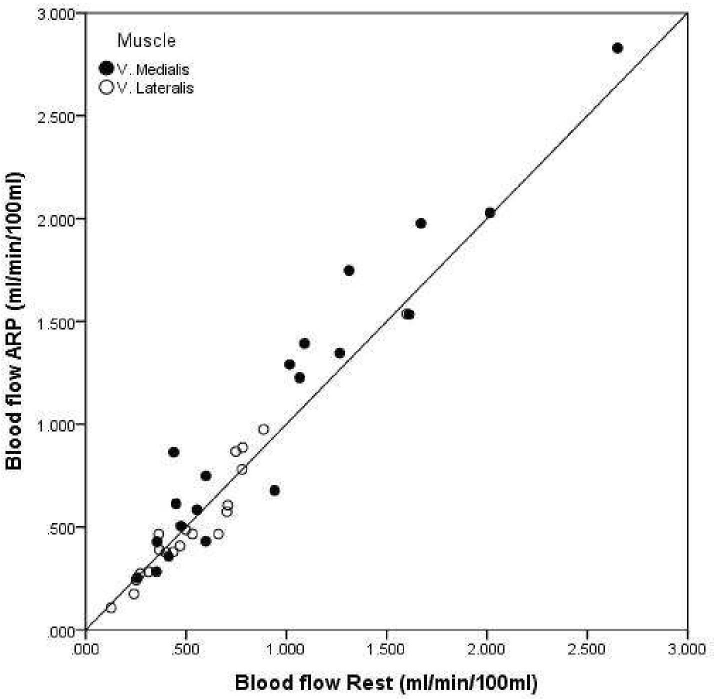

Figure 6. Individual differences in blood flow between the two conditions.

We found a 'muscle x condition' interaction effect, meaning the responses were different for both muscles, $F(1, 19) = 5.126$, $p < .05$, $\eta_p^2 = .212$. In the VM, blood flow in the ES-10KHZ condition was significantly higher (M = 1.06, SD = 0.70), when compared to resting condition (M = 0.96, SD = 0.64), $F(1, 19) = 3.994$, $p < .05$, $\eta_p^2 = .174$. However, in the VL, there was no significant difference between blood flow in the ES-10KHZ condition (M = 0.54, SD = 0.33), when compared to the resting condition (M = 0.56, SD = 0.33) ($p = .177$).

Subjects had a significantly higher blood flow in the exercise condition (1.07 ± 0.58), when compared to the ES-10KHZ condition (M = 0.54 ± 0.33), $t(19) = 7.311$, $p < .001$, $r = 0.86$, 95% CI [0.35, 0.72].

Blood flow was higher in the VM (M = 1.01, SD = 0.67) compared to the VL (M = 0.55, SD = 0.33), $F(1, 19) = 21.176$, $p < .001$, $\eta_p^2 = .527$. This was the case both in rest and during electrical stimulation.

Discussion

In the present study the effect of ES-10KHZ on upper leg blood flow was investigated. No overall increase in blood flow to the treated area was expected. Finally, it was expected that the effect of light exercise would be larger than the potential effect of ES-10KHZ.

ES-10KHZ

The results of the study show that there was no overall statistically significant increase in blood flow to the treated area when subjected to ES-10KHZ. This result is in line with our hypothesis. Previous studies on the effect of TENS on blood flow have shown mixed results [7-17]. However, most of these studies looked at cutaneous blood flow rather than muscle blood flow. Only a few researchers studied the effect of TENS on muscle blood flow, with mixed results [9, 17, 18]. One of these studies showed an increase in muscle blood flow when subjected to electrical stimulation, but only when stimulation intensity exceeded the motor threshold [9]. It has been previously suggested that electrical stimulation at intensities above the motor threshold promote blood flow due to metabolic demand of contracting muscles [15]. It should be taken into account when discussing prior studies that the ES-10KHZ signal operates at a much higher frequency (10 kHz) than other devices.

The results of the study show that there was an increase in blood flow to the VM when subjected to ES-10KHZ. For the VL, no such effect was found. A difference between the two muscles is the proximity of the VM to the nervus saphenus. It has been proposed that TENS over a peripheral nerve induces the release of substance P (a neurotransmitter related to the sensation of pain) from the sensory nerve endings and therefore triggers vasodilation of the vessels, resulting in an increase in blood flow [32]. This could explain our different results for both muscles. However, this is speculation on our part, and should be further investigated. Another mechanism that could explain our finding is that stimulation at sensory level threshold causes alterations of sympathetic vasomotor activity which increases blood flow [33]. In a study on dorsal stimulation of sympathectomized rats, an increase in microcirculation of both skin and muscle blood flow was found in healthy controls but not in the experimental group. These results suggest that induced sympathetic vasomotor activation has an influence on blood flow. A direct comparison with our study is not possible, since the stimulation sites were different: The rat's dorsal columns were stimulated, whereas in our study only peripheral nerves were stimulated.

One finding we did not necessarily expect was that blood flow was not the same for the VM and VL. This was the case not only in rest ($p < .001$), but also during electrical stimulation ($p < .001$).

Previous studies on upper leg blood flow heterogeneity have shown that blood flow to different muscles is not uniformly distributed, either in humans [34] or in animals [35, 36].

Clinical implications

Comparison of the effects of ES-10KHZ and light exercise was difficult, because of two reasons: The VL showed a non-significant decrease in blood flow during ES-10KHZ (1) and differed significantly from the VM, both in rest and during stimulation (2). Since blood flow during exercise was only measured in the VL, this makes a direct comparison of effect sizes impossible. We can, however, compare the relative increases in blood flow during stimulation (VM) and exercise (VL).

In the VM, an increase of roughly 10% was seen in the ES-10KHZ condition. This means an extra 6ml blood per 100ml tissue when subjected to ES-10KHZ for an hour. In practice, this could mean that the supply of fuel back into the exercised skeletal muscle and the clearance of metabolic byproducts from the muscle and blood can be accomplished 10% faster when compared to rest. Although this effect is small compared to light exercise, where a 100% increase in blood flow was found, ES-10KHZ has a benefit: it can be used while sleeping. This means that users can be subjected to ES-10KHZ for a whole night, and thus receive any potential effects for a whole night. This is actually how ES-10KHZ is commonly used in practice by the national Dutch football team. It should also be taken into account that the increase in blood flow during the ES condition is net profit, whereas the increase in blood flow after exercise is gross profit (due to the increased metabolic demand of contracting muscle). However, we would argue that the net profit for exercise is larger than 10%, because even for exercises performed at low intensities (7.5%-15% MVC) an increase in blood flow of about 50% has been found [37]. Such exercises have been hypothesized to be equivalent to walking at 1 mile per hour [37].

Keep in mind that, since no increase in blood flow was found in the VL, the 10% increase could represent the ceiling of ES-10KHZ (i.e. the maximum increase one could reasonably expect). This is in stark contrast with light exercise, where a 50% increase in blood flow is the floor (i.e. the minimum increase one could reasonably expect). The above results suggest that walking at a moderate pace is better suited for both short-term recovery and training recovery (when time is limited) than ES-10KHZ.

Methodological considerations

The study was carried out in two different rooms, with different dimensions. A complete session always took place in one room. Since the rooms were not climate controlled, the smaller room tended to get heated up rather quickly; at least that is how it was experienced by our subjects. This could have had an effect on blood flow. However, one would expect limb blood flow to increase with higher ambient temperatures. Since our blood flow values were on the lower side, we assume that ambient temperature did not influence our results much.

Adipose tissue thickness (ATT) was not measured in this study. NIRS measurements assess not only muscle tissue, but also all the overlying tissue, such as fat and skin. This means the light travels through multiple layers of inhomogeneous tissue. The subcutaneous layer can vary considerably due to individual differences in ATT. It is known that ATT can have a confounding effect on NIRS measurements [38]. However, the subjects in this study were taken from an active population (mostly sporting students with a normal BMI). They all probably have relatively low ATT values which should not influence our measurements significantly [27].

It was advised by Manufacturer to place the electrodes directly at the motor trigger points of the VM and VL. Due to spatial limitations on the upper leg, it was not possible to comply with their advice. We are skeptical about placement being an issue, since no muscle contractions were evoked. It has previously been shown that TENS applied over a peripheral nerve only has a positive effect on blood flow when the motor threshold was exceeded [9, 10].

Concluding remarks

In general, electrical stimulation using ES-10KHZ does not enhance upper leg blood flow. However, we did find an increase in blood flow in one of the two studied muscles. We have not found a conclusive argument for this finding. Several mechanisms that could possibly explain the increase in blood flow to the VM have been discussed earlier and should be explored further.

In future researches on this topic, all methodological considerations from this study should be taken into account. ATT should ideally be measured for every subject, especially when researching the general population and using NIRS as a measurement device, because large discrepancies between individuals can exist and NIRS only has a limited reach.

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