Lasers in Medical Science (2019) 34:1681–1688
https://doi.org/10.1007/s10103-019-02769-6

ORIGINAL ARTICLE

Changes in local skin temperature after the application of a pulsed Nd:YAG laser to healthy subjects: a prospective crossover controlled trial

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Received: 23 October 2018 / Accepted: 6 March 2019 / Published online: 22 March 2019

Abstract

Pulsed Nd:YAG laser (1064 nm) is a recent modality that is used for the rehabilitation of musculoskeletal disorders, but there is no evidence about its thermal effects. The aim of the study was to investigate the changes in local skin temperature (LST) after the application of a pulsed Nd:YAG laser to healthy subjects. The study participants were 30 male subjects with an average age of 21.96 (± 0.92) years. A rectangular area ($15 \times 10\ cm^2$) was marked at the front of the dominant thigh and scanned with a laser beam at 3000 J with 20 J/cm^2 for 15 min. The other thigh was considered as a control side. The minimum, average, and maximum LSTs were measured using a thermographic camera. The measurements were performed before laser application, immediately after, and then every minute until the LST returned to the pre-treatment value. An independent t test and repeated measures ANOVA were used to analyze the changes in LST. The level of significance was set at $p < 0.05$. The pulsed Nd:YAG laser significantly increased the minimum, average, and maximum LSTs in comparison with the control. The increase was significant for up to 5 min after the application, and it took 10 min to reach the baseline values. The level of increase was 1.23–4.03 °C, and the average increase was 2.6 °C. The pulsed Nd:YAG laser significantly increased the minimum, average, and maximum LSTs of the thigh area in normal subjects, and the thermal effect lasted for 5 min after application.

Keywords Pulsed Nd:YAG laser · Thermal effect · Thermographic camera

Introduction

Lasers have a long history of use in the rehabilitation of musculoskeletal pain and inflammation, as well as enhancing wound healing [1]. The laser power used may differ according to the laser material, wavelength, and emission mode [2]. The most common low-level lasers used in rehabilitation are helium-neon (He-Ne) and gallium arsenide (Ga-As) lasers, which are class II and IIIb lasers (power < 500 mW). Low-level laser therapy (LLLT) uses athermal or "cold" laser devices [1], which use low penetration of the exposed tissues to obtain clinical effects through photo-biostimulation [2, 3]. High-power lasers are used for cutting tissues and have benefits of simultaneous cauterization of the tissues during laser surgery [4, 5]. They are extensively used for destroying malignant tissue growth in several organs in a process called laser-induced thermotherapy [6].

Recently, a neodymium yttrium aluminum garnet (Nd:YAG) laser has been introduced in the physical therapy

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field and used extensively in the rehabilitation of musculoskeletal disorders [1]. Pulsed Nd:YAG laser is a class IV lasers with 3000 W of power, a wavelength of 1064 nm, pulsed emission at 10–30 Hz, and elevated levels of fluency (up to 1780 mJ/cm^2). Pulsed Nd:YAG laser can be applied to a large treatment area with a short treatment time. The 1064-nm wavelength works in a therapeutic window that allows more penetration than He-Ne and Ga-As lasers [1]. Pulsed Nd:YAG laser is considered as an effective modality in the treatment of pain in various musculoskeletal [7–11], inflammation [8, 11], and wound applications [12], as well as the recovery of nerves [13].

Lasers produce a large number of photons, and when absorbed, they produce kinetic energy that is converted into heat, which depends on the nature of the tissues and the laser parameters (the wavelength, power, and energy density) [14]. Excessive temperature (50–100 °C) induced by high-power lasers may be accompanied by tissue destruction (coagulation, vaporization, cutting, etc.) [15]. Therefore, it is important to control the intensity, duration, and dose of the laser pulse to minimize thermal damage to adjacent structures.

The literature suggested that high-power lasers have some thermal properties associated with their application [14, 16, 17]. The thermal effect can be measured simply by a thermographic camera, which is a non-invasive technique that allows quick and non-contact detection of the irradiated energy released from heated tissue [18, 19]. Although some clinical studies have used pulsed Nd:YAG laser devices, no study has reported on their quantitative or qualitative thermal effects. Therefore, the aim of this study was to investigate the thermal effects of pulsed Nd:YAG lasers by measuring the changes in the local skin temperature (LST) after laser application to healthy adults.

Methods

Subjects

The study design was a prospective, crossover-controlled trial. A total of 30 healthy male subjects were randomly selected from students at the Physiotherapy and Rehabilitation Department, Faculty of Applied Medical Science, Umm Al-Qura University, Mecca, Saudi Arabia. All subjects were male and had a mean age of 21.96 ± 0.92 years, weight of 71.06 ± 6.53 kg, height of 169.73 ± 4.841 cm, and body mass index of 24.67 ± 2.1 kg/m^2. All participants signed an informed consent form prior to the study, which included agreement to participate, approval of the use of the thermographic camera, and agreement to use the data to publish this study. The study was approved by the Ethical Committee of the Faculty of Applied Medical Science, Umm Al-Qura University (local registry number: 15-STU-MED-1438). The study was performed according to the 1964 Declaration of Helsinki and subsequent amendments or comparable ethical standards.

A power analysis was performed with G-power 3.1 software for Windows to determine the proper sample size to detect differences between two dependent means (matched pairs) with the following: α err prob = 0.05, power (1 − β err prob) = 0.95, and effect size = 0.8. The recommended sample size was 23, which was increased to 30 participants to account for possible dropout. A total of 30 subjects were recruited, who had normal health and no complaints of any lower limb pain or weakness. Subjects did not perform any strenuous exercises within 1 h prior to the experiment (such as a long-distance walking or running and ascending or descending stairs). All participants received a proper explanation of the purpose and methods of the experiment.

An air conditioner kept the room temperature constant at 25 °C with 60% relative humidity. The temperature and humidity of the room were recorded with a thermo-hygrometer. Reliable measurements of the temperature distribution over the thigh areas were obtained by exposing every subject while lying in a relaxed position on a couch for 20 min to adapt to the conditions of the surroundings before imaging.

A test of thermal skin sensation was performed using test tubes. Three transparent glass tubes (30 mm × 165 mm, 10-ml flat glass test tubes with screw caps) were filled with hot (45 °C), room temperature (25 °C), and cold water (10 °C). The tubes were applied to the subject's skin, who was asked to report the differences between the three temperatures while blindfolded. The subjects participated in the study if they were able to differentiate between the three temperatures.

The front thigh areas were exposed. A rectangular area (15 cm × 10 cm) on the anterior aspect of both thighs was marked with tape (Fig. 1). A pulsed Nd:YAG laser was applied over the thigh of the dominant side, and the other thigh was considered as a control side.

Measurement of local skin temperature

A high-resolution thermal image with a thermal sensitivity of 0.1 °C was obtained to detect the skin temperature of the fronts of both thighs by a thermographic camera (FLK-TIS10, Fluke®, Everett, WA, USA). According to the product information, the camera has a measurement range of − 20 to + 250 °C, a thermal sensitivity of ≤ 0.15 °C at a target temperature of 30 °C, and an accuracy of ± 2%. The high-resolution thermal images give detailed information about the thermoregulation of tissue when subjected to heat [18, 19]. The thermographic camera has been shown to be a valid and reliable method for measuring LST in humans [20, 21].

The minimum, average, and maximum LSTs obtained by the camera provided a thermal profile of each subject for comparisons between and within subjects [22]. The LST measurements were performed by the same therapist and at the same

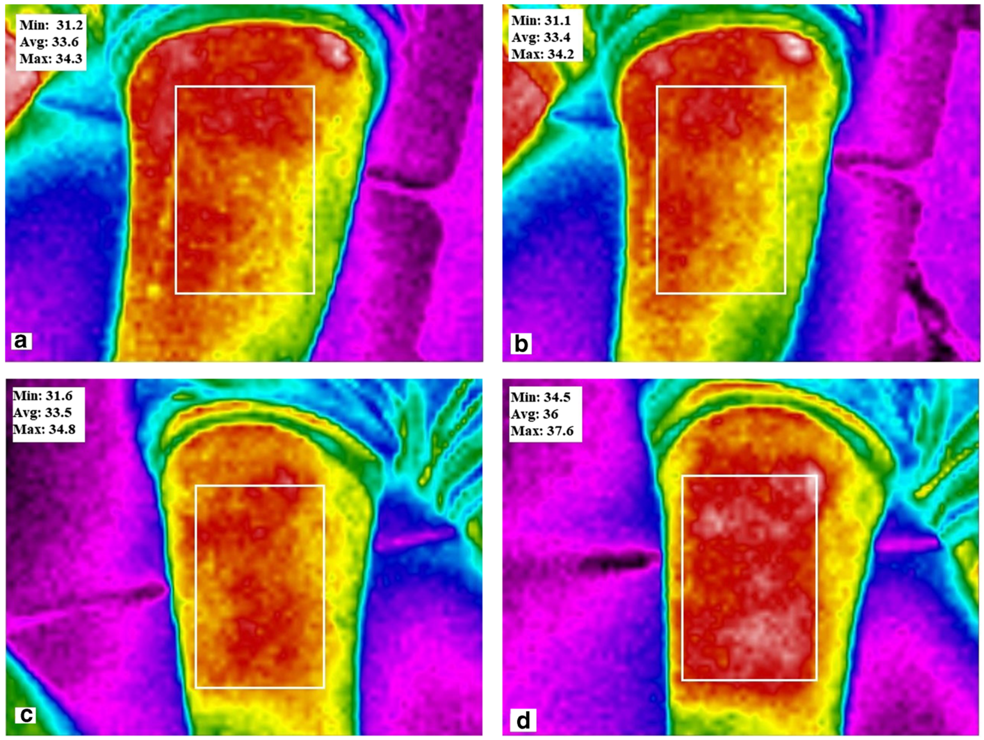

Fig. 1 Thermal images of thigh skin temperature: **a** Left control before treatment (Pre), **b** left control after the first treatment ($Post_0$), **c** right thigh before treatment (Pre), and right thigh after treatment ($Post_0$). The minimal, average, and maximum local skin temperatures were displaced on each photo

time of the day. The thermographic camera was kept perpendicular to the center of the tested area, and the distance from the front of the camera and the subject's test area was constant at 0.5 m (Fig. 1). The photos were captured manually before laser application (pre-scanning), immediately after ($Post_0$), and every minute for up to 10 min ($Post_{1-10}$) until the LST returned to the pre-treatment values.

To obtain more accurate temperature measurements, the emissivity, span, temperature units, and background temperature were adjusted in the camera configurations. The thermographic camera was calibrated before starting the study. The calibration was performed according to the international temperature scale (ITS-90) [23] against a blackbody with an emissivity ε of 0.99 and distance of 1 m.

The thermal images were transferred from the thermographic camera to a computer in the IS2 photo file format. The photos were processed using SmartView 4.3 software for Windows, which is provided with the thermographic camera. When marking the predetermined box spot (15 cm × 10 cm) on the photos, the software displayed the numerical temperature data of the minimum, average, and maximum LSTs of the treated and untreated thighs.

Pulsed Nd:YAG laser

The pulsed Nd:YAG laser (HIRO 3 device ASA, Arcugnano, Vicenza, Italy) was applied over the anterior part of the thigh on the dominant side. The laser had the following parameters: 1064-nm wavelength, pulse duration of 100 μs, peak power (max) of 3 kW, intensity (max) of 15,000 W/cm^2, energy per pulse (max) of 350 mJ, elevated levels of energy density of 710, 970, and 1070 mJ/cm^2, frequency of 20 Hz, duty cycle of about 0.1%, 0.5-cm probe diameter, and 0.2-cm^2 spot size. Both the subject and the therapist wore laser goggles.

While the patient was in a supine position, the therapist used the laser probe to perform perpendicular manual scanning transversely and longitudinally on the treated area. Based on the literature, each laser session was divided into an initial phase and a final phase. In the initial phase, scanning was applied with a fast speed to cover 3 to 5 cm in 1 s. The energy density was gradually increased in three subphases with energy densities of 710 mJ/cm^2 (500 J) (3 min), 970 mJ/cm^2 (500 J) (2 min and 15 s), and 1070 mJ/cm^2 (500 J) (2 min) to apply a total of 1500 J. The final phase was the same as the initial phase except that the manual scanning speed was decreased to cover 1–2 cm in 1 s. Transverse and longitudinal scanning was repeated until the laser beam covered the whole treated area with a predetermined energy density. The total energy delivered to the corresponding area was 3000 J with an energy density of 20 J/cm^2, and the total application time was approximately 15 min. The laser scanning was performed by the same therapist throughout the study. Throughout the session, instantaneous feedback was obtained from the subject to report any uncomfortable sensations during the application. The device calculated the energy emitted in each phase, as well as the total energy delivered to the patient over the entire treatment session. The laser device was calibrated by the manufacturers for constant output throughout the experiment.

Data analysis

Demographic data and the minimum, average, and maximum LSTs were collected from every subject and recorded in an Excel sheet. An independent *t* test was performed to compare each LST value on the treated and un-treated thighs at the same measurement intervals. Repeated measures ANOVA and a post hoc Bonferroni test were performed to detect any significant changes in LST on both thighs in the pretreatment and post-treatment intervals. The level of significance was set at $p < 0.05$.

Results

At pre-treatment, the independent *t* test showed non-significant differences in the main values of the minimum, average, and maximum LSTs. The minimum LST significantly increased at $Post_{0-5}$ (post-treatment intervals from $Post_0$ to $Post_5$) with non-significant changes between $Post_{6-10}$ intervals in comparison with the controls. The post-Bonferroni test showed a significant increase in the minimum LST $Post_{0-5}$ as compared with the mean values of the minimum pre-scanning LST (Min_{pre}) (observed power 1.00). There were non-significant changes between the mean values of Min_{pre} and $Post_{6-10}$ (Table 1).

Similar results were obtained in the average and the maximum thigh skin temperatures as the minimum LST. There was a significant increase in the average LST at $Post_{0-8}$, and non-significant increases in $Post_{8-10}$ in comparison with the controls (Table 1 and Fig. 2). Compared with average pre-scanning LST (Avg_{pre}), the average LST significantly increased after laser application at $Post_{0-5}$, but there were non-significant differences between $Post_{6-10}$ intervals.

There were significant increases in the maximum LST at $Post_{0-9}$, but there was a non-significant change in $Post_{10}$ in comparison with the controls (Table 1 and Fig. 2). Furthermore, there were significantly increases at $Post_{0-6}$ (observed power 1.00) with non-significant changes between $Post_{7-10}$ in comparison with the mean maximum pre-scanning values (Max_{pre}). In the controls, there were non-significant differences between the pretreatment mean values of the minimum, average, and maximum LSTs and the mean $Post_{0-10}$ values (Table 1 and Fig. 2).

Discussion

The results showed that the pulsed Nd:YAG laser significantly increased the minimum, average, and maximum LSTs in comparison with the controls. The significant increase lasted up to 5 min after laser application, although the thigh temperature took 10 min to reach baseline values. The pulsed Nd:YAG laser has a high power level of 3000 W and high intensity of 15,000 W/cm^2. Moreover, the wavelength of 1064 nm works in a therapeutic window that has a low absorbability rate in superficial tissue layers, so it penetrates more deeply than other types of lasers, such as He-Ne or Ga-Al-Ar lasers [1].

Table 1 Change in thigh skin temperature before and after application of a pulsed Nd:YAG laser

	Minimum LST			Average LST			Maximum LST		
	Laser	Control	*p* value	Laser	Control	*p* value	Laser	Control	*p* value
Pre	32.06 ± 0.64	31.91 ± 0.78	0.399^C	33.19 ± 0.58	33.02 ± 0.81	0.364^C	34.20 ± 0.56	34.41 ± 0.49	0.124^C
$Post_0$	34.70 ± 0.50	31.92 ± 0.78	0.0001^a	35.61 ± 0.65	33.01 ± 0.83	0.0001^a	36.93 ± 0.43	34.24 ± 0.65	0.0001^a
$Post_1$	34.00 ± 0.49	31.91 ± 0.79	0.0001^a	34.98 ± 0.58	33.01 ± 0.87	0.0001^a	36.57 ± 0.57	34.24 ± 0.98	0.0001^a
$Post_2$	33.65 ± 0.39	31.86 ± 0.75	0.0001^a	34.79 ± 0.92	32.98 ± 0.79	0.0001^a	36.22 ± 0.51	34.16 ± 1.02	0.0001^a
$Post_3$	33.19 ± 0.41	31.88 ± 0.74	0.0001^a	34.38 ± 0.51	32.98 ± 0.81	0.0001^a	35.87 ± 0.52	34.11 ± 1.08	0.0001^a
$Post_4$	32.77 ± 0.58	31.85 ± 0.73	0.0001^a	34.01 ± 0.85	32.98 ± 0.75	0.0001^a	35.48 ± 0.92	34.11 ± 1.02	0.0001^a
$Post_5$	32.37 ± 0.69	31.87 ± 0.71	0.008^a	33.92 ± 0.77	32.94 ± 0.75	0.0001^a	35.29 ± 0.88	34.09 ± 1.05	0.0001^a
$Post_6$	32.18 ± 0.73	31.82 ± 0.70	0.057^c	33.75 ± 0.82	32.91 ± 0.79	0.0001^a	35.07 ± 0.96	34.09 ± 0.87	0.0001^a
$Post_7$	32.00 ± 0.77	31.79 ± 0.69	0.292^c	33.65 ± 0.88	32.92 ± 0.61	0.0001^a	34.91 ± 1.19	34.07 ± 0.78	0.002^a
$Post_8$	31.89 ± 0.70	31.79 ± 0.70	0.583^c	33.39 ± 0.82	32.92 ± 0.64	0.017^a	34.71 ± 0.87	34.02 ± 0.95	0.005^a
$Post_9$	31.82 ± 0.75	31.78 ± 0.70	0.832^c	33.23 ± 0.89	32.90 ± 0.65	0.109^c	34.65 ± 0.89	33.96 ± 1.09	0.009^a
$Post_{10}$	31.56 ± 0.78	31.79 ± 0.69	0.227^c	33.09 ± 0.88	32.83 ± 0.68	0.206^c	34.45 ± 0.97	33.94 ± 1.192	0.075^c
p value	0.0001^b	0.361^c		0.0001^b	0.839^c		0.0001^b	0.316^c	

LST: local skin temperature

[a] Significant difference between two treatment groups (unpaired *t* test; $p < 0.05$)

[b] Significant difference in the same treatment group (repeated measure ANOVA; $p < 0.05$)

[c] Non-significant difference

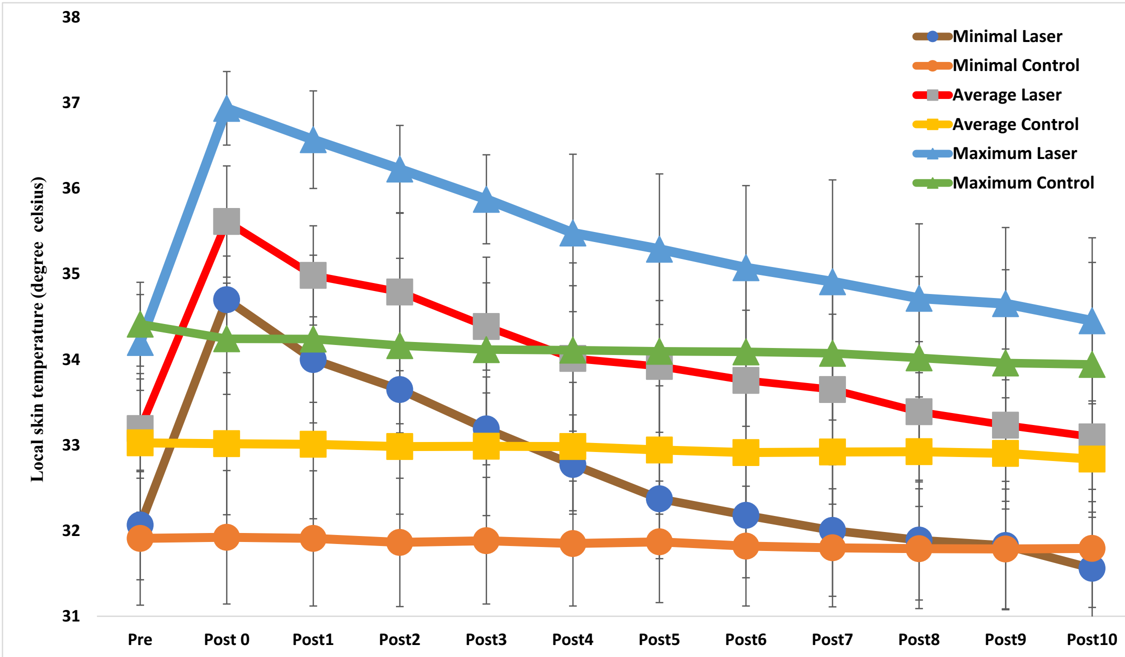

Fig. 2 Changes in the minimum, average, and maximum local skin temperatures

Thus, it can have photothermal, photochemical, and photomechanical effects [14, 24, 25].

With the advantages of pulsed Nd:YAG laser to deliver high energy densities to large and deep areas, great caution is taken for patients that receive this high fluency. Excess energy delivered to tissues may have adverse effects on the human body [26]. According to the biphasic dose response described by the Arndt-Schulz law, the irradiation parameters are considered to be the main issue in whether lasers have negative, positive, or no effects [26].

A local increase in tissue temperature to 37–43 °C produces hyperemia, but it is considered as safe and has no adverse effects on the surrounding tissues. Hyperemia results from relaxation of the smooth muscles of the blood capillaries and activation of the local spinal reflexes [27, 28]. Heat results in the dilation of blood vessels, increased blood flow and lymph circulation, and increased diffusion through the walls of capillaries, which result in faster metabolism. Heat also intensifies the process of removing exudates from the inflamed tissues. Defense mechanisms of the body against infections are activated, and the pain subsides. The muscles relax, and the extensibility of the connective tissue is increased. Local heat may also act on the function of other organs through reflex mechanisms [20, 29].

Vasodilatation is caused by a variety of mechanisms, including direct reflex activation of the smooth muscles, activation of the blood vessels by the cutaneous thermoreceptors, or by increasing the release of local chemical mediators of inflammation [30]. At the neuromuscular level, increased temperature has been known to increase nerve conduction velocity and decrease the conduction latency of both sensory and motor nerves [31]. Nerve conduction velocity increases by approximately 2 m/s when there is a 1-°C increase in tissue temperature [1, 5].

The present study showed increases in the LST of 1.23–4.03 °C with an average increase of 2.6 °C, which was significant for up to 5 min and returned to the baseline at 10 min after application. Mild hyperthermia is considered to be sufficient to accelerate or increase most cellular activity, and heat-induced vasodilatation can enhance local blood circulation in the tissues [32]. Heat can increase the extensibility of connective tissues, tendons, ligaments, and to some extent, muscle, which occurs by increasing extensibility and reducing tone and spasm [5, 32]. Therapeutically, a rise in tissue temperature by more than 1 °C helps to relieve mild inflammation, and an increase of 2–3 °C helps to reduce pain and muscle spasm. An increase of 3–4 °C can produce changes in tissue extensibility [5]. This level of increase may affect the nerve conduction velocity, although it was not measured in the current study.

Although the local increase in tissue temperature was limited, this study provides an objective measurement of the level of increase in LST after the application of a pulsed Nd:YAG laser, which is a main concern among laser researchers. The specific irradiation of the pulsed Nd:YAG laser with low frequency, brief duration (100 μs), and 0.1% duty cycle does not allow the temperature to exceed the thermal tolerance of tissue or cause any adverse effects described by the Arndt-Schulz law [26].

The thermal effects of a 200-mW infrared class 3B laser (810 and 904 nm) were investigated previously in healthy subjects. Laser irradiation was delivered to the subjects' hands at 2, 6, 9, and 12 J. The laser was able to increase the skin temperature significantly (5.7 ± 1.8 °C at 12 J) and produce photothermal effects, but the thermal pain threshold for humans may be exceeded at higher doses [33].

Another study examined the thermal effect of a cluster of 905-nm super-pulsed laser diodes on healthy individuals. The anterior thigh was irradiated with 10, 30, and 50 J. The results showed no significant increase in the skin temperature among different skin-color groups, age groups, and gender groups [34]. The skin temperature near the elbow was evaluated using energy doses of 2, 6, 9, and 12 J using visible (635 nm, 36 mW) and infrared laser diodes (808 nm, 40 mW). The mean increase in skin temperature was greater at 808 nm, with the temperature increase was 0.43 °C larger than with the 635-nm laser [35].

The physical modalities used in rehabilitation produce different physiological effects that depend on the surface of the body treated, the intensity of the stimulus, the stimulus duration, and changes in the intensity of the stimulus [36]. Therefore, a main concern of researchers is to adjust the physical stimulus dose to cause a specific response without any undesired effects [20, 37]. Ultrasound therapy produces a significant increase in the local temperature and blood flow in human skeletal muscle with high intensities of more than 3 W/cm^2, and there is evidence of vasodilatation at 2 W/cm^2 [38]. Another study measured the rate of increased temperature during the application of ultrasound therapy at 1 and 3 MHz. With increased frequency, there was a greater increase the temperature of tissues (0.38 °C at 2.0 W/cm^2 using 1 MHz and 1.4 °C at 2.0 W/cm^2 using 3 MHz) [39]. The effect of infrared irradiation was compared with that of diadynamic currents on the distribution of LST. After the infrared irradiation, the average LST of the right thigh increased by more than 4 °C, but no significant temperature changes were detected after diadynamic currents [20]. Recently, capacitive and resistive radiofrequency therapy was shown to significantly increase skin temperature, which was sustained for over 45 min of observation [40].

In the current study, the duration of the temperature increase was limited for the minimum LST (5 min), but the time was extended for the average LST (8 min) and the maximum LST (9 min). The area of laser application was the frontal aspect of the thigh, which was a muscular area. It was reported that the rise of temperature in muscular areas has a short duration due to the adaptation of the microvasculature of the skeletal muscle to increased blood flow, so the hyperemia serves to remove heat rapidly [41]. The different durations for the minimum, average, and maximum LST could be attributed to the manual scanning. Although the same operator applied the scanning to cover all the treatment areas equally, the manual scanning may have caused differences. Moreover, only the surface temperature of the subjects was measured, and the subdermal temperatures might have been significantly higher. Therefore, predictions cannot be made about whether this temperature increase is optimal or safe.

The use of different doses with different protocols may be necessary in future research to investigate the dose-dependent effects. Moreover, the use of other types of lasers, such as light-emitting diode, pumped Nd:YAG, and Q-switched Nd:YAG lasers, may be recommended for future works. Automatic laser scanning is also recommended to overcome the limitations of manual scanning.

Conclusion

The pulsed Nd:YAG laser significantly increased the minimum, average, and maximum LSTs of the thigh area in normal subjects. The thermal effect lasted for 5 min after application.

Limitations

Automatic scanning was not available for the pulsed Nd:YAG laser, so the laser beam was distributed manually all over the treating area. Although the laser operator was the same for all applications, the unequal distribution of the laser beam was considered as a limiting factor. Lastly, all the participants were males with no females, which may also be considered as a limiting factor.

Acknowledgments The authors would like to express their appreciation to all subjects participated in this study and special thanks to our colleagues at the Department of Physical Therapy, Faculty of Applied Medical Science, Umm AL-Qura University, Saudi Arabia.

Funding information This research received no specific grant from any funding agency in the public, commercial, or non-profit sectors.

Compliance with ethical standards

Conflict of interest There is no financial and personal relationship with other people or organizations that could inappropriately influence this work.

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