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Pulsed inductive laser on $3p-3s$ transitions of neutral neon atoms in the red spectral region

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The experimental studies results of the pumping conditions influence on the lasing characteristics of a pulsed inductive laser in the red spectral region based on transitions in neutral neon atoms are presented. Lasing was achieved on neon $3p-3s$ transitions at wavelengths of 607.4, 614.3, 630.4, 650.6, and 692.9 nm in optimized gas mixtures of neon with helium, oxygen, and hydrogen at operating pressures of 0.5 Torr and charging voltages ranging from 24 to 28 kV. The influence of the gas mixture composition and discharge tube geometry on the spectral and temporal characteristics of lasing is demonstrated. The influence of molecular oxygen concentration in neon-containing mixtures was also studied. It was shown that the formation of laser pulses started simultaneously, and their duration increased with increasing concentration of molecular oxygen in two-component mixtures with neon and could vary from 8 ± 1 to 14 ± 1 ns (FWHM). The total laser energy reached $1 \mu\text{J}$, corresponding to a pulse power of 150 W.

Keywords: pulsed inductive laser, neon laser, longitudinal inductive discharge, laser generation spectrum, neon red lines.

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Introduction

Lasers based on gaseous active media play a significant role in the modern science, engineering and daily life of people [1]. Unique combinations of emission characteristics make them irreplaceable tools in many fields of medicine and biology [2]. The example of such applications today is laser emission of red wavelength range, actively used in photodynamic therapy due to successful balance between the peak of absorption of photosensitizers and penetrability [3], diagnostics and treatment of ophthalmological diseases [4], low-level laser therapy (LLLT) [5].

The main factor that determines the efficiency of laser action on biological tissues is the ability of light to penetrate for the sufficient depth due to their optical properties, which has become a key for both diagnostic and therapeutic applications of lasers [6]. One of such areas was low-level laser therapy or photobiomodulation therapy, being a non-invasive method of treatment of skin diseases, ischemic ulcers and nonhealing wounds of various etiology, requiring healing stimulation, reduction of pain and extent of inflammatory processes, activation of restorative functions of biological cells [7,8]. Besides, the absorption of emission with mitochondrial chromophores with subsequent activation of the proliferation process happens in the skin cells, which makes the sources of laser emission of red and near IR-range especially effective in this aspect [9].

The first laser sources for therapeutic action of low-level laser emission were helium-neon and ruby lasers that generate at wavelength 632.8 and 694 nm accordingly [10].

The subsequent research showed that the highest proliferation effect arises in the „therapeutic window“, which is characterized by the minimum coefficient of hemoglobin and water absorption, which makes it possible for the light to penetrate deeper into the biological tissues [11]. Currently the practically used medical lasers operating in the red wavelength range include mostly solid-state lasers with diode pumping [12]. Besides, this type of lasers has certain disadvantages related to the low pulsed power (not more than 50 W), the need for use the parametric generators for the conversion of the frequency of emission into the visible range of the spectrum, complexity of scaling of laser units and cooling systems, vulnerability to the external actions and conditions. In connection with this the search for the alternative sources of laser emission used for the described purposes continues to be relevant.

The active laser medium making it possible to generate emission in the designated spectral area may be the inert gas, neon, excited by the electric discharge, having the relatively high quantity of electronic transitions in the red wavelength range [13]. The additives to the working gas, neon, may be different quenching particles and buffer gases, making it possible to influence both the spectral and the energy characteristics of laser emission. The specified influence was also shown in pumping of neon by a pulsed inductive discharge generated at the expense of the change in the magnetic flow in the contour of a solenoid that induces the electromotive force in the gas medium. The pulsed inductive discharge as the method of pumping of gaseous media of low pressure makes it possible to achieve

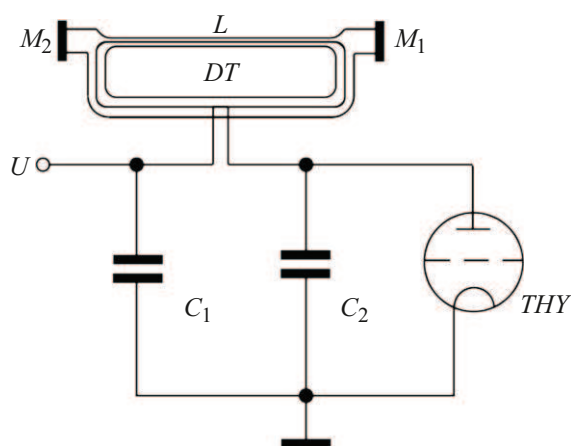


Figure 1. The electric circuit of neon active medium pumping with the pulsed inductive longitudinal discharge: U — charge voltage, $C_1 = 7.8$ nF, $C_2 = 13$ nF, THY — gas discharge tube TPI1-10k/20, DT — discharge tube, L — inductor-antenna made of wire PV-3, M_1 and M_2 — sealing plate made of CaF_2 and a dense aluminium mirror, accordingly.

the mode of laser generation in various active media in dozens of laser transitions [14], including near the spectral range of interest — in the transitions $3p \rightarrow 3s$ of neutral atoms of neon with wavelength of 614.3 nm [15]. The vast set of neon transitions in the above „therapeutic window“, where the laser generation may be obtained, and especially the conditions of excitation of the active medium of neon with the pulsed inductive discharge, provide for a separate and practical interest in this method of active media generation.

Therefore, the purpose of this paper was to search for the conditions to generate the inversion of populations and to achieve the mode of laser generation in the transitions of the neutral atoms of neon in the red area of the spectrum when pumped by the pulsed inductive longitudinal discharge.

Experimental setup

In this paper the experimental studies were carried out using a system for the formation of the pulsed inductive discharge arranged according to a type of a Blumlein circuit (Fig. 1), which proved effective due to technical simplicity and stability of operation.

The inductive laser emitter DT was a glass tube with a closed discharge circuit, making it possible to generate the pulsed inductive longitudinal discharge in the gas active medium. The tube included a working area with the length of the active zone of 300 mm, having an internal and an external diameter of 3 and 5 mm, accordingly. To close the path of current flow of the inductive discharge, the tube had a bypass channel with an external diameter of 20 mm. This ratio of diameters made it possible to increase the density of the discharge current in the working area, with the relatively low losses of energy in the bypass channel. The tube had

an inductor L , made of 8 multistrand wires-antennas (wire PV-3 with a cross section of 4 mm^2), located in 4 pieces in two adjacent circuits on each side of the tube. The resonator was a sealing plate from CaF_2 with $R \sim 8\%$ and a dense aluminium mirror. In some experiments a tube was used with similar linear dimensions, but having an increased diameter of the working area of up to 8 mm.

Spectral measurements were conducted using a spectrometer S-150 made by Solar Laser Systems, where the emission was introduced with the help of a long-focal-length lens. The working spectral range of the instrument was 190–1160 nm, and its resolution reached 0.44 nm. The detector was a linear sensor Toshiba TCD 1304AP with the length of the light-sensitive area of 29 mm. According to the technical documentation, the error of spectrometer operation did not exceed $\pm 3\%$.

To analyze the time characteristics of emission, a coaxial photodiode FEK-15, having spectral sensitivity in the range of 380–1200 nm. This detector made it possible to record short optical pulses with duration of up to 0.5 ns. The studies of the spontaneous and forced emission were also conducted with the help of a silicon semiconductor photodiode FD-24K with the area of spectral photosensitivity from 400 to 1100 nm. The pulses of voltage oscillations in the capacitors of the pumping system were recorded with the help of high-voltage feelers Tektronix P6015A and AKTAKOM ACA-6039, signals from which were supplied to a digital multi-channel oscillograph Rigol MSO5354 with the bandwidth of 350 MHz. Energy parameters of emission were evaluated using a portable meter of energy by Ophir.

Laser pulse repetition rate was controlled within 1 to 50 Hz, which enabled studies of the processes in a wide range of generation modes. The charge voltage U varied from the minimum limit of 16 kV, at which the inductive charge was ignited consistently, up to 28 kV, limited by electrotechnical capabilities of the pumping system.

Results and discussion

The study of the spectral characteristics of neon spontaneous emission when pumped by the pulsed inductive longitudinal discharge demonstrated the presence of multiple lines in the spectrum's red area, the intensity maximum of which was observed at pressures of around 30 Torr. When the pressure dropped below 3 Torr, laser generation occurred at the wavelength of 614.3 nm, which was previously obtained from neon pumping with the pulsed inductive discharge of a cylindrical type [15]. The optimal pressure corresponding to maximum intensity of emission of this line was near 0.5 Torr. It was also noted that the intensity of laser emission on this line increases as the charge pressure increases, and the maximum is achieved at charge voltage of 28 kV. Apart from the above line, radiation in the generation spectrum with the wavelength of 1114.3 nm was recorded, corresponding to the $4s \rightarrow 3p$ -transition of Ne I, however, its intensity was much lower and

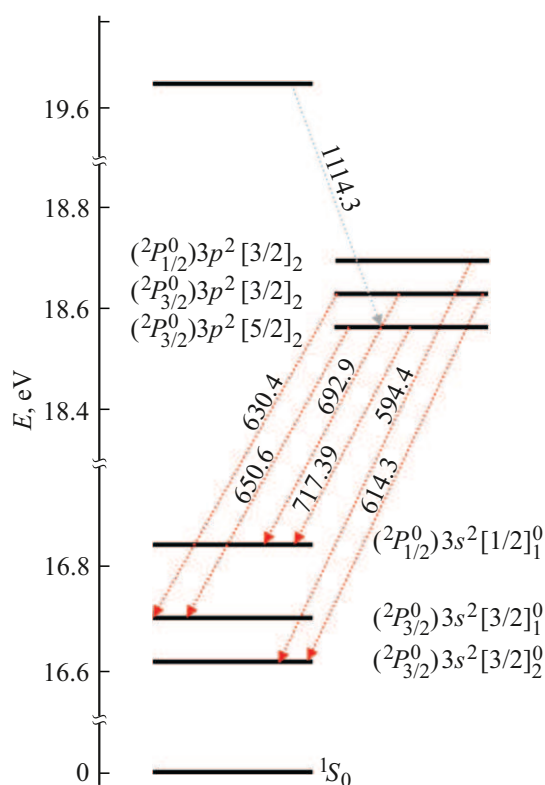


Figure 2. Some laser transitions of neutral atoms of neon [13].

did not exceed the intensity of emission with the wavelength of 614.3 nm in the entire range of the variable pumping parameters. The differences in the observed distributions of emission intensities between the lines may be caused by the difference in the energy of excitation of the upper laser levels of these transitions in neon (Fig. 2), and also by substantial differences between the values of cross sections of their excitation [16].

One of the most common additives to neon is inert gas helium, which was used in our studies as well. Helium makes it possible to effectively excite some of the neon transitions as a result of the resonant transfer of energy in nonelastic collisions, minimizing the losses of energy for the external processes in the plasma due to high ionization potential. Apart from helium, this paper also used other gas components, such as argon, xenon, krypton, however their use did not result in the improvement of generation characteristics at wavelengths of 614.3 and 1114.3 nm or appearance of new lines in the generation spectrum. Besides, the best results were obtained from using two-component and three-component mixtures of neon and helium, and also with molecular oxygen or hydrogen.

Additives of helium to neon, when excited by a pulsed inductive longitudinal discharge in a tube with an inner diameter of 3 mm, had negative effect on the intensity of emission of both spectral lines of generation, up to complete disappearance of emission from $\lambda = 1114.3$ nm, starting from small additives of helium — from 5% of

the total pressure. Similar effect was noted in paper [17], where the increase of the partial pressure of helium in the two-component mix resulted in the increased probability of three-particle collisions playing a dominant role in the depopulation of the neon levels. In their turn, laser generation also related to $3p \rightarrow 3s$ -transitions of neutral atoms of neon, but with different wavelength values, was obtained in neon mixtures with molecular oxygen: 607.4, 630.4, 650.6, 692.9 nm (Fig. 3, a), besides, laser emission at wavelength of 607.4 nm was obtained for the first time. Besides, no laser emission was noted with wavelength of 614.3 nm, emitted by pure neon and mixtures of neon with helium, in mixtures of Ne-O₂ with the prevailing content of oxygen. Such change of the spectral characteristics of laser emission of neon in mixtures with oxygen having a large quantity of vibrational and rotational transitions, may indicate also the decrease in the average energy of electrons, and also the change of populations in the laser levels of neon. These processes, in their turn, may cause a change in the concentration and electron energy distribution function, which may be the reason for the recording of new lines of emissions in the spectrum.

The optimal two-component composition with maximum intensity of emission of each line was a gas mixture of Ne:O₂ = 1 : 5. Further increase of oxygen content caused redistribution of intensity between the recorded spectral components and their subsequent disappearance, starting from the compositions of Ne:O₂ = 1 : 10. Besides, the decrease in the optimal charge voltage was noted in the mixtures with oxygen, when its content increased. For example, in the mixture of Ne:O₂ = 1 : 1 the optimal charge voltage was presented at 28 kV vs. 24 kV for the mixture of Ne:O₂ = 1 : 5. This process may be caused by the change of the temperature and concentration of electrons in the plasma of the pulsed inductive discharge as a result of the increased share of reactions flowing with the participation of the molecular and atomic oxygen, due to high values of cross sections of reactions in nonelastic collisions.

In their turn, use of the tube with a large inner diameter when two-component mixtures of neon with helium are pumped, on the contrary, made it possible to achieve the mode of emission at wavelengths of 607.4, 630.4, 650.6, 692.9 nm in the mixtures of He:Ne = (5...130) : 1. The effect of the joint increase of the inner diameter of the discharge tube and partial pressure of helium in the mixtures of neon was also observed previously in paper [18]. In this paper the authors demonstrate that the average speeds of reaction influencing the population of laser levels of neon, increase quickly as the ratio He/Ne grows, whereas the speed of deexcitation processes Ne*, on the contrary, decreases as this ratio grows. At the same time it was obtained that as the inner diameter of the discharge tube increased to a certain value, the maximum achievable inversion of populations in laser transitions of neon also increased. In our case the maximum intensity of emission of the previously specified spectral lines was achieved in the

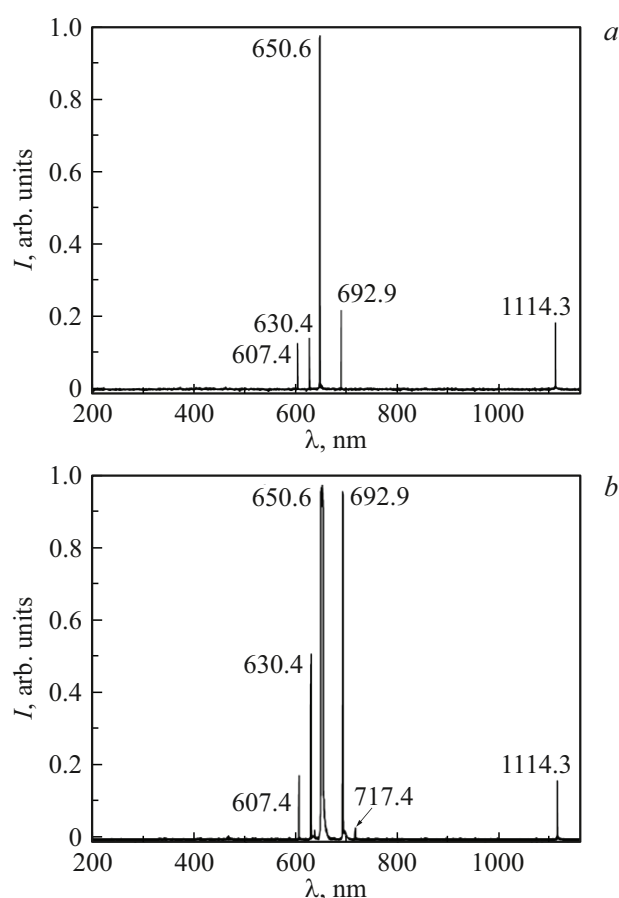


Figure 3. The spectrum of emission of neutral atoms of neon the following mixture pumped by the pulsed inductive longitudinal discharge: (a) Ne:O₂ = 1 : 5 in a tube with an inner diameter of 3 mm; (b) He:Ne:H₂ = 30 : 1 : 0.01 in a tube with an inner diameter of 8 mm.

mixture of He:Ne = 30:1 at discharge voltage of 28 kV and pressure near 0.5 Torr. This optimal ratio of gas components was also obtained by the authors of paper [18]. In their turn, apart from the parameters of the discharge plasma, in the inductive emitter of larger diameter the homogeneity and gradients of intensity of electric fields induced by the current flowing in the inductors, vary, as well as the thermal diffusion processes, which may cause a change in the efficiency of population of laser levels. Besides, as the diameter of the discharge tube increases, the ratio of the surface area of the internal surface to the volume decreases, and this results in the decrease of the probability of collisions between the excited particles and the tube walls and the decrease of the influence of deactivation processes for the excited states of neon atoms.

Addition of the third components in the form of helium and molecular hydrogen (in the high and low concentrations, accordingly) into the compositions of active media of Ne-O₂ and He-Ne for the discharge tubes of various diameter positively influenced the stability of operation of these lasers, and also caused minor redistribution of energy

between the spectral lines (for example, Fig. 3, b). Besides, low-intensity lines with the wavelength value of 638.3 and 717.4 nm, related to $3p-3s$ -transitions of neutral atoms of neon (Fig. 3, b) could have been observed in the spectrum of laser emission of the studied laser. The maximum energy of laser emission in all recorded transitions of neutral atoms of neon reached 1 μ J, which corresponds to the pulse power of 150 W.

The study of the time characteristics of emission of the pulse inductive neon laser was conducted in the discharge tube with the inner diameter of 3 mm in various mixtures of neon with the molecular oxygen at charge voltage of 24 kV. At the working pressures that are optimal for achievement of the laser generation mode, the integral registration of optical pulses of emission was carried out at all wavelengths in the coaxial photocell operation range due to inability of their spectral selection. However, according to Fig. 3, a, b, the main share of emission energy was contained in two lines of 650.6 and 692.9 nm. Besides, the shape of optical pulses did not have pronounced features, which indicates the simultaneity of their appearance. Duration of the laser generation pulses W varied in the range from 8 ± 1 ns (FWHM) in the active medium of pure neon without additives and to 14 ± 1 ns (FWHM) as the partial pressure of molecular oxygen increases from 50 to 80 %. The reason for the increase of the duration of emission pulses may be the processes of free electron capture with molecular oxygen in the discharge plasma, causing the formation of the negative ions and „pulling“ of the discharge current. In the three-component mixtures of neon and helium the value of the duration of optical pulses reached a lower value of 12 ± 1 ns (FWHM). The shape of some pulses of generation was presented by several peaks with the common base, separated with a time interval of several nanoseconds, which could have been provided for by both multiple passage of emission in the resonator and periodical change of populations in the energy levels as a result of oscillations of the electron temperature in the discharge.

The study of the influence of molecular oxygen concentration in the two-component compositions with neon at the time characteristics of the spontaneous and forced emission was conducted using a silicon photodiode (see „Experimental setup“). Besides, this detector with the time constant of $\sim 10 \mu$ s could not resolve short optical pulses, however, made it possible to record the moment of time corresponding to the occurrence of emission, and, as a result, appearance of the initial conductivity in the discharge gap with subsequent ignition of the pulsed inductive discharge. Emission focused using a lens telescope located on the optical axis of laser at the distance of 5 cm from the laser emitter, was brought into the fibrous light guide connected to the photodiode.

The pulses of spontaneous and forced emission were recorded in active media of pure neon and its mixtures with molecular oxygen Ne:O₂ = 1 : (1...9) in the working gas mixture pressure range from 0.5 to 12 Torr. The studies demonstrated that at pressures close to 9...12 Torr, at

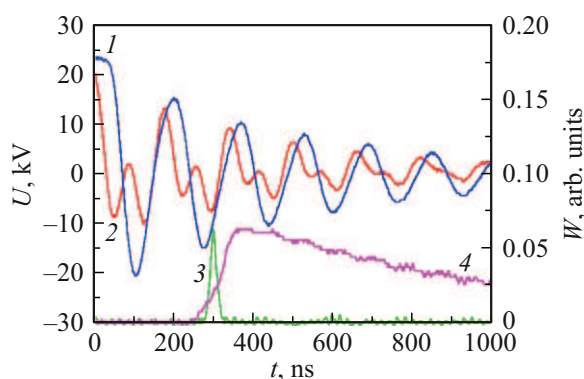


Figure 4. The optical pulse of emission of the neon laser with pumping using the pulsed inductive longitudinal discharge of gas mixture of He:Ne:O₂ = 20 : 1 : 5 at charge voltage of 24 kV and working pressure of 0.5 Torr: blue (1) and red (2) lines — voltage in the capacitor batteries with the total capacity value of C_1 and C_2 accordingly (Fig. 1); green line (3) — specific position of the optical pulse of laser generation; violet line (4) — specific position of the pulse of spontaneous emission.

which laser generation was absent, the highest amplitude of intensity of spontaneous emission recorded by a photodiode was observed from pure neon pumping, besides, the amplitude of intensity of mixture emission with the ratios of Ne:O₂ = 1 : (1...9) was approximately twice lower. However, starting from the working pressure of 6 Torr, the intensity of emission in pure neon and its mixtures became same. With further decrease of the active medium pressure down to 3 Torr (and below) the intensity of spontaneous emission of oxygen-containing compositions exceeds the value recorded in a single-component medium. The increase of the concentration of molecular oxygen at pressures close to the optimal ones, also resulted in the increase of delay between the start of the oscillatory process in the capacitor batteries and in the ignition of the inductive discharge with appearance of the optical pulse of radiation (Fig. 4). The value of this delay varied from 80 ns in the mixtures of Ne:O₂ = 1 : (1...2) to 600 ns in the mixture of Ne:O₂ = 1 : 9. Besides, the optimal pressure corresponding to the maximum intensity of the forced emission did not change practically.

The moment of formation of the pulses of forced emission varied depending on the composition of the active medium and was recorded between the second and fifth half-period of voltage oscillations in the capacitor batteries of the pumping system. Namely the generation of the emission pulse in pure neon was recorded in the front of the second half-period of current and voltage oscillations in the inductor. Besides, in the two-component compositions with the molecular oxygen the increase of concentration of O₂ from 50% to 80% also caused the increase of the time delay between the start of the oscillatory processes in the excitation system and the appearance of the optical pulse of laser generation. These time studies of the spontaneous

and forced emission may confirm the previous conclusions in respect to the change of the electron energy distribution function as a result of „cooling“ of electrons, which resulted in formation of negative ions and decrease of the coefficient of impact ionization. Besides, the speed of response of dissociative attachment of electrons to the molecular oxygen with subsequent formation of atomic oxygen causing the formation of additional channels of discharge energy dissipation, in a rather wide range of the given electric fields exceeds the constant of the ionization speed, which may additionally decrease the Townsend's coefficient and increase the time of discharge ignition. At the same time the formation of the inversion of populations most probably happened as a result of electron impacts, and not due to the processes of nonelastic collisions of molecular ions of oxygen with neutral atoms of neon.

Conclusion

In process of the conducted experimental studies, the mode of laser generation is achieved in transitions $3p \rightarrow 3s$ of neutral atoms of neon at wavelengths of 607.4, 630.4, 650.6, 692.9 nm when pumped by the pulsed inductive longitudinal discharge. For the first time, when pumped by the pulsed inductive discharge, laser generation was obtained at wavelength of 607.4 nm. The study of the influence of the gas mixture demonstrated that the increase of partial pressure of molecular oxygen in two-component mixtures with neon promoted the expansion of the laser generation spectrum. Addition of the third gas components in the mixture with neon and molecular oxygen, such as helium and molecular hydrogen, positively influenced the stability of operation of laser and assisted the redistribution of energy between the spectral lines. Measurement and analysis of the time characteristics of emission demonstrated that the shape of the emission pulse may be presented with several peaks having a common base, the duration of which increases with the growth of oxygen content in the active medium of the laser and may vary from 8 ± 1 ns (at half maximum) in pure neon up to 14 ± 1 ns (FWHM) in the mixture of Ne:O₂ = 1 : 4. Besides, it was also found that the moment of the start of laser pulse generation depended on the composition of the active medium and may be recorded in different phases of the oscillatory process in the pumping system. The overall energy of laser generation achieved $1 \mu\text{J}$, which corresponds to the pulse power of 150 W.

Therefore, the results of the study demonstrate the ability to create a compact source of laser emission in the red wavelength range based on neon gaseous mixtures excited by the pulsed inductive longitudinal discharge. The results obtained within the described experimental studies open the prospects for further improvement of such laser systems and their use in medicine.

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Conflict of interest

The authors declare no conflict of interest.

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