



Breathing Aid Devices to Support Novel Coronavirus (COVID-19) Infected Patients

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Abstract

Novel coronavirus (COVID-19), an ongoing pandemic, is threatening the whole population all over the world including the nations having high or low resource health infrastructure. The number of infection as well as death cases are increasing day by day, and outperforming all the records of previously found infectious diseases. This pandemic is imposing specific pressures on the medical system almost the whole globe. The respiration problem is the main complication that a COVID-19 infected patient faced generally. It is a matter of hope that the recent deployment of small-scale technologies like 3D printer, microcontroller, ventilator, Continuous Positive Airway Pressure (CPAP) are mostly used to resolve the problem associated with medical equipment's for breathing. This paper aims to overview the existing technologies which are frequently used to support the infected patients for respiration. We described the most recent developed breathing aid devices such as oxygen therapy devices, ventilator, and CPAP throughout the review. A comparative analysis among the developed devices with necessary challenges and possible future directions are also outlined for the proper selection of affordable technologies. It is expected that this paper would be of great help to the experts who would like to contribute in this area.

Keywords Novel coronavirus · COVID-19 · Breathing aid · Respiratory support · Oxygen therapy device · Ventilator · Continuous positive airway pressure

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Introduction

It is announced by the World Health Organization (WHO) that the novel coronavirus (COVID-19) has become a pandemic in recent times. The severity of this pandemic is increased from day to day and created new records almost every day. The infected, death and recovered cases for this disease are 18,514,884, 699,027, and 11,731,138, respectively, around the world [1]. Due to this pandemic, almost all the sectors including the healthcare system [2] are facing a serious crisis of infrastructure both in developed and developing countries.

There are several types of diseases such as heart disease [3], breast cancer [4, 5], liver disorder [6], diabetes [7] available in medical science that causes a lot of problems in human health but the current pandemic is COVID-19 [8, 9]. The major symptoms for COVID-19 are fever, tiredness, breathing difficulties, and dry cough [10]. Among these symptoms, the respiration problem is more severe and acute [11]. There are crucial devices [12, 13] usually available within the healthcare technology [14, 15], but they simply do not occur in a high sufficient density to deal with the

increased number of patients related to epidemics. Various assistant devices [16–19] are developed to support humanity in different applications like fall detection for elderly [20, 21], staircase detection [22, 23], path hole as well as road surface smoothness detection [24–27], and any types of hindrances detection [28, 29] using modern technologies. The recent development of respiratory support systems assists infected patients for initial treatment. Oxygen therapy devices [30, 31] are an appropriate solution for the COVID-19 patients, generally available in hospitals as well as ambulance. Ventilators both invasive and non-invasive are mostly used devices for breathing assistance in the hospital environment [32, 33]. The recent deployment of CPAP devices [34, 35] has emerged a direction for the patients having breathing problem.

The paper aims to overview the recent technologies that are evolved for the COVID-19 infected patients for breathing assistant. The review described breathing aid devices like oxygen therapy devices, ventilators, and CPAP devices. The developed systems are demonstrated in terms of the working principle, the construction procedure, the used hardware components, cost analysis, and comparative advantages and disadvantages. To find the best technology, a comparative analysis among the available devices with challenges and possible future trends are outlined in the review.

The rest of the paper is organized as follows. Section “Breathing Aid Devices for COVID-19 Patients” describes the existing technologies for breathing support for the patients infected with COVID-19. A relative analysis among the available technologies with the necessary challenges and possible future directions are described in Section “Discussions”. Section “Conclusion” concludes the paper lastly.

Breathing Aid Devices for COVID-19 Patients

Breathing aid devices are used to support the patients who have acute respiration problem due to pneumonia associated diseases like COVID-19, asthma, and dry coughing. The most used devices which are utilized for COVID-19

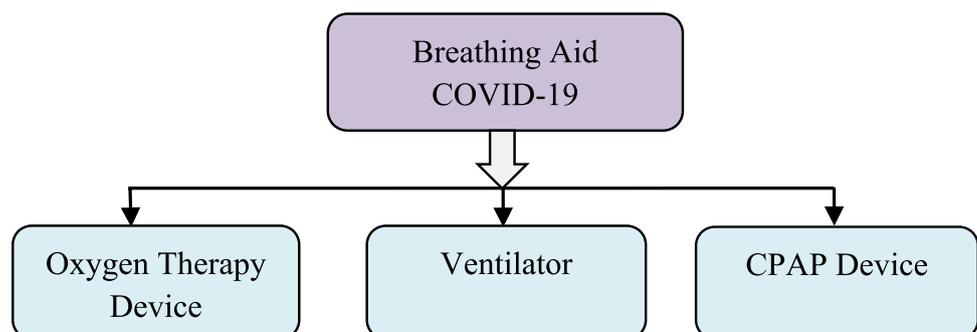
treatment are oxygen therapy device, ventilator, and CPAP device. The possible categorization is shown in Fig. 1 for easy understanding.

Oxygen Therapy Device

Oxygen gas which is found in the air is necessary for human life for breathing. While one feels short of breath and the level of oxygen being very low than supplemental oxygen, oxygen therapy is needed as a breathing aid. Oxygen therapy is generally received using tubes wearing in nose or trachea, face mask, or windpipe. From various kinds of oxygen therapy, direct oxygen gas, or liquid stored in a portable tank is used widely all over the world. Besides, oxygen concentrators that take oxygen from the room and another device named hyperbaric oxygen therapy in which oxygen gas is pressurized in a room or chamber are used mostly. Though oxygen has a fire risk, this therapy is normally safe and can improve survival rates [36]. Oxygen therapy can play an important role in COVID-19 patients like other breathing-related diseases including pneumonia and asthma.

Oxygen therapy by nasal cannula is a well-known procedure in controlling and preventing respiratory diseases like COVID-19. It provides 5–6 L of oxygen flow per minute [37]. In the nasal cannula system, a small amount of air is continuously vacuumed and transferred to a sensor located on the display [38]. A face mask is also used as an oxygen serving system. This mask is fitted with one unidirectional valve for inspiration and two unidirectional valves for expiration. A high oxygen flow is provided to the mask continuously that dilutes the carbon dioxide exhaled by the patient [39]. There are two types of face mask which are used to deliver inspired oxygen (FiO_2) flow. Non-Rebreathing Mask (NRM) provides supplemental oxygen with the rates of approximately 5–10 L/min; while, Partial Rebreathing Mask (PRM) can provide a flow rate of 90% of 15 L/min [40]. Farias et al. [41] described a system in their study that PRM can deliver high oxygen flow than NRM. Nasal cannulas and face masks can be used for COVID-19 patients in low-risk cases. In serious respiratory failure, high-flow

Fig. 1 Breathing assistant available for COVID-19 infected patients



nasal cannula (HFNC) is used for its safety and efficacy. It consists of an air/oxygen blender, a nasal cannula, a single heated tube, and an active humidifier [42]. It can deliver about 60 L/min oxygen flow. The use of HFNC limited the mortality in hypoxemic respiratory failure. In addition, it can decrease the risk of subsequent intubation and the need for Intensive Care Unit (ICU) admission [43–45]. It can be commonly used in COVID-19 patients having respiratory failure as a method to administer high concentrations of oxygen.

Another type of oxygen serving device is Hyperbaric Oxygen Therapy (HBOT) [46] in which patients are entered in a special chamber or room to breathe in 100% oxygen in air pressure. The target of this device is to repair and restore normal body function by filling the blood with adequate oxygen. Air pressure is raised 1.5–3 times from the normal air pressure in a hyperbaric oxygen treatment chamber. In such circumstances, patients' lungs could collect more oxygen than normal air pressure to breathe pure oxygen. This oxygen transports blood all over the body. This helps to kill bacteria and encourages the release of cures of substances such as growth factors and stem cells. There are two types of HBOT (1) Monoplace chamber, (2) Multiplace chamber. Monoplace unit is designed for one person where the patient lies down on a table. It is like a Magnetic resonance imaging (MRI) machine with a long plastic tube. With 100% oxygen, it is slowly pressurized. In contrast, a room designed for several persons is called multiplace chamber. This chamber usually looks like a large room in the hospital where a patient can sit down or lie down. In this case, the oxygen is normally supplied with a thin, transparent hood. Though this therapy is normally a safe procedure, it carries some risk. In certain situations, fire may trigger due to the oxygen-rich atmosphere in the treatment chamber. In addition, a lung may collapse due to certain changes in air pressure [47, 48]. A recent study [49] shows that using additional oxygen up to certain concentrations can improve mortality in certain populations. The oxygen therapy devices which are frequently used are shown in Fig. 2.

Ventilator

Ventilator known as a mechanical ventilator is widely used as a breathing aid tool while a disease makes the respiration difficult or can not bring enough oxygen into the blood. It works like a bellows for moving air in (oxygen) and out (Carbon Dioxide) of the lungs. It can be fitted with a mask, a helmet, or a breathing tube if the respiration problem is more serious to get air into the lungs. The major advantages of the use of a ventilator are no trouble occurs in respiring because the muscles are relaxing in the patients' breathing. In addition, the patient will recover from the failure of normal breathing. Ventilators can play a significant role for COVID-19 patients having acute respiratory distress syndrome (ARDS) and pneumonia.

Recently, a new high-pressure ventilator called Ventilator Intervention Technology Accessible Locally (VITAL) is developed by NASA engineers which is approved by the Food and Drug Administration (FDA) for emergency treatment of COVID-19 patients [50]. Like other ventilators, this ventilator also requires sedation in patients and insertion in their airways of an oxygen tube to breathe. Before the FDA review, on 21 April at the Icahn School of Medicine at Mount Sinai, NY, a critical test was performed with the VITAL prototype. The important benefit of this device is it can be faster designed and easier to maintain than a conventional ventilator and consists of far fewer components. "AmboVent" [51] is the bag valve mask (BVM)-type ventilator that provides breathing speed, volume controls, and maximum peak pressure controls of an emergency patient. It is normally used in an ambulance. This device is developed with a Volume control ventilation (VCV) machine, BVM, Positive end-expiratory pressure (PEEP) adapter, PEEP valve, Heat and moisture exchanger (HME) filter, oxygen reservoir bag. The main features of this device are it has a big range of tidal scale, varying from 30 to 100% of maximum tidal capacity, and large rates of ventilation of 6–24 cycles per minute. MIT Emergency Ventilator (E-Vent) [52], which is formed on March 12, 2020, designed a simple ventilator in response to the rapid spread of the COVID-19

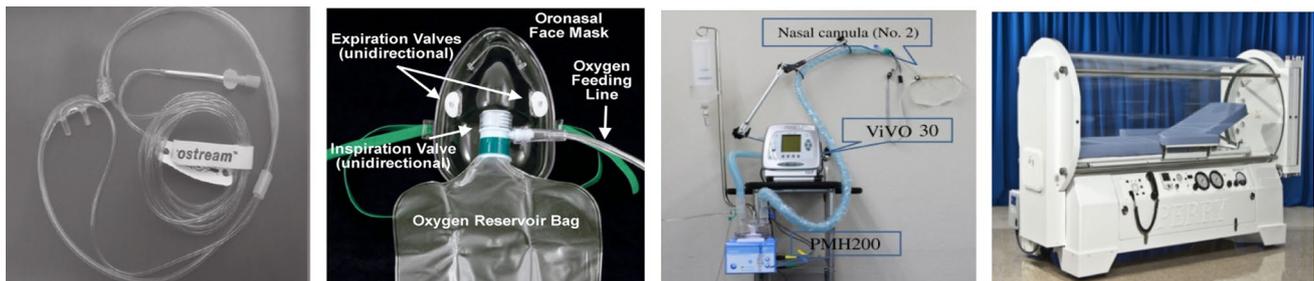


Fig. 2 Typical oxygen therapy devices for breathing support. **a** Nasal Cannula [38], **b** NRM [39], **c** HFNC [42]. **d** Hyperbaric oxygen therapy [46]

pandemic. This new system fits into an Ambu bag that is already used in many hospitals. These types of bags are designed to be manually operated by a doctor or emergency nurse in circumstances such as a heart attack to breathe of a patient. But in MIT E-Vent, a mechanical system is developed to perform squeezing and releasing of the Ambu bag. This leads air through a tube in the airway of the patient. The developed device is very reliable and handled manually immediately.

Lu et al. [53] designed a portable high-frequency ventilator which is low cost, portable, and light weight. Here, advanced technologies of electronics and mechanical are integrated throughout the work. As a mechanical instrument, two check valves, two flow meters, two flow control valves, one pressure sensor, one solenoid valve, and one gas chamber are used to regulate the airflow. Multiplexer, comparator, oscillator, capacitor, Digital to Analog (D/A) converter, MOSFET, and voltage converter are utilized as electronic instrument in the control circuit board to control the frequency. The measurable parameters of this device are shown on a digital display as flow per minute (0–40 L/min), output frequency (2–4 Hz), oxygen concentration flow per once (0–160 mL). The main advantages of this device are its small size, configurable features, and instant feedback control. Using the concept Artificial Manual Breathing Unit (AMBU) bag, Shahid [54] proposed a cost-effective prototype of a ventilator. The main components of this prototype are microcontroller, pressure sensor, breath detection elements (Thermistor and CO₂ sensor), and mechanical mechanism (chained plank mechanism and cam shaft mechanism). Moreover, the key features of this prototype are that various parameters like Breaths Per Minute (BPM), delivered air volume by this ventilator, peep rate and inspiration to expiration ratio can be regulated or adjustable. The considerable cost of this proposed prototype is less than \$80.

Islam and Ahmad [55] developed a microcontroller-based mechanical ventilator using BVM ventilation mechanism and AMBU bag. Here, this AMBU bag is operated (compressed and decompressed) with computer-aided manufacturing (CAM) arm which is controlled via a control signal sent from microcontroller. The main merits of this device

are its portability, compact design, light weight, and easily performable. This repairable and riskless device serves 90% accuracy in respiratory measurement. Jürß and Degner [56] described a concept of compact and low-cost ventilator having the blower unit and an integrated sensor unit. The key feature of this study is that without any respiration tubes, the proposed device can provide necessary ventilation to the patient's lungs with the blower unit. In addition, the relevant respiration data can be monitored with the sensor unit. In another work, a low-cost ventilator is proposed by Garmendia et al. [57]. The major components of the developed system are Arduino Nano as a controlling device, high-pressure blower, and two pressure transducers. This non-invasive high commercial device is low cost as the authors declare the fabrication cost is less than \$75. Further, a portable ventilator is described in [58] based on BVM and cam arm operated by an electric motor. Though it serves a short time solution, it delivers the essential features of conventional ventilators at low cost, low power, and easy portability. The estimated price of manufacturing this device is less than \$200. A pre-stage public access ventilator (PAV) [59] is designed with a turbine and sensors. The developed prototype can detect leakage and airway occlusion using the signals from sensors. The PAV was verified under three conditions 1) pressure-controlled ventilation (PCV), 2) PCV with controlled leakage and 3) PCV with simulated airway occlusion. Also, there a proposal is available for Cardiopulmonary resuscitation (CPR) victim by Fogarty et al. [60] using an electric blower ventilator in replace of traditional BVM. The proposed work can reduce the chance of injury from ventilation of the BVM. The available ventilators for breathing assistant are shown in Fig. 3.

Continuous Positive Airway Pressure (CPAP)

Continuous Positive Airway Pressure is a well-known device that is used for breathing assistant for the treatment of patients having a mild respiratory problem. The positive airway pressure is delivered through a tight face or nasal mask in CPAP device. The main advantage of CPAP device is that it can deliver positive pressure in each cycle of respiration.

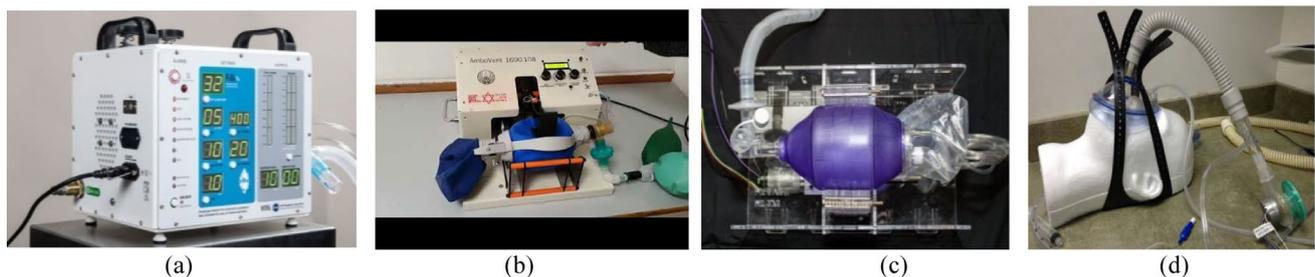


Fig. 3 Ventilators for breathing assistant. **a** VITAL [50], **b** AmboVent [51], **c** MIT E-Vent [52], **d** electric blower Ventilator [60]

The pressure facilitates the alveoli to remain open during the breathing out of patients that is very helpful for oxygenation and easy breathing. The device is proper suited for the patients having pneumonia related problems like COVID-19 for initial treatment.

There are several CPAP devices already developed for breathing aid of the coronavirus infected patients. A low-cost, microcontroller controlled electro-mechanical device is developed in [61] for the respiratory support of COVID-19 infected patients. The developed system consists of a control unit, a power supply with battery backup, a digital display (LCD), an air pump, and a nasal mask. The main unit is here the air pump that is utilized for making pressurized air. The current cost of the developed prototype is approximately \$140. An open-source breathing aid device is under development in [62] which is low cost. The developed system used an Arduino Nano as a microcontroller, DC motor, power supply, inflator pump, facial mask, and some 3D-printed parts. The considered cost of the prototype is about \$20. However, the prototype is not recommended for medical applications due to the lack of enough tests with targeted people. In another research, a bubble CPAP is introduced that provides a combined oxygen supply and space air to the respiratory-depressed babies [63]. The developed system is a cost-effective device with high durability and provides easy-to-use facility with a simple design. Dundek et al. [64] developed a low cost bubble CPAP with the use of limited resources. The main component which is used here is an air blender where pressurized oxygen is delivered as input and the output is the combination of air and oxygen. The prototype was developed with the combination of several parts printed in a 3D printer. Although the actual cost is not mentioned here, it is noted that the cost is 1% less than the gold standard device. Gehlot et al. [65] introduced a multi-power breathing aid device named as ‘Saans’ for the infants having severe respiration problem. The prototype is

comprised of battery-powered air pump, bubble jar, heated humidifier, and resuscitation circuit. The developed device is tested with targeted people (newborn baby). Further, Mukkundi et al. [66] proposed a multi-powered CPAP device for respiratory support for the patients having a breathing problem. In this system, two flow meters are used to control air and oxygen. The prototype is cost effective and easy to use. The developed system is tested in a real-time environment and achieved reasonable output. The popular CPAP devices that are extensively used or under development are shown in Fig. 4.

Discussions

In this review, a comparative analysis among various breathing assistant devices supporting the COVID-19 pandemic situation is described. All of the necessary features of the reviewed technologies are depicted in Table 1.

Among the reviewed systems, ventilators and CPAP devices are comparatively low cost. Some study shows their cost less than \$100 in [54, 57, 62] and higher than \$100 in [58, 61]. In contrast, oxygen therapy has a relatively higher cost than others [46]. Similarly, both ventilator and CPAP are light weight [53, 55, 58] where oxygen therapy device has heavy weight as it consists of many complex parts [48]. Except medical technologies, there are several technologies that are used to develop these devices such as microcontroller, CAM, electronics, and mechanical. Arduino Nano is frequently used in many breathing aid systems [55, 57, 61, 62] to control the signal received from other equipment. Different electronic devices such as multiplexer, comparator, oscillator, capacitor, D/A converter, MOSFET, 3D printer, digital display are used in oxygen therapy devices [38], ventilators [53, 54, 58], and CPAP devices [61]. AMBU bag is normally designed to be operated manually, but in some

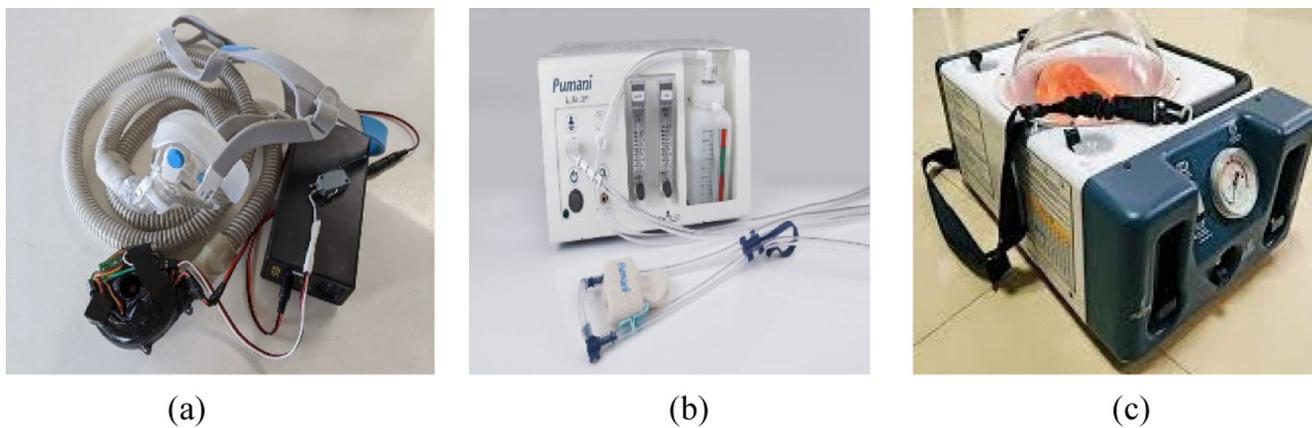


Fig. 4 CPAP devices for respiration support. **a** PAPR [62], **b** PUMANI bubbleCPAP [63], **c** Saans [65]

Table 1 Comparative analysis of existing technologies available for breathing support

Breathing aid devices	Cost	Technology used	Weight/Portability	Coverage environment	Case handled in COVID-19	Merits	Demerits/Risks
Oxygen therapy	High	Medical	Heavy weight	Hospital, Ambulance	Acute	Improve survival rates	Fire risk
Ventilator	Low	Microcontroller, CAM, Electronic, and Mechanical	Light weight	Home, Hospital, Ambulance	Acute	Comfortable, respiratory muscle in rest	Infection in lungs
CPAP	Low	Microcontroller, Electronic, and Mechanical	Light weight	Home, Hospital, Ambulance	Mild	Emergency support	Dry nose

devices, it is operated mechanically or using CAM arm [52, 55]. Almost all of the devices can be used in a different environment like home, hospital, and ambulance. But some devices are specially developed for the hospital environment [46], and ambulance [51]. In COVID-19 disease, oxygen therapy and ventilator can provide better treatment in acute respiratory problems where CPAP is commonly used in mild cases as preliminary treatment. Recently several devices are developed only for handling COVID-19 patients [50–52, 61]. Oxygen therapy is used to improve survival rate [36] of patients though it has fire risk in contact with flame or smoke [48]. Among all of them, CPAP devices can provide emergency support in the primary stage of respiratory problems and a ventilator is the most comfortable device for use [52].

In this study, sufficient breathing aid devices are reviewed for COVID-19 patients. It is noticed that most of them are under development or in prototype only. There may have some lack of sufficient funds for significant progress in their development. Government or health-related organizations can provide proper funding to complete these underdeveloped projects. Besides, in electronic-based devices there are much instrumental errors in providing original signal or result. A proper selection of electronic devices may overcome this type of problem. In addition, it is important to produce more breathing supporting devices in a short time in this pandemic situation. Still, there is not enough technology or manufacturing method to do this in this lockdown situation due to maintaining social distance. In this circumstance, 3D-printing technology can play an important role in the mass production of such breathing aid devices.

Conclusion

The COVID-19 is still an ongoing pandemic that is creating a lot of crisis in all sectors for humanity all over the world. This outbreak aims at increasing the threat–benefit investigation of assessing the modality of breathing assistant for the infected patients. This paper overviews the recent available

technologies that are frequently used for COVID-19 patients in hospitals, homes as well as the ambulance. The existing breathing aid devices are categorized into oxygen therapy devices, ventilators, and CPAP devices for proper demonstration. The devices are described in terms of working principle with construction, the equipment and technology used, cost, and relative analysis of merits and demerits throughout the paper. The current challenges of existing technologies with possible future trends are also outlined in this review. In this and future epidemics, there is a strong technological ability to mitigate respiratory support devices by utilizing modern small-scale technologies. The researchers with medical practitioners would provide an appropriate solution by developing necessary tools for the patients having breathing-related problems.

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Compliance with Ethical Standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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