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REVIEW ARTICLE - ENGINEERING

Short Review for Design and Implementation of a New Low-Cost Prototype Portable Smart Ventilator

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Abstract

This paper presents a set of research and an overview of the stages of development of the ventilator. The results of this research show how to produce a portable, smart, easy-to-manufacture and use device that can be developed at the lowest costs. Mechanical ventilation has become a lifesaver, especially during the outbreak of the Coronavirus COVID-19 where the patient needs continuous ventilation in order to help the respiratory system to perform its functions correctly due to the accumulation of fluid in the lungs resulting from viruses that infect the respiratory system, thus improving survival.

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1. Introduction

The outbreak of the Coronavirus and the lack of health facilities caused the death of many people. Because this virus causes lung failure, the patient needs continuous mechanical ventilation in order to pump air into the lungs. This is what prompted researchers to develop the ventilator and make it a device (smart, portable and small in size) in order to be able to use it in homes and ambulances, thus reducing treatment costs as well as reducing the number of patients in hospitals to reduce the spread of diseases among them and also support the situation in remote areas [1]. There are different types of respirators, and because of the great demand for the device, it was developed and made capable of accommodating various uses at a low cost [2]. The process of delivering oxygen to all parts of the body by breathing is one of the main processes for human survival. Where the human respiratory system is affected for many reasons with different diseases such as barotrauma, pneumonia, pulmonary embolism and acute respiratory distress syndrome, which is one of the serious diseases that cause death.

The mechanical ventilation process causes damage to the respiratory system. As excessive ventilation causes an increase in the size of the alveoli and thus ruptures its wall, and also limited ventilation leads to the constriction of the alveoli. Therefore, it is necessary to mode PEEP-style respirators in order to maintain the size of the alveoli and prevent their collapse during the exhalation process[3]. Respiratory distress syndrome is one of the symptoms of coronavirus infection, as it impairs the lung's ability to exchange gases from oxygen and carbon dioxide, which causes hypoxia in blood, shortness of breath, bluish skin and thus death. Therefore, there was an urgent need to develop a mechanical breathing device in order to support the condition of patients in the intensive care unit, as well as to overcome this pandemic[4]. Where different designs and sizes of the ventilator were produced in order to compensate for the shortage of ventilators all over the world, especially during the outbreak of the virus. As ventilators support digital systems, the internet of things, telemedicine and artificial intelligence, especially nowadays, they have kept pace with technological development and thus succeeded in saving many people[5].

2. Literature Review

A study by Adamo et al. (2020) presented a device to support remote areas with few medical resources because it was an easy device to handle as the airbag was manually pressed in order to operate it. It is made of aluminum, and by a 3D printer its parts are made. This ventilator provides sensors to measure airway pressure as well as to measure flow rate when air is in and out, and the device has a backup power supply.

Nomenclature & Symbols

PEEP	Positive End-Expiratory Pressure	MRI	Magnetic Resonance Imaging
RR	Respiration Rate	HEPA	High-Efficiency Particulate Air [Filter]
BiPAP	Bi-Level Positive Airway Pressure	TPU	Thermoplastic Polyurethane
CPAP	Continuous Positive Airway Pressure	BVM/ AMBO	Bag Valve Mask
PIP	Peak Inspiration Pressure	HFNC	High Flow Nasal Cannula
FiO2	Fractional Portion of Inhaled Oxygen	ICU	Intensive Care Unit
HFJV	High-Frequency Jet Ventilation	CAMV	Computer-Aided Manufacturing Ventilator
PID	Proportional–Integral–Derivative Controller	BPM	Beats Per Minute (Heart Rate)
IoT	Internet of Things	NIPPV	Nasal Intermittent Positive Pressure Ventilation
LC	Low Cost	HFHP	High Flow High Pressure
Vent	Ventilator	ARDS	Acute Respiratory Distress Syndrome
PEV	Portable Emergency Vent	RCV	Remote Control Vent
PL	Programmable Logic Controller	LCD	Liquid-Crystal Display
MMV	Multi-Mechanical Ventilator	UPS	Uninterruptible Power Supply
TBV	Target Tidal Volume		

The battery is used for a short period of time (a few hours) and manual work were the main disadvantages [6]. Another study by Ramadi (2020) proposed a single ventilator ISAVE as shown in Fig.1 that was attached to multiple patients at the same time with respiratory disorders. It is possible to maintain the ventilation settings for each patient by dividing the airflow between patients by using multiple channels and this aims to reduce the use of additional ventilation devices and thus reduce cost and reduce pollution among patients [7].

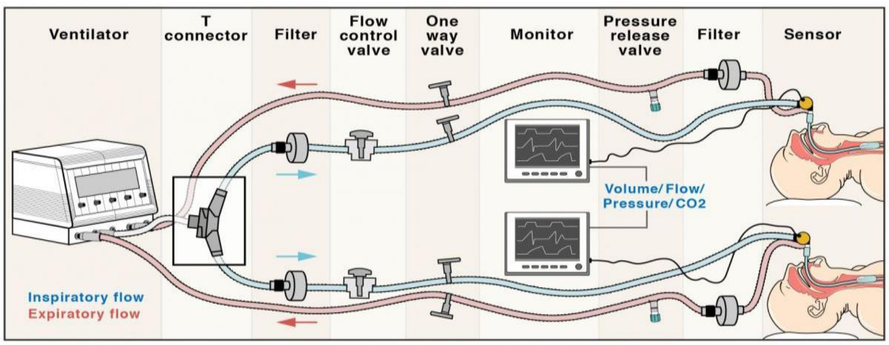

Fig. 1. ISAVE ventilator device [7]

Królewska et al. (2020) presented a respirator combined with an MRI machine where the patient's lung diseases were diagnosed at the same time that mechanical ventilation was provided to the patient by producing an image of the patient's lungs by magnetic imaging. Where a system was used, it had the ability to recirculate the patient's exhaled air and isolate the pure helium 3He and use it to generate the image by hyperpolarization, while the ventilator was controlled by the LabView program [8].

Another study by Ricconi et al. (2020) presented a respirator powered by a pressure sensor and an alarm system in Fig. 2. This system triggered an alarm if the patient's breathing cycle is abnormal. Where the patient's breathing pressure signal was analyzed by the pressure sensor and alarm system in order to detect device malfunctions. This ventilator also provided PEEP, PIP and RR measurement modes. Its operation was imprecise compared to a commercial ventilation system was the main disadvantage [5].

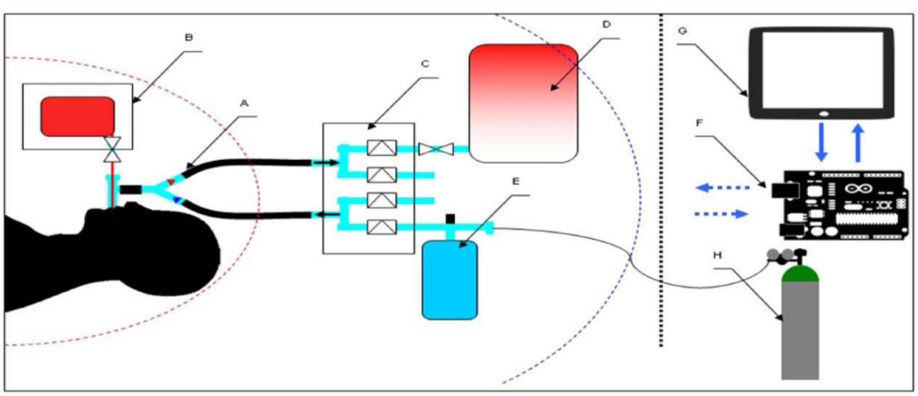

Fig. 2. Ventilator setup. The red, blue and black dashed lines indicate the area of high magnetic Field of the medical scanner magnet, 0.5 MT stray field limits, and the area outside the Faraday Cage, respectively: A—three-way junction, B—Tedlar bag with HP 3He inside the pressure chamber, C—system of pneumatically controlled gas valves, D—helium-tight metalized bag for the exhaled gas Collection, E—nitrogen reservoir for lungs flushing, F—electronic control module for pneumatic valves, G—a computer with the LabView program for ventilator control, H—high-pressure nitrogen bottle [5].

Grover et al. (2021) presented a Cosmic Bubble Helmet as shown in Fig. 3 that was used for patients with acute respiratory distress syndrome. Because the patient's exhaled air contains infectious viruses, the HEPA filter was used, which prevents the exit of these viruses in order to maintain the safety of people close to the device. The patient can move easily and can lie comfortably without affecting the functions of the device due to the use of TPU polyurethane, which makes the movement of the device flexible. The main disadvantage was that the device did not provide a measurement of the BiPAP mode [9].

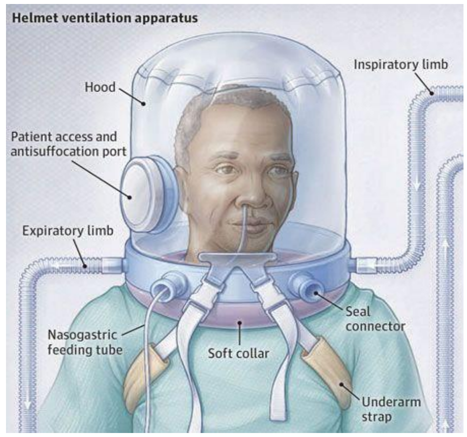

Fig. 3. Helmet ventilator device [9]

Shivu et al. (2021) introduced a device to treat pulmonary barotrauma by manipulating pressure in real-time. The device supported the internet of things, which was the most important feature in it, where the patient could be monitored remotely and thus reduce the spread of the virus among patients as well as the medical staff. The device was smart, gas, supported the internet of things, and could be designed easily to support the health situation in remote areas. The main disadvantage were that there were no determinants for the high percentage of oxygen and temperature, as well as the increase in pressure in the blood vessels of the patient, in addition to the area of the device and its large size [10].

Ongtrakul et al. (2021) presented a ventilator that was made of metal and it was controlled by a smartphone as well as manually operated. The device contained an AMBO bag and a BVM valve mask bag and supports PEEP mode. The device also emited an annoying sound during operation, so it needed a manual resuscitation device in to operate it when the air inside the bag was low.

Disadvantages:

- Airbag limited (contains a limited amount of air)
- The device was operated manually
- It caused an annoying sound during its operation
- It requires constant electricity to operate the functions [2].

In another study by Kurniadi et al. (2021), the ventilator provided FiO2 at high pressure and flow for the treatment of respiratory diseases for newborns and infants by using a nasal bottle HFNC. This bottle produced FiO2 from four to six liters per minute. The device also provided two modes: CPAP Positive Airway Pressure and BiPAP bi-level positive airway pressure. Where its disadvantage was that it is only used for patients with split sleep apnea syndrome [11].

A study by Saputra et al. (2021) used a PID controller to automatically adjust the amount of air and oxygen in equal proportions and then mix them and send them to patients through the nose or mouth. The device was developed by using Arduino and the C. Programming language. However, its disadvantage was that it provided only FiO2 suitable for the patient because it was used only in the ICU [12].

Eldosoky et al. (2021) presented a ventilator depends on its work on the Matlab program, where a large set of mathematical equations has been proposed to be implemented by the MATLAB program, and its results were accurate because all its equations were calculated directly without any assumptions. As the medical condition of the patient's respiratory system was self-diagnosed and detected by the proposed mathematical model [4].

Restuccia et al. (2022) proposed a developed ventilator that could be remotely controlled by a smartphone and communication networks such as Wi-Fi and Bluetooth, and this had led to the improvement of health care by reducing the economic cost where one doctor can monitor a number of patients at the same time It also reduced the need for personal protective equipment and to support the health situation in remote areas. Its disadvantage was controlling the proposed ventilation due to the limited number of doctors [13].

Eldeib et al. (2017) designed a home ventilator that was controlled remotely by a wireless camera. It worked on taking pictures and recording videos of the patient and sending them to the system's web page. The camera relied on infrared radiation. The patient's respiratory signals were transmitted to the doctor remotely via communication networks, where the doctor, using a program installed on his computer, controls the settings of the home ventilator [14].

Biawat et al. (2022) presented a ventilator that was made of a wooden material weighing 6 kg, and its dimensions were (9 x 7 x 14) inches. The device consisted of a pressure sensor, an oxygen sensor, an input unit, a DC battery with a capacity of 12 volts, an Arduino, and a cystic valve mask by which oxygen was delivered to the patient, and the device was portable as it measures BPM on breaths per minute.

Disadvantage: The fans used for ventilation are small due to the small size of the device and the small size of the battery [1].

In Alhammadi et al. (2022), the proposed device consisted of several sensors represented by the pressure sensor, body temperature, and pulse oxidation sensor, in addition to containing a stepper motor that was controlled by the microcontroller (Arduino). The most important feature of this device was that it supported self-pressure on the inflatable bag by using a lever, so it does not need human intervention, in addition to that, it contains stimuli for abnormal conditions. However, Carbon dioxide buildup in the air tube because the pressure valve was located away from the patient [15].

Shao-Yung et al. (2019) presented a developed ventilator as shown in Fig. 4 that was equipped with a digital control unit and a feedback system to achieve stability. This device also provided air with a low pressure and a frequency higher than the natural frequency of breathing in order to avoid the rise and enlargement of the alveoli as well as preventing improper air pressure[16].

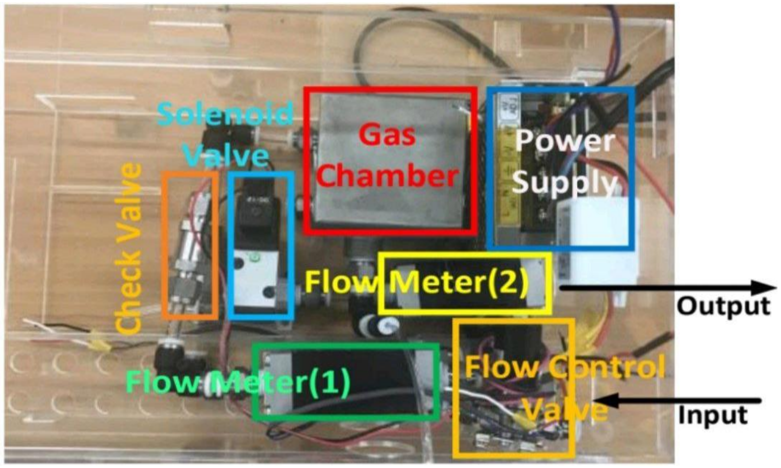

Fig. 4. HFJV ventilator device [16]

Rakibul et al. (2019) proposed a CAMV ventilator shown in Fig. 5 that provided patient ventilation using a BVM airbag. It was pressed by the CAM arm. However, it did not provide a measurement of important patterns (respiratory rate, auric and expiratory volume, etc.)[17].

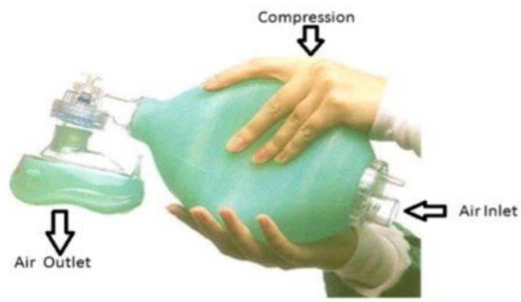

Fig. 5. CAMV ventilator device [17]

Santivanez et al. (2021) proposed a Fenix ventilator to provide ventilation based on the PLC control system. This device measures PEEP and PC-CMV modes. However, the large error in fixture flow measurements in PC-CMV mode was its main disadvantage [18].

Sailul, et al. (2021) presented a MMV ventilator with a pressure sensor to measure pressure, flow rate, and air volume during inspiration.

Its disadvantage was a problem with the sensor (pressure sensor) affecting the controller[19].

A study by Acho et al. (2020) presented a mechanical ventilator device to support the Raspberry_Pi controller and used only commercial spare parts. It also contributed to maintaining the integrity of the patient's respiratory system through the availability of the PEEP pattern. The device worked to provide an alert system for doctors to warn about the patient's condition (normal or abnormal). Moreover, that is through the use of a digital method in order to measure air pressure in the case of inspiration. Its disadvantage was the inability of the artificial respirator to regulate the excessive pressure and thus affect the patient's respiratory system [20].

Another study by Tran et al. (2021) presented a ventilator based on the simulation program Matlab and using some mathematical equations, the device was modeled. The purpose of this was to provide a high-precision medical respirator in action by comparing the results of the experiments applied to the simulation program with the results of the proposed device, where their study used heart rate and oxygen saturation sensors.

Disadvantage:

- The weaning technique cannot be used during the patient's treatment period.
- Bad indication of patient feedback [21].

In Kiruthika, et al. (2022), the adoption of IoT technology in the ventilator has greatly improved its work. Where the patient's condition was monitored remotely by smart phone devices. The ventilator is also able to send patient data to doctors in real-time. This helped keep patients at home as well as keep them safe during outbreaks of infectious viruses. The device provides the measurement of oxygen saturation, heart rate and temperature [22].

In Rakib et al. (2021), reliance on external energy in the work of this ventilator, as it provides important warnings, including low battery during work, and also does not require the human hand to operate. It is made of wooden pieces, and its dimensions are 9 x 14 x 7 inches. It consists of an electric motor that operates at a voltage of 24 volts and is programmed by a microcontroller. Thus, provideing a measurement of the PEEP mood [23].

In Radogna et al. (2020), an advanced respirator with multiple sensors such as oxygen, carbon dioxide, temperature and humidity sensors was proposed. It was inexpensive, easy to use, and monitors COPD patients. It relies on the Arduino microcontroller and supported telemedicine, so it could be used in homes [24].

A study by Dijemeni et al. (year) presented a mechanical ventilator to support portable oxygen cylinders, smartphone, face mask and oximeter in order to provide an automatic ventilation system. Where the smartphone monitors the level of oxygen in the blood and then transmits its value along with the heart rate to the mobile phone in real-time. This system supported the development of oxygen monitoring for patients while they are at home during (work and rest). The disadvantage was that the smartphone communicates with the ventilator via Bluetooth (Bluetooth technology does not communicate over long distances)[25].

In a study by Derbel (2021), a respirator was wirelessly accessed by hospitals and health centers. It also supported the measurement of heart rate and also provided cardiopulmonary resuscitation for the patient. The device was portable and easy to use as it could be used in homes and health care places in remote areas. However, it costs of up to 800 US dollars [26].

Another study by Jawad et al. (2020) presented a mechanical ventilation device that relies on artificial intelligence in its work by using a model with multiple layers of nerve in order to know the level of oxygen coming from the ventilator during the breathing period, and this helps support health care. The neural model is programmed using an open-source programming language (Python). This device provides the measurement of PEEP, FiO2, and SpO2 patterns. However, the air pressure inside the device was manually controlled by doctors or observers during the day 3-4 times [27].

In Ramos et al. (2022), a respirator supports joint ventilation to provide ventilation for two patients at the same time was proposed with independent ventilation and was different from the ventilation of the other patient, but from the same source. This ventilation relies on a computer that provides electrical stimulation of the industrial ventilation device. However, the ventilator needed a large amount of oxygen and air for the purpose of providing adequate ventilation for patients (the large size of the device)[28].

Rodriguez-Olivares et al. (2021) designed a mechanical ventilator shown in Fig. 6 based on the D-lite sensor that worked on the venture effect and was affordable. The device also provided sensors to measure air pressure. This technology supported a dichotomous algorithm instead of the traditional technique to measure the amount of FiO2 flow well and in little time [30].

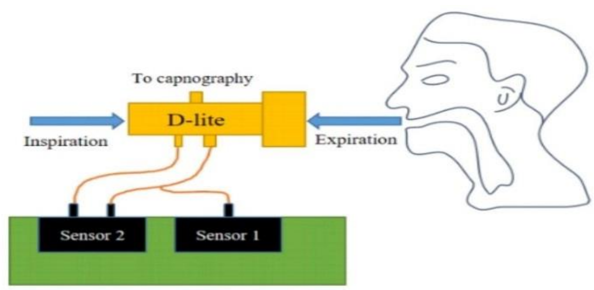

Fig. 6. D-lite spirometer [30]

Finally, Ticllacuri et al. (2022) presented a respirator that works on a linear-quadratic model using an electrical circuit, which was dealt with mathematically through differential equations. Thus, through this model, it could control the work of the ventilator, and mechanical ventilation was provided to patients [29].

3. Design and Implementation of a New Low-Cost Prototype Portable Smart Ventilator

The Coronavirus causes a sharp decrease in the level of oxygen in the blood of people infected with this virus, which leads to an increase in the urgent need to provide respirators, and since the respiratory devices do not cover the huge numbers of people infected with this virus. Patients, so many researchers have directed the design of low-cost, easy-to-use and portable respirators with open licenses. All these measures will limit or control a large part of the spread of this virus, as well as respirators, including a respirator, provide pulmonary care for people suffering from acute respiratory syndrome and pulmonary fibrosis by adding more features in the design of the breathing apparatus, such as methods of controlling the respiratory rate, inhalation and exhalation, with air determination, as well as measuring the patient's temperature and oxygen saturation as well. The volume made available to the patient will lead to the development of guidelines that will help meet the treatment requirements of patients with covid-19 directly affecting the pulmonary function of the patient's respiratory system. Also, IOT can play an important life-saving base while monitoring and controlling the patient's condition, especially during emergencies or commuting, and this will add more functions for the new generation of the ventilator, see Table 1.

Table 1. Ventilator name, mode, and structure design comparison

No. of refer/year	2019[16]	2019[17]	2021[18]	2021[19]
Name of vent	HFJV Vent	CAMV Vent	Fenix Vent	MMV Vent
Vent mode	Control essential variable	Control essential variable	PEEP	PEEP
Structure of design	flow control valves, low meters, check valves, gas chamber, LCD, solenoid valve	microcontroller, some mechanical switches, two servo, CAM arm	proportional flow valves, (PLC), sensors, (UPS), two filter, regulators	two filter, regulators microcontroller, MPX5050DP sensor,

					two air pressure sensors
No. of refer/year	**2017[14]**	**2020[5]**	**2020[6]**		**2020[7]**
Name of vent	Hamilto galileo Vent	Low Complexity Vent	Glas Vent		ISAVE Vent
Vent mode	PEEP	PEEP, PIP	Emergency ventilator		Control essential variable
Structure of design	Arduino mega, camera, mobile or computer, SD card	Pressure sensor, alarms system	Made from Aluminum, use controller, PEEP valve, stepper motor, pressure sensor, mask, BVM		Valves, channels, filters, flow control valve, controller, flow and pressure sensor
No. of refer/year	**2020[8]**	**2020[10]**	**2021[2]**		**2021[11]**
Name of vent	Versatile Vent	Net-Vent	LC Blower Vent		HFHP O2 Vent
Vent mode	TBV	PEEP, PIP	PEEP		CPAP, BiPAP
Structure of design	Gas valves, bag, chamber, controller, Faraday gage	Arduino mega, Node Mcu 8266, filter monitoring sensor, air Flow control sensor, O_2 pressure and flow sensor, humidity sensor CO_2 level sensor, alarms	Made from metal, Ambo bag, sensor, esp32, FiO_2 sensor, motor blower, Microcontroller, solenoid valve		High flow and, pressure BVM, smart phone, filter, mixer
No. of refer/year	**2021[12]**	**2021[4]**	**2022[1]**	**2022[15]**	**2022[13]**
Name of vent	PID Vent	ARDS Vent	Portable Vent	PE Vent	RCV
Vent mode	FiO_2	Interpretations of Different Pulmonary Variables	PEEP	FiO_2, PEEP	Monitor ventilator parameter
Structure of design	Arduino, O_2 and pressure regulator, control valves, filters, O_2 sensor, maxing tank	MATLAB program, simulated program	Arduino, pressure sensor, O_2 sensor, DC-battery, cystic Valve	Arduino Mega 2560, pressure sensor, body temp, Pulse O_2 sensor, stepper motor, LCD Screen	Arduino Uno, smart phone, motor control compatible, flow and pressure sensor

4. Conclusion

This study explains the stages of the development of the respirator and how to have it keeping pace with technological development by using low-cost, easy-to-manufacture and easy-to-maintain components. The work also aims to reduce the side effects on the patient and strive to make the ventilator meet the need of poor areas for health resources and reduce the risk of disease outbreaks among patients by monitoring them remotely, as IOT technology has been introduced in the ventilator. We seek to develop the device and make it safer for the patient, easy to move and use, and suitable for homes and ambulances through its small size, and work to extend the battery life and make it keep pace with development, as it can be controlled remotely and at the lowest costs.

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