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Unmasking Effectiveness: A Comprehensive Analysis of CPAP Devices in Treating Sleep Apnea

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ABSTRACT

Background: This paper aims to fill a research gap in the existing literature by investigating the impact of control, transient, and steady-state responses on the effectiveness of continuous positive airway pressure (CPAP) devices in the treatment of obstructive sleep apnea syndrome (OSAS).

Method: Bench tests were conducted on five CPAP devices: DreamStar Duo ST (SEFAM), Point 2 (Hoffrichter), Respironics PR System One Pro (Philips), iBreeze 20A (ResVent), and Respaps (MedTech). The evaluation focused on the transient responses of these devices to a pre-adjusted breathing pressure of 10 cmH2O. Parameters such as delay time, rise time, peak time, settling time, overshoot percentage, and steady-state error were measured and analyzed.

Results: The study revealed significant variations in the transient responses among the tested CPAP devices, attributed to the unique manufacturer algorithms. The observed differences underscore the importance of understanding and considering device-specific characteristics when selecting a CPAP device.

Conclusions: This research emphasizes the critical role of choosing the appropriate CPAP device for optimal patient outcomes, particularly for individuals experiencing breathing difficulties associated with OSAS. The findings highlight the need for careful consideration of device characteristics to ensure the effective treatment of sleep apnea using CPAP machines.

1. Background

1.1. Ventilator vs. CPAP

A ventilator and a CPAP (continuous positive airway pressure) device are both devices that provide respiratory support to patients, but they differ in their mode of operation and the level of support provided.

While both CPAP and ventilators deliver pressurized air to the patient, the goals and indications for their use are different. Ventilators are used to support patients with acute respiratory failure, such as in the case of severe pneumonia or acute respiratory distress syndrome (ARDS), while CPAP is used to treat chronic respiratory disorders such as obstructive sleep apnea syndrome (OSAS).

A ventilator is a device that delivers a controlled amount of air or oxygen to the lungs of a patient who is unable to breathe effectively on his own. Ventilators can be used for both short-term and long-term respiratory support and can provide a range of different modes of ventilation, such as pressure-controlled or volume-controlled ventilation. Ventilators are commonly used in critical care settings, such as intensive care units (ICUs), to support patients with acute respiratory failure, lung injury, or other conditions that affect breathing [1].

On the other hand, a CPAP machine is a non-invasive device that provides continuous positive pressure to the airways to help keep them open. CPAP is typically used to treat OSAS, a condition in which the airway becomes partially blocked during sleep, leading to pauses in breathing and reduced oxygenation. CPAP machines can also be used to treat other respiratory conditions, such as chronic obstructive pulmonary disease (COPD) or congestive heart failure [2–4].

While both ventilators and CPAP machines provide respiratory support, ventilators are more sophisticated and provide more intensive support than CPAP machines. Ventilators can be used to fully control a patient’s breathing, while CPAP machines only provide support to help keep the airways open. Additionally, ventilators are typically used in a critical care setting, while CPAP machines are used in a less acute setting such as at home or during sleep [5, 6].

In general, CPAP delivers a constant level of positive pressure to the patient's airway throughout the respiratory cycle. In CPAP mechanism, the pressure delivered by the device is the primary parameter that should be controlled.

Actually, CPAP devices do not have the same range of modes as mechanical ventilators, as they are designed to provide a static level of pressure support. However, some CPAP devices may offer different pressure settings or modes (such as ramp mode, which gradually increases the pressure to the prescribed level over a period of time), depending on the specific device and the patient's preferences.

Besides, it is worth noting that some modern CPAP devices may incorporate advanced control algorithms to improve patient comfort and adapt to changing respiratory patterns. For example, some CPAP devices may use auto-titrating algorithms that adjust the pressure delivered by the device based on the patient's breathing patterns and other parameters [7].

1.2. Types of CPAPs from control point of view

The controller type for a CPAP machine will depend on the specific needs of the patient and the underlying respiratory condition being treated. In general, the goal of a CPAP machine is to provide a continuous prescribed positive airway pressure using a blower to help keep the airway open during sleep through a flexible hose applied to a nasal mask fastened over the patient’s nose, which can improve oxygenation and prevent apneas (pauses in breathing).

The controller type for a CPAP machine can include both open-loop and closed-loop control strategies. Open-loop control refers to a system in which the input (i.e., the level of positive airway pressure) is set manually and does not change in response to feedback from the patient or the environment. Closed-loop control, on the other hand, uses feedback from sensors to adjust the input in response to changes in the patient's condition or the environment.

One common closed-loop control strategy for CPAP machines is auto-titrating CPAP (APAP), which uses algorithms to adjust the level of positive airway pressure in response to changes in the patient's breathing patterns or other factors, such as body position or sleep stage. APAP can help optimize the level of positive pressure for each patient, which can improve treatment outcomes and reduce side effects.

In terms of controller response, the ideal response for a CPAP machine is one that achieves a balance between maintaining adequate airway pressure to prevent apneas and minimizing discomfort for the patient. A too rapid or too aggressive response can result in discomfort or intolerance to the therapy, while a too slow or inadequate response can lead to persistent apneas and inadequate treatment.

Closed-loop control strategies such as APAP can help to achieve a more responsive and adaptive response to changes in the patient's respiratory pattern or other factors that may affect therapy. For example, APAP can adjust the level of positive airway pressure in real-time to match the patient's needs and reduce discomfort [7–12].

In addition to closed-loop control strategies, other features of the CPAP machine can also affect the controller response, such as the ramp-up time, which refers to the time it takes for the machine to gradually increase the level of positive pressure from the initial low setting to the prescribed therapeutic level. A longer ramp-up time may be more comfortable for some patients, while a shorter ramp-up time may be necessary to prevent apneas [13].

1.3. Previous work

Literature review has revealed some studies that have examined the effectiveness of CPAP devices in treating OSAS. In 2005, Shi et al. [14] conducted a study to assess the therapeutic properties of third-generation flow-based (f-APAP) and second-generation vibration-based (v-APAP) devices during the first night of treatment. The researchers analyzed polysomnography (PSG) recordings of 43 OSAS patients who underwent a diagnostic overnight PSG to confirm the disease, and then they used an APAP device for the first night under another PSG evaluation, using either f-APAP (n=22) or v-APAP (n=21). According to their analysis, f-APAP is more effective than v-APAP in eliminating breathing abnormalities in OSAS patients.

Isetta et al. [15] examined the response of different APAP devices in 2015. They connected various APAP devices to a computer-controlled model simulating a patient with OSAS to measure flow, pressure, and breathing during two-hour tests. Six different devices were tested, and the results showed that there was a significant difference in response between each APAP device due to the use of proprietary algorithms.

In 2022, Kumagai et al. [16] and Brajer-Luftmann et al. [17] conducted retrospective studies to investigate the efficacy of CPAP in treating OSAS. They evaluated and confirmed CPAP devices as a diagnostic tool and a treatment device for OSAS. The researchers found that APAP algorithms can be used to assess the effectiveness of CPAP in patients with OSAS.

1.4. Motivation and aim of the study

Despite the numerous studies that have examined the effectiveness of CPAP devices in treating OSAS, none of them have explored the impact of control, transient, and steady-state responses on their efficacy. This paper aims to address this research gap and contribute to the existing literature.

The aim of this study was to assess and compare the response of various currently available CPAP devices to a pre-adjusted breathing pressure (10 cmH2O) using a bench test with a computer and a specialized sensor. The study's objective was to provide critical insights for medical professionals to choose the most suitable CPAP device for their patients.

2. Material and Methods

2.1. Bench test protocol

The most important control parameter for the CPAP devices is the delivered air pressure. The CPAP machine must maintain a consistent positive airway pressure to ensure that the patient's airway remains open to prevent sleep apnea.

The devices under test were Dreamstar Duo ST (SEFAM), Point 2 (Hoffrichter), Respironics PR System One Pro (Philips), iBreeze 20A (ResVent), and Respaps (MedTech). The only

Table 1: The main information about the five CPAP devices under study

CPAP Device					
	C1	C2	C3	C4	C5
CPAP Model	DreamStar DUO ST	Point 2	Respironics PR System One Pro	iBreeze 20A	Respaps
Manufacturer	SEFAM Medical	Hoffrichter GmbH	Respironics Inc. - Philips	Resvent Medical Technology	MedTech Medical
Country of Origin	France	Germany	USA	China	Turkey

criterion used when selecting these devices was their availability. These devices were procured as new equipment to scrutinize their performance and contribute to this research. **Error! Reference source not found.** is showing the five CPAP devices under study. These five devices were designated as C1, C2, C3, C4, and C5.

All devices were programmed to deliver 10 cmH2O, an initial CPAP level of 0 cmH2O, and the initial waiting time or the ramp period were set to 0 min (when possible). All other parameters were set at their default values. Each device under test was connected to the flow-pressure meter with its own tubing, and pressure readings were taken for one minute with a 20-milliseconds (ms) sampling time; resulting in 3000 measures.

2.2. Flow-pressure meter

A TSI 5300 series gas mass flow meter was used to conduct these bench tests. This flow meter has the option to measure different parameters including flow, temperature, absolute pressure, volume, low differential pressure, and humidity; and can save these data to the meter and easily export it using the USB port.

The setup instructions for logging data from TSI are as follows:

1. Connect Device Under Test (DUT) to the inlet of TSI by tube.
2. Connect the outlet of TSI by either resistance tube for testing stability or tube plus mask to test breathing.
3. Connect TSI to PC by using an USB.
4. Open the DUT and TSI.

Error! Reference source not found. is showing the TSI 5300 series gas mass flow meter, and how it is connected to the computer. **Error! Reference source not found.** is showing the TSI 5300 series gas mass flow meter specification concerning the low differential pressure (parameter of interest).

Table 1: TSI 5300 series gas mass flow meter specifications for low differential /breathing pressure measurement

Range	±150 cmH_2O
Accuracy	±0.5% of reading or 0.15 cmH_2O, whichever is greater.
Response	<= 4 ms to 63% of final value for step change.
Units	Pa, hPa, kPa, mbar, PSI, mmHg, cmH_2O, inH_2O.

2.3. Step response characteristics

In control systems, delay time, rise time, peak time, settling time, overshoot percentage, and steady state error are some important performance parameters that are used to assess the transient response of a system to a step input. A step input is a type of input signal that abruptly changes from one value to another, typically from zero to some non-zero value [4]. In our bench test, it is the pressure signal that changes from 0 to 10 cmH2O.

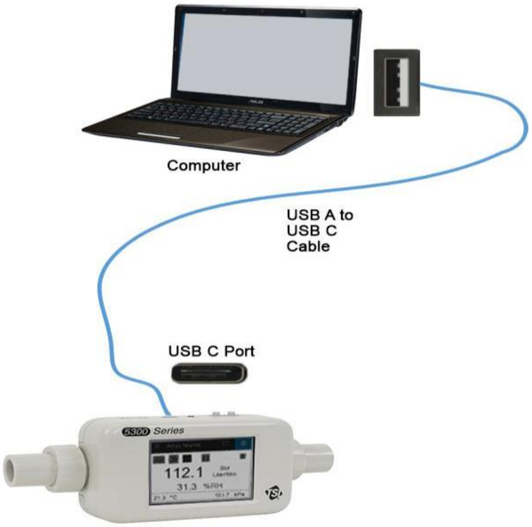


Figure 1: Connection of TSI 5300 series gas mass flow meter to computer

1. Delay time (Td): the delay time is the time it takes for the system’s response to rise from zero-state to 50% of the steady state value.
2. Rise time (Tr): The rise time is the time it takes for the system's response to rise from 10% to 90% of the steady state value. It can be calculated by finding the time at which the response first reaches 10% of the steady state value and subtracting it from the time at which the response reaches 90% of the steady state value.
3. Peak time (Tp): The peak time is the time it takes for the system's response to reach its maximum overshoot. It can be calculated by finding the time at which the response reaches its maximum overshoot.
4. Settling time (Ts): The settling time is the time it takes for the system's response to settle within a specified error band of the steady state value. It can be calculated by finding the time at which the response first enters the error band and subtracting

it from the time at which the response first reaches the steady state value.

5. Overshoot percentage (%OS) or Maximum Peak (Mp): The overshoot percentage or maximum peak is the maximum deviation of the system's response from the steady state value, expressed as a percentage of the steady state value. It can be calculated by finding the maximum deviation of the response from the steady state value and dividing it by the steady state value, then multiplying by 100%.
6. Steady state error (SSE): The difference between the desired and actual values of the output when the system has stabilized, and the input is constant.

These parameters are shown graphically in Figure 2.

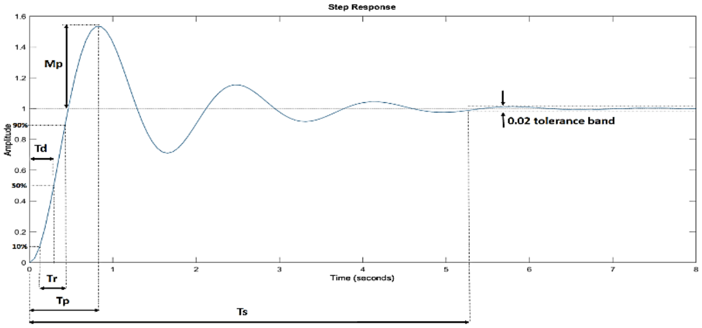


Figure 2: Step response characteristics

These performance parameters were used to evaluate the response of each CPAP device under test and help to assess each CPAP transient response to a step input, which is significant as it provides information about how quickly and accurately this device responds to changes in the input. The computed step response characteristics are relative to the initial state pressure P_{init} and the final steady state pressure P_{final}. In our bench test $P_{init} = 0$ and $P_{final} = 10$ cmH2O. Table 3 illustrates how to compute the step response characteristics.

3. Results

Figure 3 shows the recorded pressure signals from the five CPAP devices under study. Table 3 is showing the computed step-response characteristics for the five CPAP devices under study.

4. Discussion

Based on the results represented by the pressure signal curves, and the step response characteristics, it is possible to evaluate the performance of the different CPAP devices under the test. Considering the delay time, as a parameter represents the time taken by the device to respond after receiving a signal, a lower delay time is desirable as it ensures a quicker response from the device. Among the devices under test, C2 and C3 have the lowest delay time of 0.32 seconds while C5 has the highest delay time of 6.76 seconds. Therefore, C2 and C3 are the best performers, while C5 is the worst performer in terms of delay time.

From the rise time point of view, as a parameter represents the time taken by the device to rise from 10% to 90% of its maximum value after receiving a signal, a lower rise time indicates a faster response from the device. Among the devices under test, C3 has the lowest rise time of 0.08 seconds while C4 has the highest rise time of 2.5 seconds, and unfortunately C5 could not fulfill this criterion as it did not reach the 90% of the desired final steady state pressure (10 cmH2O). Therefore, C3 is the best performer, while C5 is the worst performer in terms of rise time.

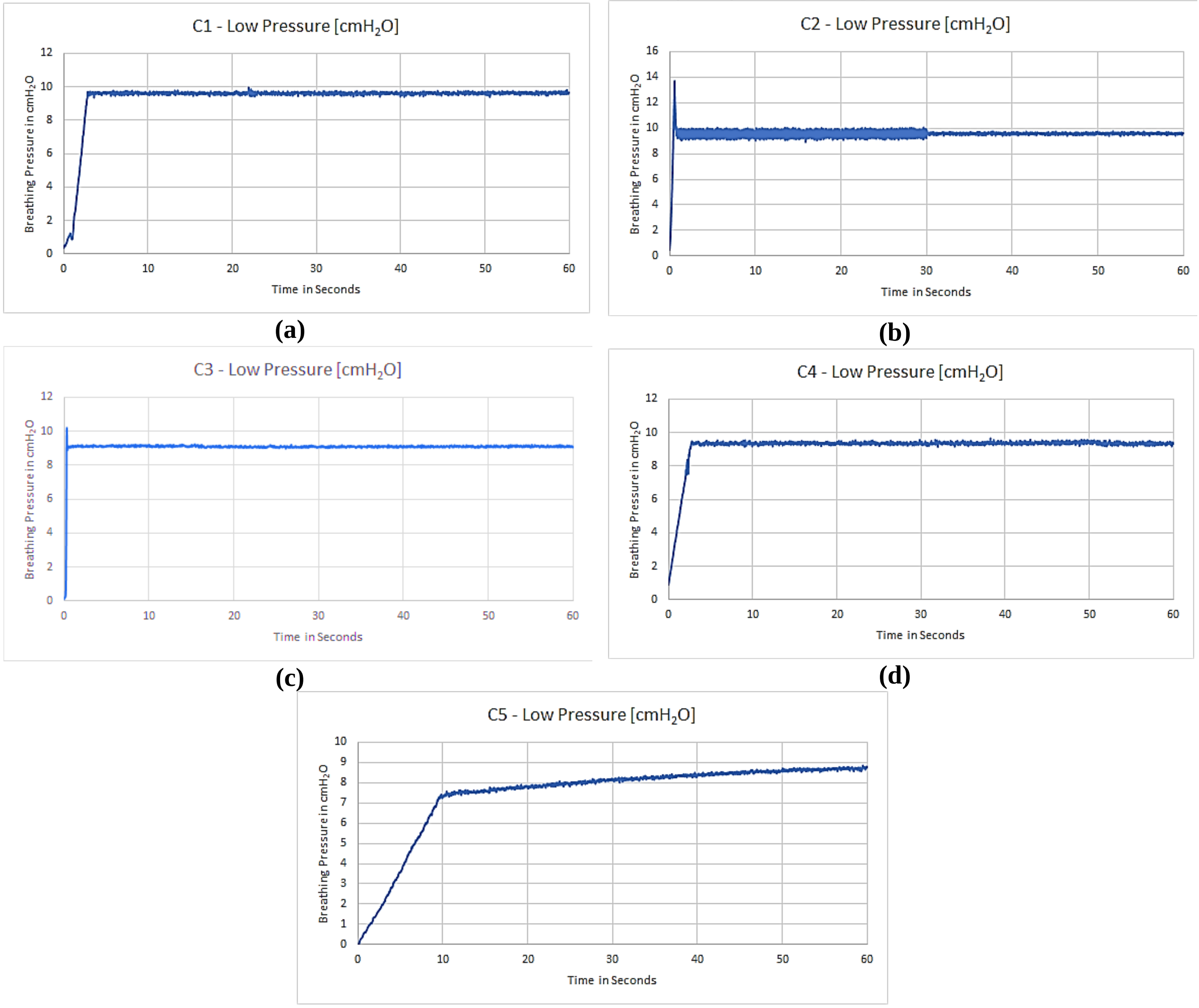
Table 3. How to compute the step response characteristics.

Parameter Name	Computation
Delay Time (Td)	Time it takes for the pressure response to rise from 0% to 50% of the way from P_{init} to P_{final}
Rise Time (Tr)	Time it takes for the pressure response to rise from 10% to 90% of the way from P_{init} to P_{final}
Settling Time (Ts)	The first time T such that the error $\|P_{final} - P(t)\| \leq SettlingTimeThreshold \times \|P_{final} - P_{init}\|$ for $t \geq T$. $SettlingTimeThreshold$ could range from 0.02 (2% of the peak error) to 0.05 (5% of the peak error) tolerance band. Settling Time measures the time it takes for the error to stay below 2% or 5% of $\|P_{final} - P_{init}\|$. The 0.02 tolerance was selected for calculations.
Overshoot Percentage (%)	Relative to the normalized pressure response $P_{overshoot}(t) = (P(t) - P_{final})/(P_{final} - P_{init})$, the overshoot percentage is the larger value of zero and $100 \times max(P_{overshoot}(t))$.
Maximum Peak Value (Mp)	Peak pressure value of $\|P(t) - P_{final}\|$
Peak Time (Tp)	Time at which the peak pressure value occurs
Steady State Error (SSE)	The error between the desired pressure response and the actual pressure response $\|P_{final} - P(t)\|$ when the pressure response has stabilized after $t \geq T$

Table 4: Computed step response characteristics for the five CPAP devices under study

CPAP Device Parameter	C1	C2	C3	C4	C5
Settling Pressure Value (cmH_2O)	9.85	9.78	9.27	9.51	8.90
Delay Time (sec)	1.96	0.32	0.32	1.30	6.76
Rise Time (sec)	2.10	0.36	0.08	2.50	NA
Settling Time (sec)	22.72	30.10	0.46	31.01	NA
Overshoot Percentage (%)	NA	37.23	1.90	NA	NA
Maximum Peak Value (cmH_2O)	NA	3.72	0.19	NA	NA
Peak Time (sec)	NA	0.62	0.36	NA	NA
Steady State Error (cmH_2O)	0.15	0.22	0.73	0.49	1.10

Regarding settling time, as a parameter represents the time taken by the device to reach a steady state value after receiving a signal, a lower settling time is desirable as it ensures that the device stabilizes quickly. Among the devices under test, C3 has the lowest settling time of 0.46 seconds while C4 has the highest settling time of 31.01 seconds, followed by C2 with a settling time of 30.1 seconds. Again, unfortunately C5 could not fulfill this criterion as it did not stabilize within 0.02 tolerance band from its steady state pressure value. Therefore, C3 is the best performer, while C5 is the worst performer in terms of settling time.



(a) **(b)** **(c)** **(d)** **(e)**

Figure 3: CPAP devices recorded pressure signals (a) DreamStar DUO ST CPAP (b) Point 2 CPAP (c) Respironics PR System One Pro CPAP (d) iBreeze 20A CPAP (e) Respaps CPAP.

Referring to the overshoot percentage which represents the percentage by which the device's output pressure exceeds its steady state value before stabilizing, a lower overshoot percentage is desirable as it ensures that the device does not overcompensate after receiving a signal. Among the devices under test, only C2 and C3 are showing underdamped response, while others are showing damped and overdamped responses, therefore their pressure signals are not overshooting. C3 has the lowest overshoot percentage of 1.9% while C2 has the highest overshoot percentage of 37.23%. Therefore, C3 is the best performer, while C2 is the worst performer in terms of overshoot percentage.

From the perspective of maximum peak value, as a parameter represents the maximum value reached by the device's output after receiving a signal, a lower peak value is desirable as it ensures that the device does not overcompensate after receiving a signal. Among the devices listed in the table, C2 has the highest maximum peak value of 3.72 cmH2O while C3 has the lowest maximum peak value of 0.19 cmH2O. Therefore, C3 is the best performer, while C2 is the worst performer in terms of maximum peak value. C1, C4, and C5 are not evaluated with respect to this criterion because of their damped and overdamped responses.

Regarding the maximum peak time which represents the time taken by the device to reach its maximum peak value after receiving a signal. Among the devices listed in the table, C2 has the highest maximum peak time of 0.62 seconds while C3 has the lowest maximum peak time of 0.36 seconds. Therefore, C3 is the best performer, while C2 is the worst performer in terms of maximum peak time. Again, C1, C4, and C5 are not evaluated with respect to this criterion because of their damped and overdamped responses.

Considering the steady state error, as a parameter represents the difference between the device's output and its expected steady state value after receiving a signal, a lower steady state error is desirable as it ensures that the device's output is close to its expected value. Among the devices listed in the table, C1 has the lowest steady state error of 0.15 cmH2O while C5 has the highest steady state error of 1.1 cmH2O. Therefore, C1 is the best performer, while C5 is the worst performer in terms of steady state error.

5. Conclusions

Based on the different performance parameters in Table 3, we can conclude that C3 is the best performing device overall, as it has the lowest values for delay time, rise time, settling time, and maximum peak time, which are important parameters for many applications. On the other hand, C5 is the worst performing device overall, as it has the highest values for delay time, rise time, settling time, and steady state error, which make it unsuitable for many applications.

However, let's not lose sight of the fact that, the choice of damping type (underdamped, damped, or overdamped) for different CPAP devices will depend on the specific needs and condition of the patient, as well as other factors such as comfort and tolerability.

In general, the goal of damping is to provide a smooth and stable transition between different levels of positive airway pressure, while minimizing discomfort and other adverse effects. Underdamped systems may be more responsive to changes in the patient's condition or environment but may also be more susceptible to overshooting or oscillations, which can be uncomfortable for the patient. Overdamped systems, on the other hand, may provide a smoother and more stable response, but may also be less responsive to changes in the patient's condition or environment.

While not all patients are suitable for CPAPs, they can still provide respiratory support to those in need. Recently, CPAP machines have proven to be valuable, especially in scenarios where mechanical ventilators are scarce. Although they may not be suitable for every patient, these machines offer respiratory support while minimizing the potential risks associated with more invasive medical procedures.

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Conflict of Interests

The authors have no relevant financial or non-financial interests to disclose.

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