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ACCURACY OF A NOVEL REUSABLE 3D-PRINTED DUAL $ETCO_2$–O_2 ADAPTER COMPARED WITH THE SENTRI NASAL CANNULA FOR END-TIDAL CARBON DIOXIDE MONITORING IN SPONTANEOUSLY BREATHING PATIENTS UNDERGOING REGIONAL ANAESTHESIA

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ABSTRACT

Background: End-tidal carbon dioxide ($EtCO_2$) monitoring in spontaneously breathing patients undergoing regional anesthesia is essential for the early detection of hypoventilation. Conventional devices, such as the Sentri nasal cannula, are widely used; however, limitations in sampling efficiency and oxygen delivery persist. A novel reusable 3D-printed dual $EtCO_2$–O_2 adapter was developed to address these issues.

Methods: In this prospective comparative study, spontaneously breathing adult patients scheduled for regional anesthesia were monitored using both the 3D-printed dual adapter and Sentri nasal cannula. The primary outcome measures included the accuracy of $EtCO_2$ values compared with arterial blood gas ($PaCO_2$) correlation. The secondary outcomes assessed ease of use, patient comfort, and oxygen delivery efficiency.

Results: The 3D-printed adapter demonstrated $EtCO_2$ values with a strong correlation with $PaCO_2$, comparable to those of the Sentri nasal cannula. Bland–Altman analysis revealed narrower limits of agreement with the novel adapter, indicating its improved accuracy. Patient comfort scores were similar between the devices, whereas oxygen delivery was more consistent with the dual adapter. No adverse events were observed.

Conclusion: The reusable 3D-printed dual $EtCO_2$–O_2 adapter provides accurate end-tidal carbon dioxide monitoring with reliable oxygen supplementation, offering a cost-effective and sustainable alternative to the Sentri nasal cannula in spontaneously breathing patients undergoing regional anaesthesia.

KEYWORDS: End-tidal carbon dioxide, Regional anaesthesia, Sentri nasal cannula, 3D printing in anaesthesia, Reusable medical devices, Oxygen supplementation

INTRODUCTION

End-tidal carbon dioxide ($EtCO_2$) monitoring has become an integral component of modern perioperative care because it provides continuous, non-invasive assessment of ventilation by measuring the concentration of carbon dioxide at the end of expiration. Unlike pulse oximetry, which primarily reflects oxygenation and may remain within the normal range despite significant hypoventilation in patients receiving supplemental oxygen, capnography enables early detection of respiratory depression, airway obstruction, hypoventilation, and apnoea before clinically important oxygen desaturation occurs. Consequently, continuous capnographic monitoring has been recognised as an essential patient safety measure during anaesthesia, procedural sedation, and postoperative recovery. (1–3)

Professional organisations, including the American Society of Anesthesiologists (ASA), recommend continuous monitoring of ventilation using capnography during general anaesthesia and moderate-to-deep procedural sedation whenever feasible. Several clinical studies have demonstrated that capnography identifies respiratory compromise earlier than routine clinical observation or pulse oximetry alone, allowing prompt intervention and reducing the incidence of preventable respiratory adverse events. Despite these recommendations, routine $EtCO_2$ monitoring in spontaneously breathing patients undergoing regional anaesthesia remains inconsistent because conventional oxygen delivery devices often do not facilitate reliable sampling of exhaled carbon dioxide. (4–6)

Nasal cannula-based capnography systems have been developed to permit simultaneous oxygen administration and end-tidal carbon dioxide monitoring in non-intubated patients. Among these, the Sentri Nasal Cannula is designed to sample expired carbon dioxide while delivering supplemental oxygen through an integrated dual-lumen configuration. Although such commercial interfaces provide acceptable clinical performance, accurate $EtCO_2$ monitoring may be influenced by

mouth breathing, variable respiratory patterns, oxygen flow rates, and displacement of the nasal prongs. Furthermore, these devices are generally disposable and relatively expensive, limiting their widespread use, particularly in resource-constrained healthcare settings. (7–9)

Recent advances in three-dimensional (3D) printing have enabled the rapid development of customised, low-cost medical devices with excellent dimensional accuracy and compatibility with existing clinical equipment. In anaesthesiology, 3D-printing technology has been successfully applied in airway management, procedural simulation, patient-specific devices, and monitoring accessories. Reusable 3D-printed devices manufactured using medical-grade materials offer the additional advantages of sterilisability, sustainability, and reduced healthcare costs without compromising functionality. (10–12)

To overcome the limitations associated with existing oxygen delivery interfaces, a novel reusable 3D-printed dual $EtCO_2$–O_2 universal adapter was developed for integration with a standard Hudson mask. The adapter incorporates a dual-channel coaxial design that allows uninterrupted oxygen delivery while positioning the carbon dioxide sampling port close to the patient's nose and mouth, thereby facilitating efficient collection of expired gas with minimal dilution by supplemental oxygen. Unlike conventional nasal cannula systems, the adapter is intended to provide reliable capnographic monitoring while preserving patient comfort and allowing compatibility with standard Hudson masks already available in routine anaesthesia practice. (11,12)

Although the proposed adapter was designed to improve accessibility and reduce the cost of capnographic monitoring, its clinical applicability depends on demonstrating measurement accuracy comparable with established commercial monitoring systems. Device validation requires comparison of $EtCO_2$ measurements with arterial partial pressure of carbon dioxide ($PaCO_2$), the accepted reference standard, together with assessment of agreement using appropriate statistical methods such as correlation analysis and Bland–Altman analysis. These methods determine whether a novel monitoring device can provide clinically interchangeable measurements with existing technologies. (13,14)

Therefore, the present prospective comparative crossover study was undertaken to evaluate the accuracy of a novel reusable 3D-printed dual $EtCO_2$–O_2 universal adapter by comparing its end-tidal carbon dioxide measurements with those obtained using the commercially available Sentri Nasal Cannula in spontaneously breathing adult patients undergoing regional anesthesia. In addition, the agreement of both devices with arterial partial pressure of carbon dioxide ($PaCO_2$), waveform quality, clinical feasibility, and overall performance were evaluated to determine the suitability of the novel adapter as a practical reusable alternative for routine capnographic monitoring.

MATERIALS AND METHODS

Study design and setting

This prospective comparative crossover study was conducted in the Department of Anaesthesiology, Saveetha Medical College and Hospital, Saveetha Institute of Medical and Technical Sciences (SIMATS), Chennai, India, over a period of one year after obtaining approval from the Institutional Ethics Committee (IEC Reference No. 013/11/2024/IEC/SMCH). Written informed consent was obtained from all participants before enrolment. The study was performed in accordance with the ethical principles of the Declaration of Helsinki.

Study participants

Adult patients aged 18–50 years with American Society of Anesthesiologists (ASA) physical status I or II who were scheduled to undergo elective surgery under regional anesthesia with spontaneous ventilation were consecutively recruited.

Patients with a history of smoking, bronchial asthma, chronic obstructive pulmonary disease, obstructive sleep apnea, obesity (body mass index ≥30 kg/m^2), hemodynamic instability; sepsis, hypothermia, an anticipated requirement for endotracheal intubation, intraoperative opioid administration, a surgical duration of less than one hour, or a refusal to participate were excluded from the study.

Sample size estimation

The sample size was calculated using data from a previously published study comparing end-tidal carbon dioxide ($EtCO_2$) measurements obtained using non-intubated capnography interfaces in spontaneously breathing patients. A minimum sample size of 55 participants was estimated to achieve adequate statistical power. To compensate for possible dropouts and to improve the reliability of agreement analyses, 60 participants were included in the final study. Eligible participants were enrolled using consecutive sampling.

Study devices

The investigational device was a novel reusable three-dimensional (3D)-printed dual $EtCO_2$–O_2 universal adapter developed for integration with a standard Hudson mask. The adapter incorporated a dual-channel coaxial configuration with separate lumens for oxygen delivery and sidestream carbon dioxide sampling. The carbon dioxide sampling port was positioned between the patient's nose and mouth to facilitate efficient collection of expired gas while minimising dilution by supplemental oxygen. Before clinical evaluation, the device underwent dimensional verification, leak testing, oxygen flow validation, and simulated capnography testing. The adapter was designed for repeated clinical use following validated sterilisation procedures.

The comparator device was the Sentri Nasal Cannula, a commercially available disposable dual-lumen nasal cannula designed to permit simultaneous oxygen administration and sidestream end-tidal carbon dioxide monitoring in spontaneously breathing patients. Oxygen delivery and carbon dioxide sampling were performed through separate channels incorporated within the nasal cannula according to the manufacturer's recommendations.

Study procedure

After successful administration of regional anaesthesia, patients were allowed to breathe spontaneously throughout the study period. Supplemental oxygen was administered at a flow rate of 5 L/min using the assigned monitoring interface. Following a stabilisation period of five minutes, an arterial blood sample was obtained for arterial blood gas (ABG) analysis to determine arterial partial pressure of carbon dioxide ($PaCO_2$).

Each participant subsequently underwent sequential end-tidal carbon dioxide monitoring using the novel reusable 3D-printed dual $EtCO_2$–O_2 universal adapter and the Sentri Nasal Cannula under identical clinical conditions. To minimise measurement variability, oxygen flow rate, patient position, monitoring equipment, and environmental conditions were maintained constant throughout the study. A washout period of two minutes was allowed between the two monitoring sessions.

For each monitoring device, $EtCO_2$ values were recorded at two-minute intervals over a ten-minute observation period, resulting in five consecutive measurements. The mean $EtCO_2$ value obtained from these five readings was used for statistical analysis. Capnographic waveform quality, successful acquisition of continuous $EtCO_2$ tracing, and overall device feasibility during routine intraoperative monitoring were documented for every participant.

Outcome measures

The primary outcome was the accuracy of end-tidal carbon dioxide ($EtCO_2$) measurement obtained using the novel reusable 3D-printed dual $EtCO_2$–O_2 universal adapter compared with the Sentri Nasal Cannula, using arterial partial pressure of carbon dioxide ($PaCO_2$) as the reference standard.

The secondary outcomes included comparison of the $PaCO_2$–$EtCO_2$ gradient, correlation between $EtCO_2$ and $PaCO_2$ measurements, agreement between monitoring systems assessed using Bland–Altman analysis, capnographic waveform quality, successful device utilisation during regional anaesthesia, and reusability and practical feasibility profile of the monitoring interfaces.

Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics for Windows, Version 26.0 (IBM Corp., Armonk, NY, USA). Continuous variables were expressed as mean ± standard deviation (SD), whereas categorical variables were presented as frequency and percentage. Normality of continuous variables was assessed using the Shapiro–Wilk test.

Paired Student's t-test was used to compare $EtCO_2$ measurements obtained using the novel reusable adapter and the Sentri Nasal Cannula. Pearson's correlation coefficient (r) was calculated to evaluate the relationship between $EtCO_2$ and arterial $PaCO_2$ measurements. Agreement between $EtCO_2$ values and arterial $PaCO_2$, as well as agreement between the two monitoring devices, was assessed using Bland–Altman analysis with calculation of mean bias and 95% limits of agreement. A two-sided P value of <0.05 was considered statistically significant.

RESULTS

A total of 60 adult patients undergoing elective surgery under regional anaesthesia with spontaneous ventilation were included in the study. The baseline demographic and clinical characteristics of the participants are shown in Table 1. The mean age was 32.97 ± 7.90 years, and the mean body mass index was 24.32 ± 2.72 kg/m². The study population included 33 males (55.0%) and 27 females (45.0%). Equal proportions of patients belonged to ASA physical status I and II. The mean arterial $PaCO_2$ was 39.78 ± 2.91 mmHg.

Table 1. Baseline demographic and clinical characteristics of the study participants (n = 60)

Characteristic	Value
Age (years), mean ± SD	32.97 ± 7.90
Age, median (range)	33.0 (18–50)
Male, n (%)	33 (55.0)
Female, n (%)	27 (45.0)
Body mass index (kg/m²), mean ± SD	24.32 ± 2.72
Body mass index, median (range)	24.60 (19.0–29.5)
Normal BMI, n (%)	34 (56.7)
Overweight, n (%)	26 (43.3)

Characteristic	Value
ASA physical status I, n (%)	30 (50.0)
ASA physical status II, n (%)	30 (50.0)
Pulse rate (beats/min), mean ± SD	75.87 ± 7.60
Systolic blood pressure (mmHg), mean ± SD	120.67 ± 9.79
Diastolic blood pressure (mmHg), mean ± SD	79.50 ± 5.95
Arterial $PaCO_2$ (mmHg), mean ± SD	39.78 ± 2.91

Values are presented as mean ± standard deviation (SD), median (range), or number (percentage). BMI: body mass index; ASA: American Society of Anesthesiologists; $PaCO_2$: arterial partial pressure of carbon dioxide.

The mean $EtCO_2$ measured using the novel reusable adapter was 37.89 ± 2.98 mmHg, while the corresponding value obtained using the Sentri Nasal Cannula was 37.62 ± 3.01 mmHg. Both devices recorded $EtCO_2$ values slightly lower than arterial $PaCO_2$, consistent with the expected physiological $PaCO_2$–$EtCO_2$ gradient. The mean $PaCO_2$–$EtCO_2$ gradient was 1.89 ± 1.46 mmHg for the novel adapter and 2.16 ± 1.64 mmHg for the Sentri Nasal Cannula. The paired difference between the two devices was small and not statistically significant.

Table 2. Comparison of $EtCO_2$ measurements obtained using the novel adapter and Sentri Nasal Cannula with arterial $PaCO_2$ (n = 60)

Variable	Novel adapter	Sentri Nasal Cannula	P value
Mean $EtCO_2$ (mmHg), mean ± SD	37.89 ± 2.98	37.62 ± 3.01	0.3253
Median $EtCO_2$ (mmHg)	37.70	37.45	—
$EtCO_2$ range (mmHg)	33.1–44.5	31.6–45.0	—
Mean $PaCO_2$–$EtCO_2$ gradient (mmHg), mean ± SD	1.89 ± 1.46	2.16 ± 1.64	—
Median gradient (mmHg)	1.65	1.65	—
Gradient range (mmHg)	−1.4 to 5.2	−0.3 to 5.9	—

Values are presented as mean ± SD or median/range. Paired Student's t-test was used to compare mean $EtCO_2$ values between the two devices. Gradient denotes $PaCO_2 - EtCO_2$.

Both monitoring devices demonstrated strong positive correlation with arterial $PaCO_2$. The correlation coefficient was slightly higher for the novel adapter (r = 0.8772) than for the Sentri Nasal Cannula (r = 0.8467). The inter-device correlation between the novel adapter and Sentri Nasal Cannula was also strong (r = 0.7428), indicating that both devices tracked $EtCO_2$ variation in a similar manner across patients.

Table 3. Correlation of $EtCO_2$ measurements with arterial $PaCO_2$ and inter-device correlation

Comparison	Pearson r	95% CI lower	95% CI upper	P value
Novel adapter $EtCO_2$ vs arterial $PaCO_2$	0.8772	0.8019	0.9251	<0.001
Sentri Nasal Cannula $EtCO_2$ vs arterial $PaCO_2$	0.8467	0.7551	0.9059	<0.001
Novel adapter $EtCO_2$ vs Sentri Nasal Cannula $EtCO_2$	0.7428	0.6026	0.8386	<0.001

Table 4. Bland–Altman agreement analysis of the novel adapter and Sentri Nasal Cannula (n = 60)

Comparison	Mean bias (mmHg)	SD of difference	Lower limit of agreement	Upper limit of agreement
Novel adapter vs arterial $PaCO_2$	−1.89	1.4613	−4.7492	0.9792
Sentri Nasal Cannula vs arterial $PaCO_2$	−2.16	1.6425	−5.3792	1.0592
Novel adapter vs Sentri Nasal Cannula	0.28	2.1477	−3.9346	4.4846

Bias was calculated as $EtCO_2 - PaCO_2$ for comparisons with arterial $PaCO_2$ and as novel adapter $EtCO_2$ − Sentri Nasal Cannula $EtCO_2$ for inter-device comparison. LoA: limits of agreement.
The $PaCO_2$–$EtCO_2$ gradient was within 5 mmHg in 59 patients (98.3%) using the novel adapter and in 57 patients (95.0%) using the Sentri Nasal Cannula. Only one patient (1.7%) in the novel adapter group and three patients (5.0%) in the Sentri Nasal Cannula group had gradients greater than 5 mmHg.

Table 5. Clinical acceptability of $PaCO_2$–$EtCO_2$ gradients across monitoring systems

Monitoring system	Gradient ≤2 mmHg, n (%)	Gradient ≤5 mmHg, n (%)	Gradient >5 mmHg, n (%)
Novel adapter	32 (53.3)	59 (98.3)	1 (1.7)
Sentri Nasal Cannula	33 (55.0)	57 (95.0)	3 (5.0)

Gradient thresholds of ≤2 mmHg and ≤5 mmHg were used as practical indicators of closeness to arterial $PaCO_2$.
Both monitoring systems demonstrated good waveform reliability. Stable capnographic waveforms were obtained in 58 patients (96.7%) using the novel adapter and in 58 patients (96.7%) using the Sentri Nasal Cannula. Minor waveform dropouts were observed in two patients (3.3%) with each device. All devices were successfully used in all 60 patients without integration failure.

Table 6. Clinical performance of the novel adapter and Sentri Nasal Cannula (n = 60)

Parameter	Novel adapter	Sentri Nasal Cannula
Successful capnographic waveform acquisition, n (%)	60 (100.0)	60 (100.0)
Stable waveform, n (%)	58 (96.7)	58 (96.7)
Minor waveform dropout, n (%)	2 (3.3)	2 (3.3)
Failure to obtain interpretable waveform, n (%)	0 (0.0)	0 (0.0)
Successful device integration, n (%)	60 (100.0)	60 (100.0)
Failed device integration, n (%)	0 (0.0)	0 (0.0)
Device-related complications, n (%)	0 (0.0)	0 (0.0)
Interface type	Reusable	Disposable

Values are presented as number (percentage). Formal inferential testing was not applicable for feasibility outcomes because there was no variation in successful integration. Cost profile was descriptive because monetary cost variables were not captured; the novel adapter was recorded as reusable, while the Sentri Nasal Cannula was recorded as disposable.

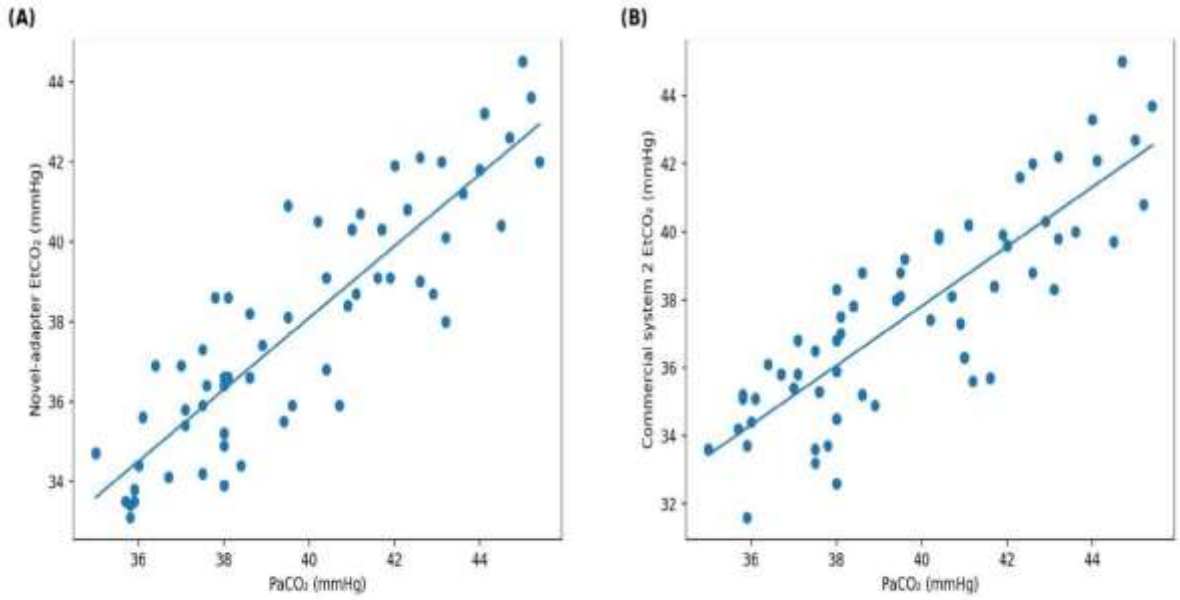

Figure 1. Correlation between end-tidal carbon dioxide ($EtCO_2$) measurements and arterial partial pressure of carbon dioxide ($PaCO_2$).

(A) Scatter plot demonstrating the correlation between $EtCO_2$ measured using the novel reusable dual $EtCO_2$–O_2 adapter and arterial $PaCO_2$.

(B) Scatter plot demonstrating the correlation between $EtCO_2$ measured using the Sentri Nasal Cannula and arterial $PaCO_2$. The solid line represents the linear regression line.

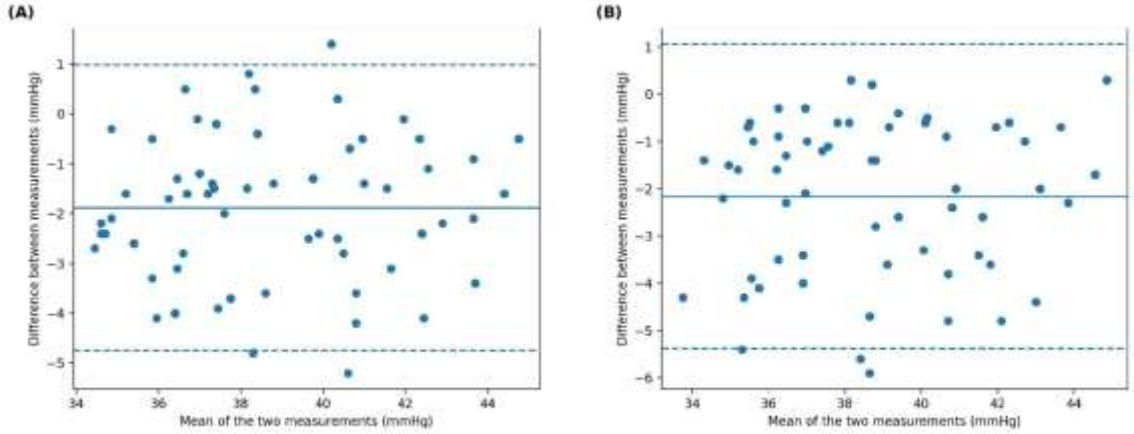

Figure 2. Bland–Altman analysis demonstrating agreement between end-tidal carbon dioxide ($EtCO_2$) measurements and arterial partial pressure of carbon dioxide ($PaCO_2$).

(A) Bland–Altman plot showing agreement between $EtCO_2$ measured using the novel reusable dual $EtCO_2$–O_2 adapter and arterial $PaCO_2$.
(B) Bland–Altman plot showing agreement between $EtCO_2$ measured using the Sentri Nasal Cannula and arterial $PaCO_2$. The central solid line represents the mean bias, and the dashed lines represent the 95% limits of agreement.

DISCUSSION

The present study demonstrated that the novel reusable three-dimensional (3D)-printed dual $EtCO_2$–O_2 adapter provided end-tidal carbon dioxide ($EtCO_2$) measurements comparable to those obtained using the Sentri Nasal Cannula in spontaneously breathing adult patients undergoing regional anaesthesia. The mean $EtCO_2$ values obtained with both devices were similar, and the paired comparison showed no statistically significant difference. Both devices also demonstrated strong correlation with arterial $PaCO_2$, acceptable Bland–Altman agreement, clinically acceptable $PaCO_2$–$EtCO_2$ gradients, and reliable capnographic waveform acquisition. These findings suggest that the novel adapter can provide clinically useful ventilation monitoring while maintaining compatibility with a standard Hudson mask.

Continuous capnographic monitoring is clinically important because it provides breath-by-breath assessment of ventilation and can detect respiratory depression earlier than pulse oximetry, particularly when supplemental oxygen is being administered. Pulse oximetry may remain normal despite hypoventilation, whereas changes in $EtCO_2$ and waveform morphology can indicate airway obstruction, apnoea, or inadequate ventilation before oxygen desaturation occurs. This is especially relevant during regional anaesthesia and procedural sedation, where patients remain spontaneously breathing but may still be vulnerable to sedative-related ventilatory compromise. (1–6,15,16)

The mean $EtCO_2$ measured using the novel adapter was slightly higher than that recorded using the Sentri Nasal Cannula, but the difference was small and not statistically significant. This finding is clinically relevant because nasal cannula-based $EtCO_2$ monitoring may be affected by mouth breathing, displacement of nasal prongs, dilution by oxygen flow, and variability in sampling port position. Yanagidate and Dohi previously highlighted the need for modified nasal cannula designs that can support simultaneous oxygen delivery and $EtCO_2$ monitoring during spontaneous breathing. (7) Similarly, Ebert et al. demonstrated that different nasal cannula designs vary in oxygen delivery efficiency and carbon dioxide waveform reliability, indicating that interface design strongly influences $EtCO_2$ performance. (8) The present findings support this concept, as the novel adapter achieved $EtCO_2$ values comparable to the Sentri Nasal Cannula despite using a different sampling approach.

Both monitoring systems underestimated arterial $PaCO_2$ by a small margin, which is physiologically expected. $EtCO_2$ is usually lower than $PaCO_2$ because of alveolar dead space and ventilation–perfusion variation. In the present study, the mean $PaCO_2$–$EtCO_2$ gradient was 1.89 ± 1.46 mmHg for the novel adapter and 2.16 ± 1.64 mmHg for the Sentri Nasal Cannula. These values are within the clinically acceptable range and are consistent with previous studies showing that $EtCO_2$ can reasonably reflect arterial carbon dioxide trends in haemodynamically stable, spontaneously breathing patients. Takano et al. reported clinically useful agreement between portable $EtCO_2$ measurements and arterial $PaCO_2$ in spontaneously breathing patients, while McSwain et al. showed correlation between end-tidal and arterial carbon dioxide measurements across different levels of physiological dead space. (17,18)

Correlation analysis showed strong positive association between $EtCO_2$ and arterial $PaCO_2$ for both devices, with the novel adapter demonstrating a slightly higher correlation coefficient than the Sentri Nasal Cannula. However, correlation alone is insufficient to establish whether two measurement methods can be used interchangeably. Bland–Altman analysis is more appropriate for method-comparison studies because it estimates mean bias and limits of agreement. (13,14) In the present study, the novel adapter showed a mean bias of −1.89 mmHg against $PaCO_2$, while the Sentri Nasal Cannula

showed a mean bias of −2.16 mmHg. The direct inter-device bias between the novel adapter and Sentri Nasal Cannula was only 0.28 mmHg, indicating close agreement between the two monitoring interfaces.

The clinical acceptability of the $PaCO_2$–$EtCO_2$ gradient further supports the reliability of the novel adapter. A gradient within 5 mmHg was observed in 59 patients (98.3%) using the novel adapter and in 57 patients (95.0%) using the Sentri Nasal Cannula. This indicates that the novel adapter not only correlated well with $PaCO_2$ but also remained within a clinically practical range for most participants. Since capnography is primarily used for continuous monitoring of ventilatory trends rather than replacing arterial blood gas analysis in all situations, such agreement is clinically meaningful in stable patients undergoing regional anaesthesia.

Waveform reliability is another important aspect of capnographic monitoring. Accurate clinical interpretation depends not only on the numerical $EtCO_2$ value but also on the quality of the waveform, which helps identify airway obstruction, hypoventilation, apnoea, and sampling problems. (2,3) In this study, successful capnographic waveform acquisition was achieved in all patients with both devices. Stable waveforms were observed in 96.7% of patients with the novel adapter and 96.7% with the Sentri Nasal Cannula, with only minor waveform dropouts. This suggests that the positioning of the sampling port in the novel adapter was adequate for continuous expired gas capture during spontaneous breathing.

The reusable 3D-printed design of the novel adapter is an additional practical advantage. Commercial capnography interfaces, including nasal cannula systems, are commonly disposable and may increase recurring expenditure in high-volume operating rooms. The ability to integrate a reusable adapter with a standard Hudson mask may reduce dependence on single-use interfaces and improve the feasibility of routine capnographic monitoring in resource-constrained settings. This is particularly relevant in low- and middle-income healthcare systems, where capnography access may be limited by cost, procurement, and supply-chain barriers. (10–12,19) However, because the present study did not perform a formal cost-effectiveness analysis, economic conclusions should be interpreted cautiously.

The safety of any reusable patient-contact device depends on appropriate material selection, cleaning, disinfection, and sterilisation. Although the novel adapter was designed for reuse following validated sterilisation procedures, long-term reprocessing durability and repeated-use performance require further evaluation. Standard infection-control principles emphasize that reusable medical devices must undergo appropriate decontamination and sterilisation to prevent cross-contamination. (20) Therefore, future studies should assess material integrity, sterilisation cycles, surface changes, microbial safety, and long-term clinical durability before widespread implementation.

The present study has certain limitations. First, it was conducted at a single centre with a relatively small sample size of 60 patients. Second, only adult patients with ASA physical status I or II undergoing elective surgery under regional anaesthesia were included; therefore, the findings may not be generalisable to paediatric patients, obese patients, patients with significant cardiopulmonary disease, or critically ill patients. Third, $EtCO_2$ monitoring was performed under controlled intraoperative conditions with a fixed oxygen flow rate, and performance under variable oxygen flows, deep sedation, mouth breathing, or emergency conditions was not assessed. Fourth, while the study compared the novel adapter with a commercial nasal cannula system, it did not include long-term reusability testing or a formal health-economic analysis.

Despite these limitations, the findings are clinically encouraging. The novel reusable 3D-printed dual $EtCO_2$–O_2 adapter demonstrated $EtCO_2$ measurement accuracy, $PaCO_2$ agreement, waveform reliability, and clinical feasibility comparable to the Sentri Nasal Cannula. Its compatibility with the standard Hudson mask and reusable design may make it a practical alternative for expanding routine capnographic monitoring during regional anaesthesia. Further multicentre studies with larger and more diverse populations are recommended to confirm these findings and evaluate long-term device durability, sterilisation safety, and cost-effectiveness.

CONCLUSION

The novel reusable 3D-printed dual $EtCO_2$–O_2 adapter demonstrated $EtCO_2$ measurement accuracy, agreement with arterial $PaCO_2$, capnographic waveform reliability, and clinical feasibility comparable to the Sentri Nasal Cannula in spontaneously breathing adult patients undergoing regional anaesthesia. The adapter may serve as a practical reusable alternative for continuous capnographic monitoring when integrated with a standard Hudson mask. Further larger studies are required to validate its performance across wider clinical settings and to assess long-term reusability and cost-effectiveness.

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