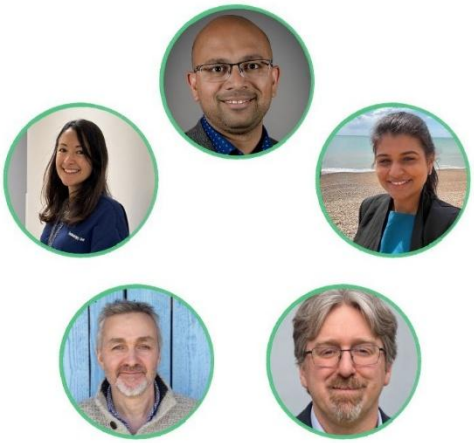
SUSQI PROJECT REPORT

Evaluating methoxyflurane (Penthrox) as an alternative to Entonox for colonoscopy in the Scottish Highlands

A single centre sustainable quality improvement project



Project title	Evaluating methoxyflurane (Penthrox) as an alternative to Entonox for colonoscopy in the Scottish Highlands
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Participating organisations	NHS Highlands, Green Healthcare Scotland

Team members

Mr George Neelankavil Davis - Registrar, General surgery, Email: george.neelankavildavis@nhs.scot,
Ms Sumathi Nadikuditi - Registrar, General surgery, Email: sumathi.nadikuditi@nhs.scot,
Ms Leila Chandler Clinical Endoscopist, Email: leila.lyons1@nhs.net
Mr Alan Grant - Consultant Surgeon, Email: alan.grant@nhs.scot,
Dr Kenneth Barker - Consultant Anaesthetist, Email: kenneth.barker2@nhs.scot

Introduction:

Colonoscopy is a high-volume procedure globally that requires adequate analgesia to facilitate procedural completion while maintaining patient comfort, safety and timely recovery. Entonox (50%

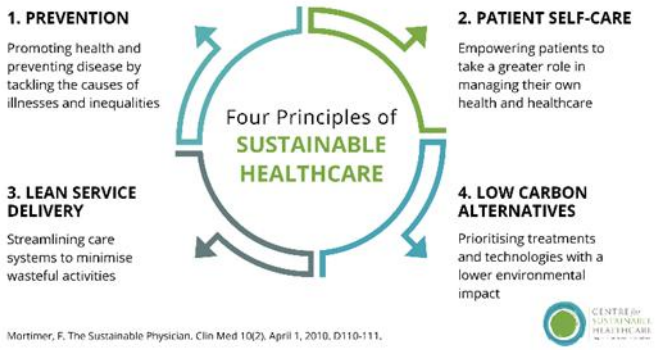
nitrous oxide and oxygen) is commonly used as a patient-controlled inhaled analgesic during colonoscopy because of its rapid onset and offset of action. However, its delivery relies on compressed-gas cylinders, requiring transportation, storage and manual handling within healthcare facilities.

The environmental impact of Entonox is an increasing concern and is detrimental to the ozone layer. Nitrous oxide is a potent and long-lived greenhouse gas, with a 100-year global warming potential (GWP_{100}) of 265-298, with a lifetime in the environment of more than 121 years. This means it remains in the atmosphere for a prolonged period and has a significantly greater warming effect than carbon dioxide. In comparison, methoxyflurane has a GWP_{100} of 4 (1), demonstrating a much lower environmental impact. Most nitrous oxide procured by the NHS is lost before clinical use due to leaks and stock control issue (2), but all used clinically is ultimately released into the atmosphere, contributing to the carbon footprint of healthcare. Reducing avoidable use therefore aligns clinical improvement with the NHS commitment to reach net zero for directly controlled emissions by 2040 and for emissions it can influence by 2045(3).

Methoxyflurane is a volatile fluorinated anaesthetic that was withdrawn from anaesthetic-dose use because toxicity was dose related(4, 5). At the substantially lower analgesic dose(6), it has been reintroduced as a rapid-onset, self-administered analgesic in prehospital pain management (7),trauma (8) and short procedures(9). Penthrox is supplied as a portable 3 mL inhaler; the recommended maximum is 6 mL in 24 hours. It has previously been used by patients undergoing minor procedures and has been highly favoured because of its ease of use and effective analgesic properties(10). Its activated-carbon filter is intended to limit exhaled methoxyflurane release.
Importantly, Penthrox may offer a substantially lower-carbon alternative to Entonox. Published life-cycle assessment has demonstrated a markedly lower carbon footprint for low-dose methoxyflurane compared with Entonox(11). However, environmental sustainability cannot be considered independently of clinical care. Any lower-carbon alternative must maintain procedural effectiveness, patient comfort and safety while remaining practical and economically sustainable for routine service delivery.

Evidence supporting methoxyflurane for colonoscopy and other ambulatory procedures is encouraging, with studies demonstrating feasibility, effective analgesia and good patient acceptability. Nevertheless, direct evidence comparing Penthrox with Entonox in colonoscopy remains limited. Local evaluation is therefore necessary before wider adoption, particularly to establish whether the environmental benefits can be achieved without adversely affecting procedure completion, recovery, patient experience or endoscopy workflow.

This project was consequently undertaken as a Sustainable Quality Improvement (SusQI) initiative to evaluate the substitution of Entonox with Penthrox for colonoscopy. In accordance with the Centre for Sustainable Healthcare framework, the project considered clinical outcomes alongside environmental, economic and social impacts. The aim was to determine whether Penthrox could provide a practical lower-carbon analgesic pathway while maintaining the quality and value of patient care.





The work was undertaken across the endoscopy department of NHS Highland (Raigmore Hospital) and funded by Green Healthcare Scotland(12). Organisations provide diagnostic and therapeutic colonoscopy and already use inhalational analgesia, making them suitable settings in which to test feasibility, acceptability and transferability.

Specific aims:

To evaluate whether introducing self-administered Penthrox for eligible adults undergoing elective colonoscopy provides feasible, safe and acceptable analgesia while maintaining procedural quality, and to compare its environmental, financial and social impacts with the current Entonox pathway.

Methods and methodology:

Study design and setting:

This SusQI project was conducted within the Endoscopy Department at Raigmore Hospital, NHS Highland and funded by Green Healthcare Scotland, to evaluate the introduction of low dose

methoxyflurane (Penthrox) as an alternative to Entonox for analgesia during elective colonoscopy. The project incorporated retrospective and prospective routinely collected clinical data and evaluated clinical, environmental, economic and social outcomes. The evaluation period was from 1 September 2025 to 31 July 2026, representing one Plan–Do–Study–Act (PDSA) cycle.

The existing pathway used Entonox as the principal patient-controlled inhaled analgesic option. The intervention involved introducing a single-use Penthrox inhaler for appropriately selected patients while otherwise maintaining the established colonoscopy pathway, clinical monitoring and escalation procedures.

Patient selection and eligibility:

Adult patients over 18 years old undergoing elective outpatient colonoscopy were considered for Penthrox. Eligibility required patients to be suitable for methoxyflurane according to local prescribing guidance, able to understand and self-administer the inhaler, and willing to provide consent.

A standardised pre-assessment checklist was used before administration. Contraindications assessed included relevant anaesthetic reactions or susceptibility to malignant hyperthermia, recent drug or alcohol use, recent head injury or loss of consciousness, significant renal impairment, severe respiratory disease, significant liver or cardiac disease, limited exercise tolerance, relevant interacting medications and regular opioid, methadone or cannabis use. Previous Penthrox exposure was also documented. Patients were provided with an information leaflet about Penthrox and their agreement to its use was confirmed.

Patients requiring intravenous conscious sedation or general anaesthesia, those with contraindications according to the local protocol, those who didn't require any form of medications during procedure and those receiving mixed inhaled analgesia & sedation were excluded from the primary comparative analysis.

Intervention and analgesia pathway:

Eligible patients were offered self-administered Penthrox using a standard 3-mL inhaler, commenced immediately before and continued as required during colonoscopy. Patients remained conscious and self-titrated inhalation according to their analgesic requirement. Administration followed approved analgesic-dose limits and local governance arrangements, with standard clinical observations and escalation processes maintained throughout the procedure.

The local pre-assessment protocol specified that methoxyflurane exposure should not exceed 6 mL in a single day or 15 mL in one week and should not be administered on consecutive days. Analgesic adequacy and patient tolerance were assessed throughout the procedure according to the locally developed pathway. Where Penthrox provided adequate analgesia, colonoscopy was continued using Penthrox alone. If analgesia was inadequate or the patient developed distress, the pathway allowed escalation from Penthrox to Entonox. If adequate analgesia was subsequently achieved, colonoscopy was continued. Where analgesia remained inadequate or patient distress worsened, the procedure was abandoned, and the patient could be rebooked using the sedation pathway.

For the comparative analysis, patients who required escalation to another analgesic or sedation modality were excluded, allowing comparison between procedures performed using Penthrox and Entonox alone as modality.

Implementation:

Before implementation, a local protocol was developed covering patient selection, contraindications, prescribing, administration, monitoring, adverse-event reporting and disposal. Relevant medical and nursing staff received training in preparation and administration of inhaler, patient instruction, clinical monitoring and escalation. A standardised data-collection proforma was introduced, and the pathway underwent local governance and multidisciplinary review before implementation.

Resources and investment: Unit cost and source of inhalers; any equipment supplied for the pilot -were funded by Green Healthcare Scotland. The endoscopists and nursing staff were trained through a few training sessions held during the morning briefs and departmental audit meetings.

Implementation learning: The project was systematically implemented through targeted staff education and awareness initiatives. Following initial departmental discussions, a dedicated working group was established, and all necessary clinical governance and pharmacy approvals were secured. In collaboration with the Quality Improvement (QI) team, we developed standardised documentation, including a patient information leaflet, a Penthrox administration checklist, and a specific consent form. Partnering with the Practice Educator, we delivered comprehensive training for nursing staff and endoscopists. To promote clinical uptake and ensure widespread awareness, we facilitated multiple multidisciplinary team briefings and targeted one-on-one meetings. While initial resistance to change and related human factors presented challenges, these were strategically managed to achieve the safe and successful clinical integration of Penthrox.

Comparator and data collection:

The comparator group comprised patients undergoing colonoscopy with Entonox alone. Data was obtained from standardised project proformas, electronic patient records, the endoscopy reporting system, procurement records and local procedural activity data.

During the study period, 2,373 colonoscopies were performed at Raigmore Hospital. The primary comparative cohort comprised 611 procedures performed using inhaled analgesia alone, including 57 Penthrox and 554 Entonox procedures. Procedures involving combined inhaled analgesia and intravenous conscious sedation were excluded from the comparative analysis.

Statistical analysis:

Continuous variables were summarised using mean and standard deviation (SD) and, where appropriate, median and interquartile range (IQR). Categorical variables were reported as frequencies and percentages. Differences between Penthrox and Entonox were presented with 95% confidence intervals (CIs).

Continuous outcomes were compared using the Wilcoxon–Mann–Whitney U test where the prespecified analysis was non-parametric. Categorical outcomes were compared using the Pearson chi-squared test or Fisher's exact test, as appropriate. Statistical significance was defined as a two-sided p value <0.05. As this is a pilot project, formal sample size is not calculated. Because this was a quality-improvement evaluation rather than a study powered to demonstrate non-inferiority, non-significant between-group differences were not interpreted as evidence of equivalence.

Measurement:

This section describes the measures selected for the project; results are reported separately. The project will compare low-dose methoxyflurane (Penthrox) with Entonox for patient-controlled analgesia during colonoscopy at Raigmore Hospital.

Clinical and activity measures will be obtained from routinely collected, patient-level endoscopy records and the project's standardised data-collection proforma for procedures undertaken between 1 September 2025 and 31 July 2026. Environmental and financial measures will use local activity, procurement, transport and waste data where available. Where direct data are unavailable, estimates will be modelled using published evidence and clearly stated assumptions.

Patient outcomes:

The primary clinical aim is to determine whether Penthrox maintains the existing standard of safe, effective and acceptable care provided with Entonox. The following measures will be compared:

- Procedure completion rate.
- Patient comfort and tolerability, using endoscopist-recorded and nurse-assessed comfort scores and available patient feedback about whether discomfort was better, the same as or worse than expected.
- Procedure duration and recovery time, measured in minutes.
- Reasons for incomplete procedures.
- Safety, measured through documented procedure-related adverse events and incident reports.

This project is not expected to adversely affect patient outcomes. Its intention is to maintain the existing high standard of safe and effective care while reducing environmental impact and delivering wider social value. Procedure completion, comfort, recovery, rescue medication and adverse events will act as balancing measures to identify any unintended effects of the change.

Population outcomes:

The project will measure the number and proportion of colonoscopies performed using Penthrox alone, Entonox alone, intravenous sedation, combined inhaled analgesia and intravenous sedation, or no pharmacological analgesia or sedation at Raigmore centre.

Local colonoscopy activity will be used to model the potential effect of wider Penthrox adoption among clinically eligible patients. NHS Scotland activity data and information on the estimated proportion of colonoscopies performed with Entonox will be used to discuss potential wider implications.

Penthrox may improve access to patient-controlled inhaled analgesia in settings where storing, transporting or handling compressed-gas cylinders is difficult. However, it will not be suitable for every patient. Eligibility, contraindications, patient preference, communication needs and the availability of alternative analgesia will therefore be considered to avoid disadvantaging particular groups.

Environmental sustainability:

A cradle-to-grave carbon footprint analysis was used to estimate the items greenhouse gas (GHG) emissions. Data was provided on the equipment used to deliver Entonox and Penthrox and were carbon footprinted using a process-based carbon footprint analysis. Items were weighed by the team and materials identified.

Data was obtained from previous studies by the Centre for Sustainable Healthcare and other references. Where data was not available, calculations were made based on the weight and material of the product. Material weights were converted into GHG emissions using emission conversion factors taken from the Department of Energy Security and Net Zero (DESNZ)'s Greenhouse Gas Reporting Conversion Factors 2026 database, ICE V4.0 database and primary research papers and LCAs. The analysis included GHG emissions associated with primary materials production, transport, and disposal.

- Materials

Material emissions are calculated by the weight of the material, emission factor of the material and number of items.

Total emissions = weight of material * material emission factor.

- Transport

Transport emissions per journey are calculated by weight of product, distance travelled and emissions per tonne.km travelled.

Total emissions = Weight in tonnes per delivery*distance in km*emission factor

The emission factor for average laden, non-refrigerated HGV is 0.127 $kgCO_2e$ per tonne.km.

- Waste

Waste emissions are calculated by amount of waste (tonnes) and the UK emission factor of average emissions by waste stream

Total emissions = volume of waste * waste stream emission factor

The emission factor for clinical waste is 1074 $kgCO_2e$, dry mixed recycling is 172 $kgCO_2e$ and domestic waste is 172 $kgCO_2e$.

Economic sustainability:

The financial assessment will compare the organisational cost of providing Penthrox and Entonox per completed colonoscopy and at projected annual activity levels. It will include:

- Cost of Penthrox and its associated inhaler and consumables.
- Cost of Entonox and the single-use filtered mouthpiece.
- Entonox cylinder delivery, collection and handling costs where available.
- Waste-disposal costs.
- One-off implementation costs, including staff training.
- Ongoing costs associated with maintaining the Penthrox pathway.

Financial information will be obtained from local procurement, pharmacy, estates, waste-management and departmental records. Costs will be reported from the perspective of NHS Highland. Figures based on assumptions rather than direct expenditure records will be identified as modelled estimates.

Potential savings experienced by patients or carers, such as reduced time at the hospital or an earlier return to normal activities, will be considered under social rather than organisational financial outcomes. But there will be no difference in both groups as both are short acting inhalational analgesics.

Social sustainability:

The social assessment will consider the effects of Penthrox on patients, carers and staff. Planned measures include:

- Patient acceptability, satisfaction, and willingness to use Penthrox again.
- Patient experience, including tolerability, self-administration and perceived control over analgesia.
- Staff experience, including ease of use, training requirements, confidence, workload and effects on workflow.
- Operational effects, including portability and reduced dependence on compressed-gas cylinder storage, transport and manual handling.
- Knowledge and engagement, including whether the project improves staff awareness of sustainable healthcare.

Qualitative information will be collected through patient and staff comments or surveys where available. Quantitative measures will include recovery time, comfort scores and staff training activity. Because patient and staff experience data may not be complete for all procedures, missing responses and the denominator for each measure will be reported clearly.

Results

1 Patient outcomes

1.1 Procedure activity and analgesic use:

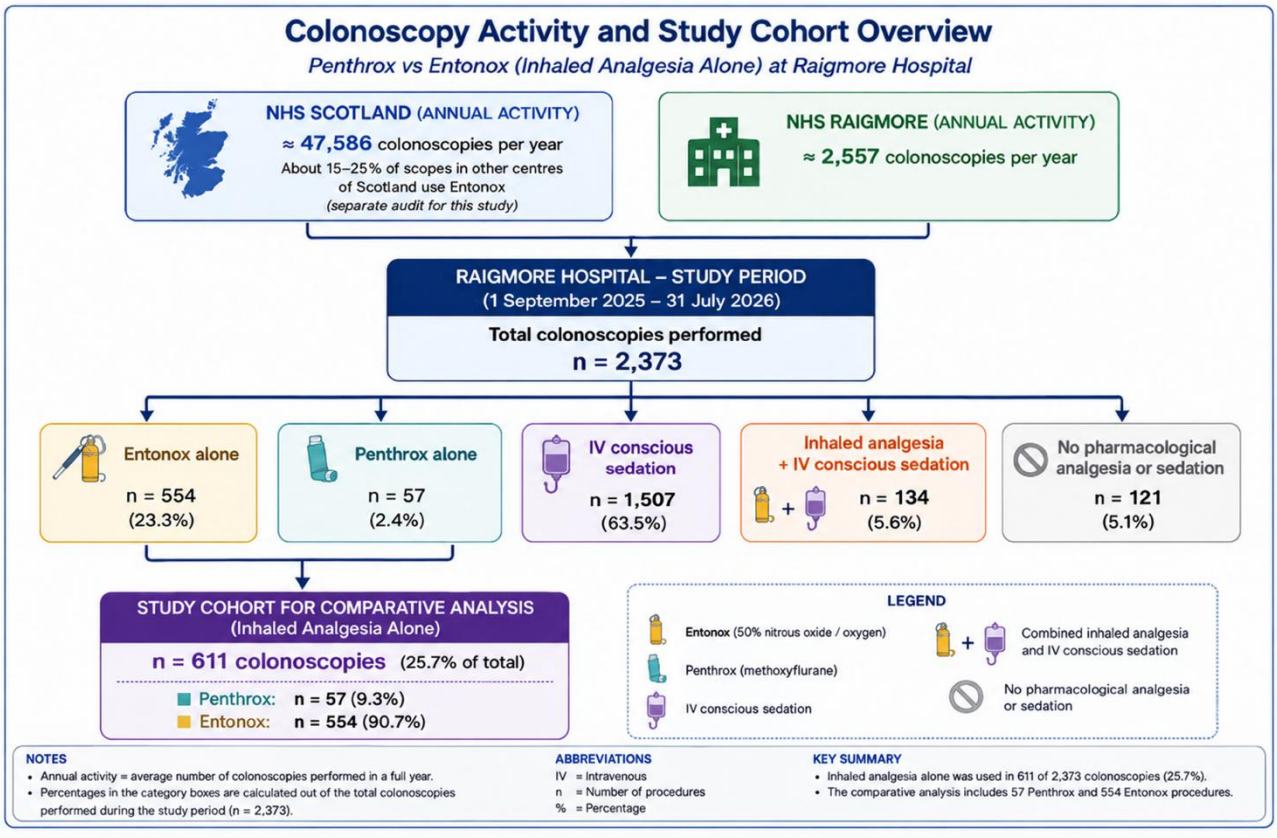
Across NHS Scotland, approximately **47,586** colonoscopies are performed in last one year. A separate audit undertaken as part of this study indicated that approximately **15–25%** of colonoscopies in other Scottish centres use Entonox as the primary inhaled analgesic option. At

Raigmore Hospital, approximately **2,557** colonoscopies are performed annually out of which **742** patients used Entonox.

During the study period, from **1 September 2025 to 31 July 2026**, a total of **2,373** colonoscopies were performed at Raigmore Hospital. Of these, **554 (23.3%)** were performed using Entonox alone, **57 (2.4%)** using Penthrox alone, **1,507 (63.5%)** with intravenous (IV) conscious sedation, **134 (5.6%)** using combined inhaled analgesia and IV conscious sedation, and **121 (5.1%)** without pharmacological analgesia or sedation. These categories accounted for all **2,373** procedures performed during the study period.

The comparative analysis was restricted to procedures performed using inhaled analgesia alone, resulting in a study cohort of **611 colonoscopies**: **57 using Penthrox** and **554 using Entonox**. Thus, **inhaled analgesia** alone accounted for **25.7% (611/2,373**) of all colonoscopies performed during the study period. Summary of procedure activity and study cohort described in Figure 1.

Fig 1: Colonoscopy activity and Study cohort overview



Notes: Annual activity= average number of colonoscopies performed in a full year, IV =Intravenous, n= Number of procedures, %= percentage

1.2 Baseline demographic characteristics:

The groups were broadly comparable in age and sex. Mean age was 58.95 +/- 13.10 years in the Penthrox group and 61.18 +/- 12.59 years in the Entonox group (p=0.244). Men represented 63.2% and 70.0% of the groups, respectively (p=0.283). Age-band distributions were also similar (p=0.329) (Table 1).

Table 1. Baseline demographic characteristics of the two inhaled analgesia groups.

Characteristic	Penthrox (n = 57)	Entonox (n = 554)	Difference (95% CI)	p value
Age at procedure (years)				0.244[a]
Mean ± SD	58.95 ± 13.10	61.18 ± 12.59	−2.23 (−5.86 to 1.39)	
Median (IQR)	61 (54–67)	62 (53–71)	—	
Range	19–82	21–93	—	
Age band, n (%)				0.329[c]
< 20 years	1 (1.8)	0 (0.0)	1.75 (−1.65 to 5.16)	
20 to 30 years	1 (1.8)	7 (1.3)	0.49 (−3.04 to 4.02)	
30 to 40 years	3 (5.3)	30 (5.4)	−0.15 (−6.25 to 5.94)	
40 to 50 years	7 (12.3)	58 (10.5)	1.81 (−7.08 to 10.71)	
50 to 60 years	12 (21.1)	130 (23.5)	−2.41 (−13.57 to 8.74)	
60 to 70 years	23 (40.4)	182 (32.9)	7.50 (−5.82 to 20.82)	
70 to 80 years	9 (15.8)	122 (22.0)	−6.23 (−16.31 to 3.84)	
80 to 90 years	1 (1.8)	24 (4.3)	−2.58 (−6.38 to 1.23)	
≥ 90 years	0 (0.0)	1 (0.2)	−0.18 (−0.53 to 0.17)	
Sex, n (%)				0.283[b]
Male	36 (63.2)	388 (70.0)	−6.88 (−19.97 to 6.21)	
Female	21 (36.8)	166 (30.0)	6.88 (−6.21 to 19.97)	

SD, standard deviation; IQR, interquartile range; CI, confidence interval. Differences are expressed as Penthrox minus Entonox, in years for continuous variables and in percentage points for proportions. [a] Wilcoxon–Mann–Whitney U test. [b] Pearson chi-squared test. [c] Fisher's exact test.

1.3 Procedure duration and recovery time:

Procedure duration was similar between groups. Mean duration was 37.04 +/- 12.91 minutes with Penthrox compared with 39.34 +/- 13.30 minutes with Entonox (p=0.107). Mean recovery time was numerically shorter following Penthrox (15.20 +/- 7.66 minutes) than Entonox (18.39 +/- 14.31 minutes), with a mean difference of -3.19 minutes (95% CI -5.57 to -0.82). However, the difference was not statistically significant using the prespecified non-parametric comparison (p=0.114) (Table 2).

Table 2. Total procedure duration and recovery time in the two inhaled analgesia groups.

Parameter	Penthrox (n = 57)	Entonox (n = 554)	Difference (95% CI)	p value
Total procedure duration (minutes)				0.107[a]
Mean ± SD	37.04 ± 12.91	39.34 ± 13.30	−2.31 (−5.90 to 1.28)	
Median (IQR)	34 (29–43)	39 (30–47)	—	
Range	15–82	3–109	—	
Recovery time (minutes)				0.114[a]
Mean ± SD	15.20 ± 7.66	18.39 ± 14.31	−3.19 (−5.57 to −0.82)	
Median (IQR)	15 (10–17)	15 (10–20)	—	
Range	3–40	0–140	—	

SD, standard deviation; IQR, interquartile range; CI, confidence interval. Differences are expressed as Penthrox minus Entonox, in minutes. [a] Wilcoxon–Mann–Whitney U test.

1.4 Procedure completion rate:

Penthrox achieved a similar procedural completion rate to Entonox. Colonoscopy was completed in 52/57 (91.2%) Penthrox procedures compared with 531/554 (95.8%) Entonox procedures (p=0.170) (Table 3).

Table 3 Completion of the procedure.

Parameter	Penthrox (n = 57)	Entonox (n = 554)	Difference (95% CI)	p value
Procedure completion, n (%)				0.170[c]
Completed	52 (91.2)	531 (95.8)	−4.62 (−12.15 to 2.91)	
Not completed	5 (8.8)	23 (4.2)	4.62 (−2.91 to 12.15)	

CI, confidence interval. The p value for procedure completion is recorded. Differences are expressed as Penthrox minus Entonox, in percentage points. [c] Fisher's exact test.

1.5 Analysis of causes for failed procedures/Incomplete procedures:

Where a limitation was recorded, inadequate bowel preparation was the commonest in the Penthrox group (2 procedures, 3.5%) and in the Entonox group (10 procedures, 1.8%). No individual limitation differed significantly between the groups, and strictures (7 procedures, 1.3%) were confined to the Entonox group (Table 4).

Table 4. Limitations recorded during the procedure

Limitation recorded	Penthrox (n = 57)	Entonox (n = 554)	Difference (95% CI)	p value
Inadequate bowel preparation	2 (3.5)	10 (1.8)	1.70 (−3.20 to 6.61)	0.310[c]
Patient discomfort	1 (1.8)	2 (0.4)	1.39 (−2.05 to 4.84)	0.255[c]
Stricture	0 (0.0)	7 (1.3)	−1.26 (−2.19 to −0.33)	1.000[c]
Unresolved loop	1 (1.8)	2 (0.4)	1.39 (−2.05 to 4.84)	0.255[c]
Patient withdrew consent	1 (1.8)	2 (0.4)	1.39 (−2.05 to 4.84)	0.255[c]
Adhesion	0 (0.0)	3 (0.5)	−0.54 (−1.15 to 0.07)	1.000[c]
Severe colitis	0 (0.0)	1 (0.2)	−0.18 (−0.53 to 0.17)	1.000[c]
Other	1 (1.8)	4 (0.7)	1.03 (−2.45 to 4.51)	0.388[c]

Values are n (%) of procedures for which the limitation was recorded; more than one limitation could be recorded per procedure, and limitations recorded in no procedure in either group are omitted. Differences are expressed as Penthrox minus Entonox, in percentage points. [c] Fisher's exact test.

1.6 Patient comfort and tolerability recorded during or immediately after procedure:

Endoscopist-recorded comfort was rated as comfortable in 59.6% of Penthrox procedures compared with 49.1% of Entonox procedures. No patient in the Penthrox group was recorded as experiencing moderate or severe discomfort, compared with 17 patients (3.1%) in the Entonox group. The overall distribution of endoscopist-recorded comfort scores did not differ significantly between groups (p=0.261).

Nurse-assessed comfort was rated as comfortable in 64.3% of Penthrox procedures and 61.0% of Entonox procedures (p=0.952). Among patients with recorded post-procedure feedback, none in either group reported discomfort that was worse than expected (Table 5). Overall documented nurse assessed comfort and patient feedback didn't defer statistically between two groups.

Table 5. Comfort outcomes in the two inhaled analgesia groups.

Outcome	Penthrox	Entonox	Difference (95% CI)	p value
Endoscopist-recorded comfort, n (%)	(n = 57)	(n = 554)		0.261[c]
Comfortable	34 (59.6)	272 (49.1)	10.55 (−2.85 to 23.95)	
Minimal discomfort	16 (28.1)	215 (38.8)	−10.74 (−23.09 to 1.61)	
Mild discomfort	7 (12.3)	50 (9.0)	3.26 (−5.59 to 12.10)	
Moderate discomfort	0 (0.0)	16 (2.9)	−2.89 (−4.28 to −1.49)	
Severe discomfort	0 (0.0)	1 (0.2)	−0.18 (−0.53 to 0.17)	
Nurse-assessed comfort, n (%)	(n = 42)	(n = 395)		0.952[c]
Comfortable	27 (64.3)	241 (61.0)	3.27 (−12.00 to 18.54)	
Minimal discomfort	14 (33.3)	130 (32.9)	0.42 (−14.57 to 15.41)	
Mild discomfort	1 (2.4)	19 (4.8)	−2.43 (−7.50 to 2.64)	
Moderate discomfort	0 (0.0)	5 (1.3)	−1.27 (−2.37 to −0.16)	
Discomfort versus expectation as recorded by patient, n (%)	(n = 20)	(n = 210)		0.772[c]
Better than expected	3 (15.0)	44 (21.0)	−5.95 (−22.54 to	

			10.64)	
Same as expected	17 (85.0)	166 (79.0)	5.95 (−10.64 to 22.54)	

CI, confidence interval. Denominators differ between outcomes because the nurse-assessed score and the patient-reported comparison with expectation were not recorded for every procedure; percentages are of the procedures for which each outcome was recorded. Differences are expressed as Penthrox minus Entonox, in percentage points. [c] Fisher's exact test.

1.7 Safety:

No procedure-related/drug related adverse events were reported in either the Penthrox or Entonox group.

2 Environmental sustainability:

Key finding: Replacing Entonox with Penthrox for **742 procedures per year** is estimated to **reduce** emissions by approximately **20,163 kgCO_2e** (**20.16 tonnes CO_2e) annually (96.0%).**

2.1 Environmental sustainability assessment:

The environmental impact of analgesia delivery was assessed for Entonox and Penthrox. The analysis included emissions associated with disposable equipment, raw-material production, waste disposal and transport. For Entonox, emissions arising from the gas itself and cylinder transport were also included. For Penthrox, the published life-cycle assessment (LCA) estimate for the inhaler/device was supplemented by additional transport to Raigmore Hospital and local clinical-waste disposal, as described below.

2.2 Entonox:

2.2.1 Disposable equipment:

The Bact Trap is a single-use filtered mouthpiece used by patients to inhale Entonox. Component weights and material composition supplied by the project team were combined with the stated carbon-emission factors for raw-material production and waste disposal as shown in Table 6.

Table 6. Inventory for equipment, weights, emissions factors and the carbon footprint for Bact trap mouthpiece.

Component/ Type of material	Weight (g)	Raw-material factor ($kgCO_2e$/tonne)	Raw-material emissions ($kgCO_2e$)	Waste route	Waste factor ($kgCO_2e$/tonne)	Waste emissions ($kgCO_2e$)	Total/item ($kgCO_2e$)
Main Filter Unit - plastic rigid	20	3352.0	0.067	Clinical waste	1074	0.0215	0.0885
Purple Adapter-HDPE plastic	5	3092.9	0.015	Clinical waste	1074	0.0054	0.0208
Clear Mouthpiece-PP plastic	4	2575.3	0.010	Clinical waste	1074	0.0043	0.0146
Packaging plastic bag-LDPE and LLDPE plastic	2	2963.6	0.006	Domestic waste	172	0.0003	0.0063
Total			0.0987			0.0315	0.1302

Rounding of component-level values means displayed row totals may not reproduce the aggregate exactly.

2.2.2 Transport of the Bact Trap:

One Bact Trap weighs 31 g. Supplies are transported from Armstrong Medical Limited, Coleraine, Northern Ireland, via the NHS Distribution Centre at Larkhall to Raigmore Hospital. Using 509 km of road transport, 60 km of shipping and emission factors of 0.127 $kgCO_2e$/tonne-km for an average laden non-refrigerated HGV and 0.020 $kgCO_2e$/tonne-km for cargo shipping, transport contributes approximately 0.002 $kgCO_2e$ per Bact Trap. Total disposable-related emissions are therefore 0.1322 $kgCO_2e$ per procedure (0.0987 kg raw materials/production + 0.0315 kg waste + 0.002 kg transport).

2.2.3 Summary for disposable equipment:

Emissions per patient for disposables for Entonox group as shown in Table 7

Table 7: Summary of emissions per patient for disposable equipment used in Entonox group

Components	Value
Raw materials and production	0.0987 $kgCO_2e$
Waste	0.0315 $kgCO_2e$
Transport	0.002 $kgCO_2e$
The total emissions per Bact Trap	**0.1322 $kgCO_2e$**

2.2.4 Entonox gas:

Entonox is a 50:50 mixture of nitrous oxide and oxygen. Twelve 3,500-L cylinders were ordered during January–June 2026, equivalent to 42,000 L. Across 371 procedures, this corresponds to 113.2 L per procedure. Applying the project emission factor of 0.248 $kgCO_2e$/L gives approximately 28.08 $kgCO_2e$ per procedure. Assuming the same activity for a full year gives 84,000 L and 20,832 $kgCO_2e$ annually.

The data from the amount of Entonox used between Jan and June 2026 is shown in Table 8.

Table 8. Entonox use at Raigmore hospital over 6 months and amount per procedure.

Measure	Value
Number of cylinders ordered in 6 months	12
Size of cylinder (L)	3500
Total volume used in 6 months (L)	42000
Number of procedures	371
Volume used per procedure (L)	113.2
Gas emissions per procedure	28.08 $kgCO_2e$

2.2.5 Transport of Entonox:

A full 3,500-L cylinder weighs 19.8 kg and an empty cylinder 15.4 kg. The return distance between BOC Worsley, Manchester and Raigmore Hospital was modelled as 590 km each way by HGV. At 0.127 $kgCO_2e$/tonne-km, transport emissions are 1.484 $kgCO_2e$ for a full-cylinder journey and 1.154 $kgCO_2e$ for an empty-cylinder return. With two cylinders per month (24 cylinder-equivalent round trips annually), estimated cylinder transport is 63.30 $kgCO_2e$/year, or 0.085 $kgCO_2e$ per procedure is mentioned in Table 9.

Table 9. Total emissions to deliver Entonox to 742 patients per year

	Emissions per procedure ($kgCO_2e$)	Emissions per year for 742 patients ($kgCO_2e$)
Bact Trap: production, waste and transport	0.1322	98.09
Entonox gas	28.0755	20,832
Entonox cylinder transport	0.0853	63.30
Total	**28.293**	**20,993.39**

2.3 Penthrox:

Emissions associated with delivery of Penthrox are from firstly the disposable equipment and secondly the Penthrox device itself.

2.3.1 Disposable equipment:

Penthrox delivery uses a filtered mouthpiece assembly. The component weights, material assumptions and waste routes supplied by the project team give an estimated disposable-equipment footprint of 0.1628 $kgCO_2e$ per procedure before transport as shown in Table 10.

Table 10. Inventory for equipment, weights, emissions factors and the carbon footprint for Penthrox filter mouthpiece.

Component/ Type of material	Weight (g)	Raw-material factor ($kgCO_2e$/tonne)	Raw-material emissions ($kgCO_2e$)	Waste route	Waste Factor ($kgCO_2e$ /tonne)	Waste emissions ($kgCO_2e$)	Total/ Item ($kgCO_2e$)
Humid-vent compact filter — PP	31	2575.3	0.080	*Clinical waste*	1074	0.0333	0.1131
Packaging — LDPE/LLDPE*	3 (*)	2963.6	0.009	*Clinical waste*	1074	0.0032	0.0121
Mouthpiece 22F — PP	7	2575.3	0.018	*Clinical waste*	1074	0.0075	0.0255
Mouthpiece packaging — LDPE/LLDPE*	3 (*)	2963.6	0.009	*Clinical waste*	1074	0.0032	0.0121
Total							**0.1628**

**Packaging weights were estimated. PP = polypropylene; HDPE = high-density polyethylene; LDPE = low-density polyethylene; LLDPE = linear low-density polyethylene.*

2.3.2 Transport of the mouthpiece:

The filter, mouthpiece and packaging weigh approximately 44 g. Using an assumed manufacturing location in Žďár nad Sázavou, Czechia, a transport distance of 2,326 km and an HGV emission factor of 0.127 $kgCO_2e$/tonne-km, estimated transport emissions are approximately 0.013 $kgCO_2e$ per procedure. Disposable-related emissions are therefore 0.1758 $kgCO_2e$ per procedure.

2.3.3 Penthrox inhaler/device:

A published LCA by Martindale and colleagues (11) reported a climate-change impact of approximately 0.84 $kgCO_2e$ for low-dose methoxyflurane delivered using the Penthrox inhaler. The project calculation used 0.83965 $kgCO_2e$, including transport to University Hospital Southampton. A reduction in distance travelled to Raigmore from supplier at Craigavon of 220 km of HGV transport was estimated to reduce emissions by 2.5gCO2e (0.0025kgCO2) and disposal of the 100-g device through the clinical-waste stream at 0.107 $kgCO_2e$. The resulting local estimate for the Penthrox device is 0.944 $kgCO_2e$ per procedure as shown in Table 11.

Table 11. Total emissions to deliver Penthrox to 742 patients per year

	Emissions per procedure ($kgCO_2e$)	Emissions per year for 742 patients ($kgCO_2e$)
Disposables, transport, waste	0.1758	130.44
Penthrox device	0.944	700.45
Total	**1.1198**	**830.89**

2.4 Overall environmental impact:

On the corrected and internally consistent assumptions above, Entonox is estimated to generate 28.293 $kgCO_2e$ per procedure compared with 1.1198 $kgCO_2e$ for Penthrox. For 742 procedures per year, this equates to approximately 20,993 $kgCO_2e$ for Entonox and 830.89 $kgCO_2e$ for Penthrox. A 100% conversion from Entonox to Penthrox would therefore **save approximately 20,163 $kgCO_2e$ annually** (20.16 tonnes CO_2e), representing a 96.0% reduction in estimated carbon emissions.

3 Economic sustainability

At the modelled annual activity of 742 procedures, the estimated direct cost was £2.58 per procedure for Entonox compared with £16.02 for Penthrox, representing an incremental cost of approximately £13.44 per procedure. Complete substitution with Penthrox would increase the projected annual expenditure from approximately £1,914 to £11,887, corresponding to an additional direct organisational cost of approximately £9,973 per year is shown in Table 12. No additional implementation or training expenditure was incurred, as implementation and staff training were undertaken by existing staff within contracted working hours.

Table 12. Estimated organisational costs of Entonox and Penthrox per colonoscopy and projected annual costs based on 742 procedures

Assuming 100% conversion of 742 procedures annually

Cost category	**Entonox (£/procedure)**	**Penthrox (£/procedure)**	**Difference (£)**
Analgesic and consumables	1.668	16.000	+14.332
Cylinder/equipment costs	0.820	—	−0.820
Waste disposal	0.0155	0.021	+0.0055
Cylinder transport	0.081	—	−0.081
Total cost per procedure	**2.58**	**16.02**	**+13.44**
Projected annual cost (742 procedures) *	**£1,914**	**£11,887**	**+£9,973**

Implementation cost	£0	£0	£0
Training cost	£0	£0	£0

*No additional implementation or training expenditure was incurred because pathway development and staff training were undertaken by existing NHS staff during contracted working hours. Projected annual costs are based on 742 procedures. Minor differences may arise from rounding of per-procedure costs. *Projected annual values are calculated using rounded per-procedure costs.*

Across 742 patients, Entonox produced markedly higher CO_2e emissions than Penthrox (20,993.39 vs 830.89 $KgCO_2e$) yet remained the less expensive option overall once combined procedure and carbon-related damage costs were calculated. Depending on the carbon pricing model applied — DESNZ 2020, DICE-EMR with mortality (Bressler, 2021), or country-level SCC (Ricke et al., 2018), Penthrox cost an additional £6, £8.3, and £5 per procedure respectively compared with Entonox, with the size of this gap varying non-linearly across models due to differences in how each valued Entonox's substantially larger carbon footprint as illustrated in Table 13.

Table 13. Carbon-Related Cost Comparison of Entonox and Penthrox Usage (n = 742 patients)

Procedure and carbon-related damage costs by social cost of carbon (SCC) model

Agent (n=742)	CO_2 (tonnes)	Cost per tonne CO_2	Carbon damage cost (total)	Procedure + CO_2 cost (total)	Extra cost per procedure vs. comparator	Pricing model
Entonox	20.993	£2793	£5732	£7646	—	DESNZ 2020
Penthrox	0.831	£273	£227	£12,114	**£6***	
Entonox	20.993	£190 (−£69 to £545)	£3989	£5903	—	DICE-EMR w/ mortality (Bressler, 2021)
Penthrox	0.831	£190 (−£69 to £545)	£158	£12,045	**£8.3***	
Entonox	20.993	£306.80 (£177–£805)	£6440.7	£8354.7	—	Country-level SCC (Ricke et al., 2018)
Penthrox	0.831	£306.80 (£177–£805)	£255	£12,142	**£5***	

DESNZ (13) 2020: *UK Department for Energy Security and Net Zero, 2020 carbon valuation.*

DICE-EMR (Bressler, 2021): *Dynamic Integrated Climate-Economy model with Epidemic-Economy-Mortality extension; central estimate with 95% confidence interval in parentheses(14).*

Country-level SCC (Ricke et al., 2018): *Country-level social cost of carbon estimate; central estimate with 90% confidence interval in parentheses(15).*

** Extra cost per procedure of Penthrox relative to Entonox, calculated as [(Penthrox procedure + CO_2 cost) − (Entonox procedure + CO_2 cost)] ÷ 742.*

All monetary values in GBP (£). CO_2 = carbon dioxide equivalent emissions. SCC = social cost of carbon.

4 Social sustainability

A total of 31 patients completed retrospectively the Penthrox patient experience questionnaire which was asked telephonically and filled in through Microsoft forms following colonoscopy.

4.1 Based on patient feedback:

4.1.1 Patient experience and satisfaction:

Patient reported experience with inhaled methoxyflurane (Penthrox) was highly favourable across all questionnaire domains. Positive ratings (agree/strongly agree) exceeded 87% across all domains. The highest rated aspects were adequacy of information to make an informed consent (100%; 95% CI 88.8-100%), ease of use (96.8%; 95% CI 83.8-99.4%), and perceived safety (96.8%;95% CI 83.8-99.4%), Adequate pain relief was reported by 87.1% of participants (95% CI 71.1-94.9%), while 90.3% (95% CI 74.2-96.6%) reported that methoxyflurane helped them tolerate the procedure. Overall satisfaction was high, with 90.3% of respondents expressing satisfaction and willingness to choose Penthrox again for future colonoscopies. Overall mean score across all the domains= 4.64/5, indicating a very high level of patient acceptance as shown in Table 14 and figures 2-3.

Table 14. Patient reported outcomes with 95% Confidence Intervals (n=31)

Outcome	Positive responses n/N (%)	95% CI (%)	Mean scores from Likert scale analysis (/5)
Instructions were clear	29/31 (93.5)	79.3-98.2	4.74
Information leaflet had sufficient information to make informed consent	31/31 (100)	88.8-100	4.97
Penthrox whistle easy to use	30/31 (96.8)	83.8-99.4	4.87
Adequate pain relief	27/31 (87.1)	71.1-94.9	4.29
Helped tolerate procedure	28/31 (90.3)	74.2-96.6	4.39
Felt safe using Penthrox	30/31 (96.8)	83.8-99.4	4.84
Overall satisfaction	28/31 (90.3)	74.2-96.6	4.58
Would choose Penthrox again	28/31 (90.3)	74.2-96.6	4.45

**Confidence interval calculated using the Wilson method. Using standard 5-point Likert scale: Strongly disagree=1, Disagree=2, Neutral=3, Agree=4, Strongly agree=5*

Figure 2. Positive response rates (%) across patient-reported outcome domains.

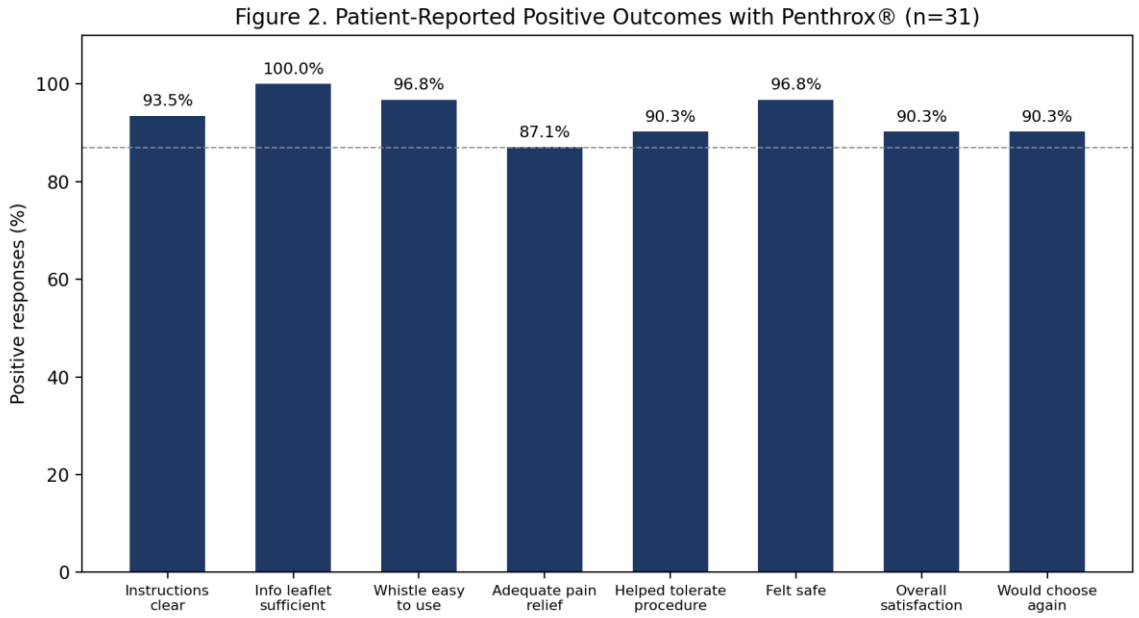
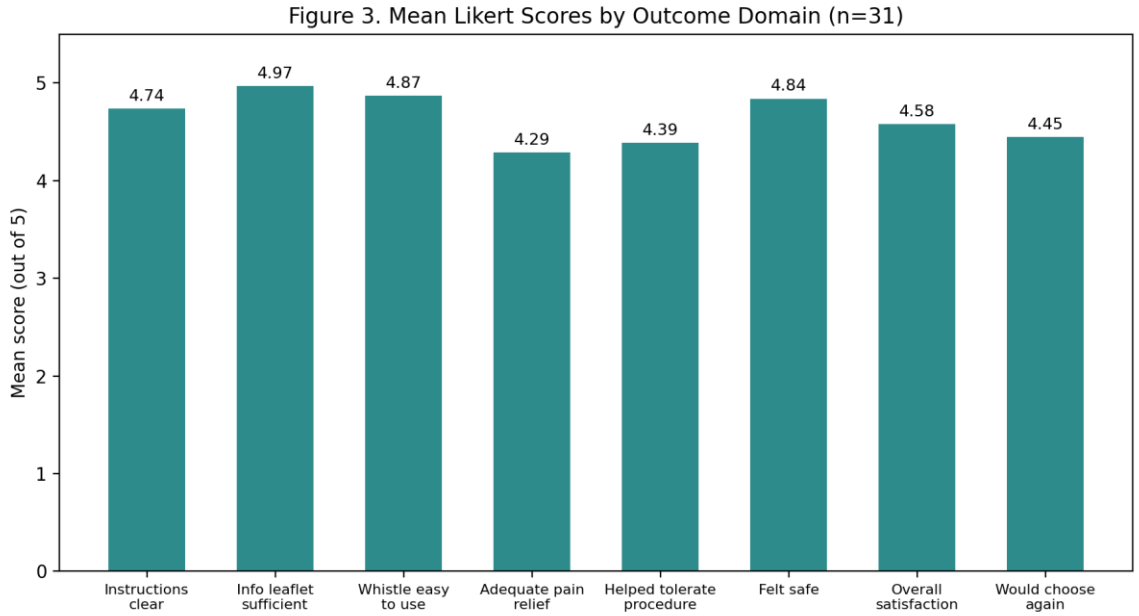


Figure 3. Mean Likert scores (out of 5) by outcome domain.



4.1.2 Safety:

Only one patient reported an unpleasant taste or smell associated with Penthrox. No other minor or serious adverse effects attributable to methoxyflurane were documented. As patient feedback was collected several months after the procedure, patients were also able to report any delayed adverse effects experienced following the procedure; none were reported. One patient experienced a vasovagal episode; however, this was specifically attributed to the colonoscopy itself rather than to Penthrox.

4.1.3 Previous colonoscopy experience:

Of the 31 respondents, 14 (45.2%) had previously undergone a colonoscopy, while 17 (54.8%) had no previous colonoscopy experience. Among patients with previous colonoscopy experience, 13/14 (92.9%) indicated that they would prefer Penthrox for a future procedure, with only one patient (7.1%) preferring IV sedation.

Among patients with prior experience of IV sedation, 8/9 (88.9%) preferred Penthrox over IV sedation, while 1/9 (11.1%) preferred IV sedation. All patients with previous experience of Entonox (7/7, 100%) preferred Penthrox over Entonox (Table 15, Figure 4). The IV sedation and Entonox subgroups were not mutually exclusive, as some patients had previous experience of more than one analgesia or sedation modality.

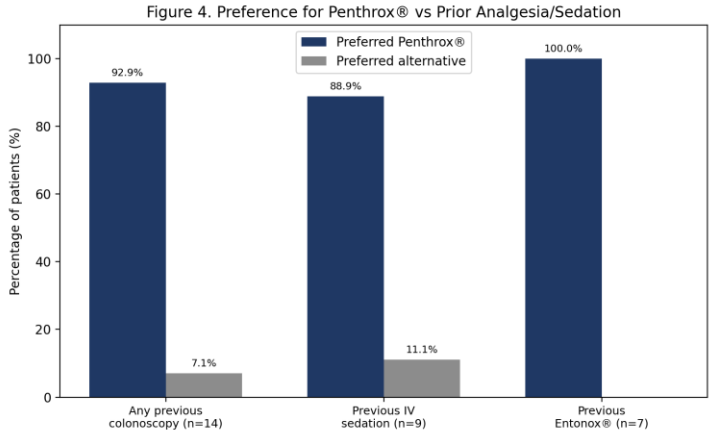
Table 15. Previous colonoscopy experience and preference for Penthrox

Previous colonoscopy/analgesia experience	Patients, n	Preferred Penthrox, n (%)	Preferred previous/alternative analgesia, n (%)
Any previous colonoscopy	**14**	**13 (92.9)**	**1 (7.1)***
Previous IV sedation	9	8 (88.9)	1 (11.1)
Previous Entonox	7	7 (100)	0 (0.0)
No previous colonoscopy	17	—	—
Total respondents	**31**	**—**	**—**

**The one patient who did not prefer Penthrox indicated a preference for IV sedation.*

Note: Of 31 respondents, 14 (45.2%) had undergone a previous colonoscopy and 17 (54.8%) had not. The previous IV sedation and Entonox groups are not mutually exclusive; some patients may have had experience of more than one analgesia/sedation modality during previous colonoscopies.

Figure 4. Preference for Penthrox versus prior analgesia/sedation modality, by experience group.



4.2 Staff feedback:

Ten endoscopists responded out of 18 in dept (55.6% response rate): six medical endoscopists (60%), two non-medical endoscopists (20%) and two trainees (20%). One respondent (10%) had performed one procedure with Penthrox, seven (70%) had performed 2–5 procedures and two (20%) had performed 6–10; none reported more than 10.

Nine respondents (90%) supported implementation in other NHS endoscopy units in Highland, and nine (90%) supported use for “3 point colonoscopy” indication in the absence of contraindications. Five (50%) requested further training or guidance.

4.2.1 Patient and procedural experience

All respondents appeared to agree or strongly agree that patient selection guidance was clear and that patients understood how to use Penthrox. Positive responses were 70% for confidence assessing suitability, 90% for adequate analgesia, 80% for effective communication, 90% for lack of adverse impact on completion and 90% for tolerability as demonstrated in Figure 5.

Figure 5 Staff agreement with patient and procedural statements (n = 10).

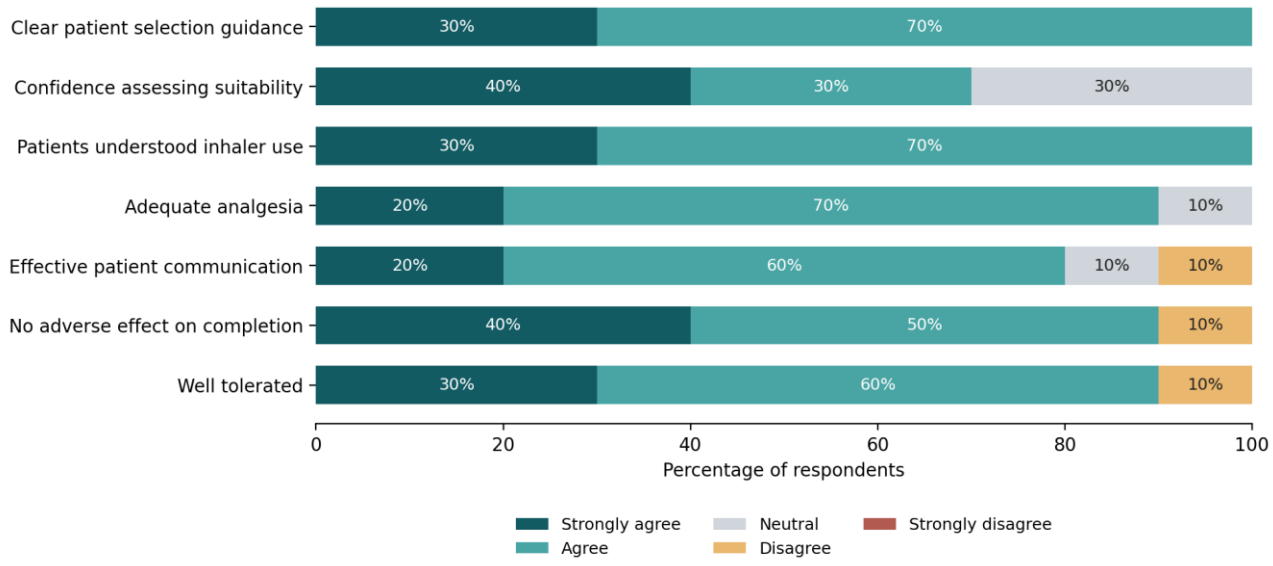


Figure 5. Patient and procedural experience. Counts reconstructed as 10 responses per item (10% for each response)

4.2.2 Service impact and future use

Most respondents considered training sufficient (90%), portability beneficial (80%) and reduced reliance on compressed-gas cylinders operationally beneficial (90%). Nine (90%) would offer Penthrox again and supported wider implementation. 100% agreed due to introduction of Penthrox no unreasonable workload increased demonstrated in fig 6.

Fig 6 Staff agreement with service impact and future use statements (n = 10).

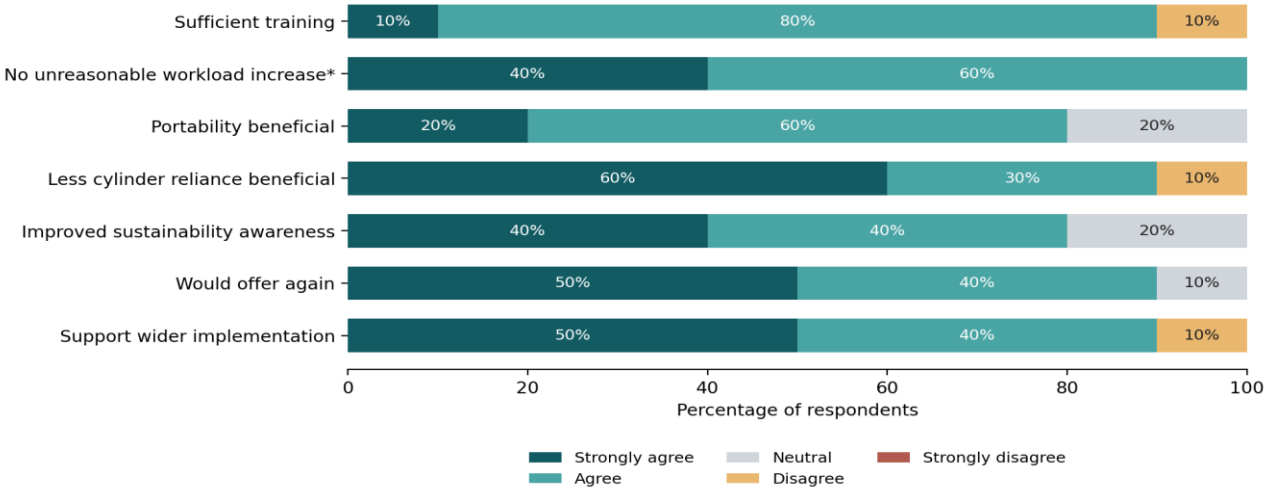


Figure 6. Service impact and future use. Counts reconstructed visually with 10 responses per item (10% for each response)

4.2.3 Staff feedback when Penthrox compared to Entonox

Overall comparison with Entonox suggested that one respondent (10%) rated Penthrox much better, two (20%) better, six (60%) about the same and one (10%) worse. None selected much worse or unable to compare.

Fig 7 Overall staff rating of Penthrox compared with Entonox (n = 10).

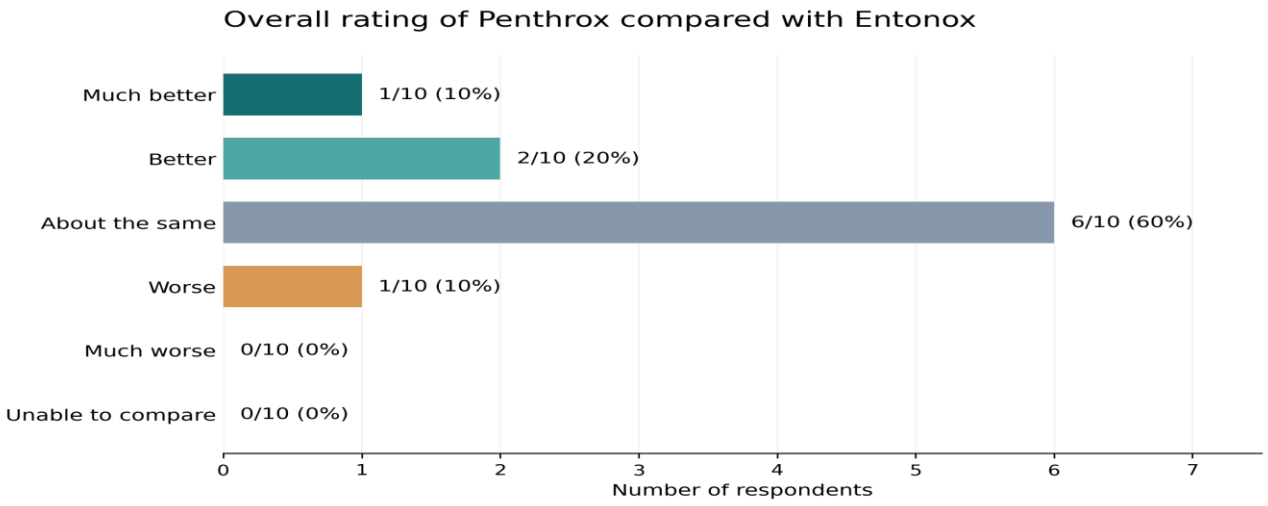


Figure 7. Overall endoscopist rating of Penthrox compared with Entonox (n = 10, each response is 10%).

Free-text feedback; Four of ten respondents provided comments on additional training or guidance, five commented on what had worked well or required improvement, and five commented on barriers to wider implementation. Good patient acceptance and tolerability, successful gradual

introduction, and the value of Entonox as a backup were all highlighted. Training needs included contraindications, dosing, practical or online teaching, and greater familiarity with the protocol. Concerns included patient disinhibition and impaired communication during procedure, one staff-reported headache during use, cost and environmental considerations. Wider education for nurses and doctors was suggested.

Discussion:

The findings indicate that Penthrox is a feasible, patient-controlled alternative to Entonox for analgesia during colonoscopy. Clinical outcomes were broadly comparable without an apparent adverse effect on procedure completion, procedural efficiency, patient comfort and safety. There was a **modelled annual carbon reduction of 20,163 kgCO_2e** (96%), The principal trade-off was financial: based on the available procurement data, Penthrox cost £13.44 more per procedure than Entonox, requiring a **yearly financial investment of £9,973.**

Patient outcomes:

The comparative cohort (57 Penthrox, 554 Entonox) was demographically balanced. Completion rates (91.2% vs 95.8%, p=0.170), duration (37.0 vs 39.3 min, p=0.107) and recovery time (15.2 vs 18.4 min, p=0.114) were statistically similar, though the ~3.19 minutes recovery advantage may be operationally relevant if confirmed at scale. Incomplete procedures were driven mainly by bowel preparation and anatomical factors rather than analgesic choice.

Procedure duration was similar between groups suggesting that introducing Penthrox did not materially disrupt procedural workflow. Both Penthrox and Entonox are rapidly acting inhaled agents and therefore a large difference in recovery would not necessarily be expected in contrast to recovery times when compared with IV sedation (16). Nevertheless, even a modest reduction in recovery time could have operational implications in a high-volume endoscopy service if confirmed in a larger cohort, through improved patient turnover and reduced demand on recovery-area capacity.

Patient comfort was maintained with Penthrox. Endoscopists rated a greater proportion of patients receiving Penthrox as comfortable than those receiving Entonox (59.6% vs 49.1%), and no patient in the Penthrox group was recorded as experiencing moderate or severe discomfort compared with 3.1% of the Entonox group. Nurse-assessed comfort was also similar, with 64.3% of Penthrox patients and 61.0% of Entonox patients rated as comfortable. Although these differences were not statistically significant, the findings are reassuring and provide no evidence that replacing Entonox with Penthrox compromised patient comfort.

These findings align with existing evidence supporting low dose methoxyflurane as an effective analgesic for short procedures (17). Nguyen et al. reported that methoxyflurane provided effective analgesia during colonoscopy when compared with conventional intravenous sedation (18). Previous studies have also described potential advantages of methoxyflurane over intravenous sedation, including reduced sedation-related effects such as respiratory depression and hypotension, faster recovery and earlier return to normal activities (16). Avoidance of respiratory depression may be particularly relevant in patients at increased risk from conventional sedation, including those with obesity or obstructive sleep apnoea.

Patient-reported feedback immediately after procedures was available for only a subset of procedures, but none of the patients with recorded responses in either group described their discomfort as worse than expected.

No procedure-related or drug related adverse events were reported in either group. This is consistent with the generally favourable safety and acceptability profile of low dose methoxyflurane reported across outpatient and procedural settings(9, 17).

Overall, the clinical findings provide preliminary support for Penthrox as a feasible alternative to Entonox for colonoscopy. The findings suggest that Penthrox can maintain procedural performance, patient comfort and safety while offering a practical alternative to Entonox.

Population outcomes:

Penthrox accounted for only 2.4% of activity during the pilot, appropriate for an initial rollout. Wider adoption could add a patient-controlled option for appropriately selected patients independent of gas cylinders, but wider implementation should preserve patient choice and alternative analgesia must remain available for ineligible or unwilling patients. Scottish-wide data (~47,586 annual colonoscopies; 15–25% using Entonox elsewhere) suggest meaningful potential for broader carbon savings, though this remains modelled rather than observed.

Environmental sustainability:

This was the clearest benefit: 1.1198 $kgCO_2e$ per Penthrox procedure vs 28.29 $kgCO_2e$ for Entonox (~96% reduction). At a modelled activity of 742 procedures/year, this equates to ~20,163 $kgCO_2e$ saved annually. Most of this difference came from avoiding nitrous oxide emissions, despite the greater material and waste footprint of the Penthrox inhaler.

This finding is consistent with Martindale et al.'s life-cycle assessment, which estimated 0.84 $kgCO_2e$ per low-dose methoxyflurane treatment and a substantially lower climate impact than

Entonox (11). Although methodological differences mean that their absolute estimate cannot be directly compared with the 1.1198 $kgCO_2e$ calculated in our project.

The finding in our study is consistent with the wider anaesthetic sustainability literature(19, 20), which identifies nitrous oxide as an important healthcare greenhouse gas and highlights that waste anaesthetic gases are predominantly released into the environment. Consequently, reducing the use of nitrous oxide where clinically appropriate represents a potentially important target for healthcare decarbonisation.

These findings therefore support substitution of a high-carbon intervention at source where a clinically appropriate lower-carbon alternative is available. This is consistent with the principles of SusQI. The environmental gain therefore appears achievable while maintaining the clinical value of the colonoscopy pathway.

Economic sustainability:

Penthrox offered substantial environmental benefit but at a higher direct cost than Entonox (£16.02 vs £2.58 per procedure). At an annual activity of 742 procedures, complete substitution would increase expenditure by approximately £9,973 per year, equivalent to approximately £495 per tonne of CO_2e avoided. No additional implementation or training costs were incurred, as these activities were undertaken by existing staff during contracted working hours. Potential operational benefits, including reduced cylinder handling and a numerically shorter recovery time, were not monetised. The estimated £495/tCO_2e abatement cost is higher than the cited UK Government non-traded carbon values of £273–£398/tCO_2e (13), and is broadly consistent with other published NHS carbon-abatement cost ratios, such as £359–£1,030 per tonne for obesity-pathway interventions (21) and the approximately £416 per tonne threshold reported for switching from sevoflurane to intravenous anaesthesia (22)— both well above the £33–£65 per tonne benchmark needed to meet Paris Agreement trajectories. This suggests that the additional expenditure associated with Penthrox is not exceptional in the context of clinical decarbonisation. Moreover, the present analysis considered direct procedural costs only. Wider costs associated with Entonox, including cylinder storage, ordering, transport and handling, were not fully monetised; incorporating these alongside the carbon externality of nitrous oxide and any confirmed recovery or throughput benefits could narrow the effective cost differential. The literature on nitrous oxide specifically indicates that Entonox's true societal cost, once its carbon externality is valued using DESNZ

rates, may be many times its direct procurement cost (2, 23) meaning the £495/tonne figure likely overstates the net cost of transition relative to a fuller cost-consequence accounting.

The wider societal value of emissions reduction should also be recognised. Bressler estimated a mortality cost of carbon of 2.26×10^{-4} excess deaths per tonne of CO_2, equivalent to approximately one modelled excess death per 4,434 CO_2 tonnes emitted, although this estimate is subject to considerable uncertainty and should not be interpreted as an individual clinical risk (14).Social cost of carbon ranges differs based on model used. Incorporating temperature-related mortality raises the 2020 SCC from $37/28 pounds to $258/190 pounds per tonne (range: −$69/51 pounds to $545/400 pounds) in the baseline scenario(14). Country-level estimates show even higher global medians — US$417/306 pounds per tonne (66% CI: $177/130 pounds–$805/591 pounds), with India, China, Saudi Arabia, and the United States bearing the largest shares(15). These estimates reinforce that the acquisition cost of lower-carbon intervention does not capture the wider health and societal value of avoided emissions.

While Entonox remains the less expensive option overall, costing £ 5-8.3 less per procedure than Penthrox depending on the carbon pricing model applied, this modest gap arguably understates the case for Penthrox once its far smaller environmental footprint is considered. With healthcare systems such as the NHS committed to net-zero targets and given that current carbon pricing likely underestimates nitrous oxide's true externality cost (excluding occupational exposure and lifecycle emissions), the marginal extra cost of Penthrox may be better understood as a modest investment in emissions reduction rather than a straightforward added expense, particularly as carbon valuations rise and this cost gap is likely to narrow further.

Although the reduction in procedure time with Penthrox did not meet the threshold for statistical significance, the direction and magnitude of the effect are worth noting. A 3.19-minute reduction, if confirmed in an adequately powered study, could be clinically meaningful in a high-throughput endoscopy setting: using NHS unit-cost estimates of approximately £25–£37 per minute of colonoscopy time (derived from an average total procedure cost of £1,105 (24) over a 30–45 minute procedure), a difference of this size would correspond to roughly £80–£118 in procedure-time cost per case. Scaled across a busy endoscopy list, this could represent a non-trivial resource implication. The lack of statistical significance here is most plausibly attributable to sample size rather than a true absence of effect, and the finding should be regarded as hypothesis-generating rather than confirmatory. A larger, adequately powered trial would be needed to determine whether this time saving, and its associated cost implications is genuine.

Social sustainability:

This evaluation found that patient-reported experience with Penthrox for colonoscopy was highly favourable, with positive ratings above 87% across all domains and a mean score of 4.64/5. This is consistent with the wider literature: across published series, most patients report satisfaction

ranging from 63% to over 98%, with the majority saying they would use Penthrox again. The 90.3% "would choose again" rate in our cohort sits at the favourable end of this range(18).

Pain relief and procedural tolerance scored lowest (87.1% and 90.3%) but remained strongly positive, mirroring trial evidence showing no significant difference in pain or anxiety versus IV midazolam/fentanyl, while Penthrox patients had no desaturation events, woke faster, and were discharge-ready sooner. This trade-off, comparable analgesia with quicker, safer recovery, likely explains why patients with prior IV sedation (88.9%) or Entonox (100%) experience preferred Penthrox on this occasion(18).

Safety was reassuring: one case of unpleasant taste/smell, no delayed adverse effects on follow-up, and a vasovagal episode attributed to the colonoscopy rather than the drug.

Sustainability implications: self-administration avoids cannulation, dedicated anaesthetist time, and prolonged recovery monitoring, supporting faster patient turnover and reduced need for a carer/escort home, both relevant to service and social sustainability.

Staff feedback suggests favourable acceptance of Penthrox, with perceived benefits in analgesia, tolerability, portability and reduced cylinder reliance. Most rated it as comparable to Entonox, supporting acceptability rather than superiority. Requests for further training highlight the need for guidance on contraindications, dosing and practical use. Reported communication difficulties and one staff member's headache warrant further assessment. Although 90% supported wider implementation, the small sample and limited experience favour gradual expansion with continued evaluation of patient outcomes and staff experience.

Limitations:

This project has several limitations that should be considered when interpreting the findings as this is pilot project to test the drug usage.

- Single centre, non-randomised allocation creates a risk of selection bias and unmeasured confounding.
- The Penthrox cohort was small relative to Entonox (57 vs 554), and the project was explicitly a pilot without a formal sample-size calculation; it was not powered to demonstrate non-inferiority,

so the non-significant differences observed (in duration, recovery time, completion and comfort) should not be interpreted as evidence of equivalence.

- Penthrox is not specifically licensed for use during colonoscopy in the UK; therefore, its use in this setting is considered off label. However, it is licensed for the emergency relief of moderate-to-severe trauma-related pain in conscious adults, including in prehospital care, and has also been used for analgesia during hysteroscopy in UK.
- Nurse-assessed comfort and patient-reported feedback immediately after procedure were available for only a subset of procedures in both groups, limiting the strength of conclusions about tolerability and experience.
- Limited feedback: Patient experience was assessed retrospectively in 31 respondents, with possible response and recall bias. Staff feedback came from only 10 endoscopists out of 18.
- No adverse events were recorded in either arm, but the sample size was too small to reliably exclude rare but clinically important harms.
- Environmental findings were partly modelled and depend on assumptions about gas use, transport, materials and waste treatment.
- Limited generalisability: Results from one unit may not apply to other services with different patients, practices and costs.

  A larger multicentre prospective evaluation would provide stronger evidence about comparative clinical effectiveness, cost-effectiveness, transferability and social value

Conclusions:

This single-centre SusQI project indicates that Penthrox is a feasible, patient-controlled alternative to Entonox for analgesia during colonoscopy. Procedure completion (91.2% vs 95.8%, p=0.170), duration (37.0 vs 39.3 min, p=0.107), recovery time (15.2 vs 18.4 min, p=0.114) and comfort scores were broadly comparable between groups, and no recorded procedure- or drug-related adverse events were reported with either agent. This is small, non-randomised study cannot establish equivalent clinical effectiveness or safety.

The clearest and most consistent benefit was environmental: Penthrox reduced the estimated carbon footprint from 28.29 kgCO_2e to 1.1198 kgCO_2e per procedure, (96% reduction), equating to a potential saving of approximately 20,163 kgCO_2e annually at the modelled activity of 742 procedures. This was achieved alongside a highly favourable patient and staff experience. Patient's feedback with over 87% positive ratings across all surveyed domains and 90.3% of respondents willing to use Penthrox again. Among the 14 respondents who had previously undergone colonoscopy, 13 preferred Penthrox for a future procedure i,e 93% overall (89% preferred over IV sedation and 100% preferred over Entonox). Endoscopist feedback suggests that

Penthrox is an acceptable option for colonoscopy, with perceived clinical and operational benefits and strong support for wider implementation

On direct procurement costs alone, Penthrox was more expensive than Entonox (£16.02 vs £2.58 per procedure), equivalent to approximately £495 per tonne of CO_2e avoided, broadly in line with other published NHS carbon-abatement costs, though above current UK government carbon values. However, this direct comparison narrows substantially once the carbon externality of nitrous oxide is incorporated: across three published social-cost-of-carbon models, the true cost gap between Entonox and Penthrox fell to between £5 and £8.3 per procedure (DESNZ 2020, DICE-EMR with mortality, and country-level SCC respectively), reflecting Entonox's disproportionately larger carbon damage cost once valued alongside its acquisition price. There is also a plausible, though not statistically confirmed, procedural-time benefit: the 3.19-minute shorter recovery time observed with Penthrox (p=0.114) would, at NHS unit costs of approximately £25–£37 per minute of colonoscopy time, correspond to roughly £80–£118 in procedure-time cost per case if borne out in an adequately powered study. Taken together, these findings suggest that the headline acquisition-cost gap overstates the net economic disadvantage of Penthrox, and that the additional cost represents a modest and plausibly justifiable investment in decarbonisation, one that may narrow further, and could even reverse, once carbon pricing and any confirmed time/throughput benefits are fully accounted for. Further evaluation work would be beneficial to support this off-licence use of Methoxyflurane, but this QI project confirms existing data from literature demonstrating the clinically appropriate and effective use of Methoxyflurane in colonoscopy.

This pilot supports the feasibility and acceptability of Penthrox during colonoscopy and suggests substantial potential environmental benefit. Larger prospective evaluation is needed to establish comparative effectiveness, safety and economic value.

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Critical success factors

Please select **one or two** of the below factors that you believe were most essential to ensure the success of your project changes.

People	Process	Resources	Context
☐ Patient involvement and/or appropriate information for patients - to raise awareness and understanding of intervention ☐ Staff engagement **X MDT / Cross-department communication** ☐ Skills and capability of staff ☐ Team/service agreement that there is a problem and changes are suitable to trial (Knowledge and understanding of the issue) ☐ Support from senior organisational or system leaders	☐ clear guidance / evidence / policy to support the intervention. ☐ Incentivisation of the strategy – e.g., QOF in general practice ☐ systematic and coordinated approach ☐ clear, measurable targets **X long-term strategy for sustaining and embedding change developed in planning phase** ☐ integrating the intervention into the natural workflow, team functions, technology systems, and incentive structures of the team/service/organisation	☐ Dedicated time ☐ QI training / information resources and organisation process / support ☐ Infrastructure capable of providing teams with information, data and equipment needed ☐ Research / evidence of change successfully implemented elsewhere ☐ Financial investment	☐ aims aligned with wider service, organisational or system goals. ☐ Links to patient benefits / clinical outcomes ☐ Links to staff benefits ☐ 'Permission' given through the organisational context, capacity and positive change culture.