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Review Article

Volatile capture technology in sustainable anaesthetic practice: a narrative review

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Summary

Anaesthetic practice contributes to climate change. Volatile capture technology, typically based on adsorption to a carbon- or silica-based substrate, has the potential to mitigate some of the harmful effects of using halogenated hydrocarbons. Anaesthetists have a professional responsibility to use anaesthetic agents which offer the greatest safety and clinical benefit with the lowest financial cost and environmental impacts. Inhalational anaesthetics should be used at an appropriate concentration with a minimal fresh gas flow via a circle system to minimise unnecessary waste. Once practice efficiencies have been maximised, only then should technical solutions such as volatile capture be employed. In this narrative review, we focus on the available literature relating to volatile capture technology, obtained via a targeted literature search and through contacting manufacturers and researchers. We found six studies focusing on the Blue-Zone Technologies Deltasorb®, SageTech Medical SID and Baxter/ZeoSys CONTRAfluran™ volatile capture systems. Though laboratory analyses of available systems suggest that > 95% in vitro mass transfer is possible for all three systems, the in vivo results for capture efficiency vary from 25% to 73%. Currently, there is no financial incentive for healthcare organisations to capture waste anaesthetic gases, and so the value of volatile capture technology requires quantification. System-level organisations, such as Greener NHS, are best positioned to commission such evaluations and make policy decisions to guide investment. Further research using volatile capture technology in real-world settings is necessary and we highlight some priority research questions to improve our understanding of the utility of this group of technologies.

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Introduction

It has long been recognised that anaesthetic medications contribute to climate change [1], and this acts as a driver for anaesthetists to demonstrate leadership in promoting sustainable healthcare. As individual clinicians, we have the ability to practise sustainable stewardship of resources; spread knowledge about the interactions between healthcare and the environment; and contribute to significant reductions in healthcare emissions whilst simultaneously improving patient care and population health.

Optimising the choice of volatile anaesthetic agents and minimising the use of nitrous oxide were the first steps in climate mitigation for many departments of anaesthesia across the country. Volatile agents and medical nitrous oxide are estimated to represent 0.02% of the global greenhouse gases that account for excess radiative forcing and thus contribute to global warming [1]. Although these figures are small, anaesthetists are far greater contributors to climate change compared with the average global citizen [2]. The key tools in reducing our emissions from these gases lie primarily in good clinical practice: seeking out and eliminating waste; using optimal doses of appropriate drugs through selection and careful administration; and employing minimal flow techniques using circle systems. The aim should be to provide just what the patient requires for safe and effective anaesthesia and no more. After dealing with the efficiency of delivery and use of anaesthetic gases, focus may then turn to systems for capturing – and potentially re-using – waste gases through volatile capture technology (VCT).

Volatile capture technology describes a variety of systems that use carbon- or silica-based filters to adsorb volatile anaesthetic agents that would otherwise be released into the environment. As well as offering advantages in terms of occupational exposure and greenhouse gas emissions, it has the potential to create the first pharmaceutical circular economy. When first developed, inhaled anaesthetics were delivered via open breathing systems and then linear breathing circuits, with the major proportion being exhaled unmetabolised by patients and released to the atmosphere. The use of low-flow anaesthesia via circle circuits now allows a significant reduction in that waste by `recycling´ exhaled volatile anaesthetics within the same case, thereby reducing the amount that needs to be manufactured, delivered and used. This process may be further optimised using anaesthesia machines with end-tidal anaesthetic gas control technology. With the addition of VCT, it becomes possible to capture the remaining exhaled volatile anaesthetic in the effluent waste streams (e.g. anaesthesia gas scavenging system (AGSS)) to prevent release to the atmosphere. The captured products can then, in theory at least, be extracted before being distilled into the active pharmaceutical ingredients for reprocessing. With regulatory approval for re-use in humans already in place in Canada [3], Austria and Germany [4], this purified product could be re-sold to hospitals, limiting the environmental impact of virgin volatile anaesthetic manufacture and reducing the release of hydrofluorocarbon compounds to the atmosphere.

The principle of capturing anaesthetic gases is not new, but its purpose has evolved. Activated charcoal has been used for decades and remains commonplace in some clinical situations in countries such as France where AGSS use is not mandatory. Additionally, activated charcoal still maintains its applicability in low-resource settings and in filters used for prevention of malignant hyperpyrexia in susceptible patients. Over the last three decades, different materials have been investigated including silica zeolites and activated carbon [5]. Once captured, volatile anaesthetics can be recovered. For example, an early study reported that approximately 85% of captured desflurane could be extracted from silica zeolites by desorption [6, 7].

An ideal volatile capture system (Box 1) would be safe; energy efficient; ergonomic; cost-effective; and minimise preventable emissions by binding 100% of the volatile anaesthetic that enters its inlet. It would also permit complete desorption of captured volatile anaesthetic in a form that can be efficiently remanufactured to medical grade purity. Hu et al. hypothesised a capture efficiency of 70% with either silica zeolites or activated carbon, and calculated that if this was achievable, the use of sevoflurane would have a lower `carbon footprint´ than propofol-based total intravenous anaesthesia (TIVA), with carbon footprints of 0.996 kg carbon dioxide equivalent (CO_2e) vs. 1.013 kg.CO_2e per hour, respectively, at 1 MAC-equivalent [8].

In this narrative review, we describe the current commercially available VCT systems, present the available evidence for their efficacy, outline knowledge gaps in the current literature and make recommendations for future work.

Methods

We conducted a focused search of the OVID MEDLINE database with the terms `anaes*´; `inhalation´; `capture´; `sevoflurane´; `isoflurane´; `desflurane´; `zeolite´; `contrafluran´; and `greenhouse gases´; from 1980 to present. Studies identified by title were then filtered by abstract review. Any studies that did not focus on the capture of used inhalational anaesthetics were excluded, as were studies published in languages other than English. Because of the paucity of research data on this novel topic, we engaged with researchers in the field through personal communication and drew on our own institutional data, some of which are described below. We also reviewed the websites of commercially available technologies, and manufacturers were offered the opportunity to share details of their volatile capture devices, including life cycle assessments of environmental impact.

Box 1 Ideal characteristics of a volatile capture system.

Environmental impact

- Minimal environmental impact during:
  - Manufacturing – produced in a centre supplied with a low-carbon power and supply chain.
  - Maintenance – serviceable locally, without requiring long-distance transit.
  - Disposal – on a local basis, with environmentally responsible waste treatment.
- Entire product to be recycled at the end of its life.
- Long operational lifespan.
- Transport of serviceable components to be embedded into the healthcare supply chain.
- Only activated in the presence of drugs for capture.
- Capture medium maintains 100% binding efficiency during high fresh gas flows.
- Desorption of captured contents occurs under all conditions and is reflected in service-user data as `prevented carbon emissions´.

Economic impact

- Cost-effective in terms of initial procurement; everyday use; servicing; and maintenance.

Ergonomics

- Easy to use and handle: small; lightweight; and easily mountable on anaesthetic machine if required or portable on wheels.
- Capable of integration into the anaesthetic machines as standard technology.
- To function independently of AGSS unit or connected in series with AGSS.
- Connected to the ventilator back up power with an additional internal back up battery supply.
- Informatics displays:
  - Volatile binding capacity
  - CO_2e mitigated
  - Battery capacity
- Data from informatics display fed into a `dashboard´ for the hospital/organisation.

Health and Safety

- Safe to use by personnel involved with use, transport and disposal.
- Airtight seals on inlet and outlet ports when not in use to prevent leaks.
- Connected to the anaesthetic waste port by flexible, robust hoses with specific connectors.
- 100% capture ability with zero breakthrough at any gas flow rate, including oxygen flush.
- No interference with the functioning of the anaesthetic machine.
- Possible to exchange a full device for an empty device without leak of anaesthetic agent into the surrounding environment or breakthrough into the AGSS.
- Audible and visual alarms.
- Easy to use with minimal training.
- Activates (and deactivates) in synchrony with the anaesthetic machine.
- Remote monitoring to identify faults.
- One-way pressure valves to prevent backflow.
- Minimal impedance of flow rates through AGSS.

CO_2e, carbon dioxide equivalent; AGSS, anaesthetic gas scavenging system.

Results

We initially identified 217 articles; following review and filtering, six studies were suitable for inclusion in this narrative review. We noted a lack of consistency in the way that the efficiency of VCT was described, which made interpretation challenging. Therefore, we have developed a taxonomy for the purpose of this review (Figure 1). We define `in vitro mass transfer´ as the increase in the mass of the capture device as a proportion of the total mass of volatile agent used, reflecting the ability of the capture medium to bind to the anaesthetic agent with no variables other than water vapour to influence the result. We define `in vivo mass transfer´ as above, but with clinical use factors incorporated (e.g. such as leak from airway, circuit breaks, humidity and residual agent in patient tissues). We define `desorption efficiency´ as the efficacy of the desorption and recovery process, and we use `breakthrough´ to refer to the presence of volatile agent vapour in the outlet of the VCT system. We define `capture efficiency´ as the mass of volatile anaesthetic recovered (and therefore available for re-use) as a percentage of mass used, which reflects the efficiency of the overall process from capture to agent recovery.

Three commercial VCT systems are available currently: Deltasorb® (Blue-Zone Technologies, Ontario, Canada); SID-Dock/SID-Canisters (SageTech Medical, Paignton, UK); and CONTRAfluran™ (Baxter Technologies (Luckenwalde, Germany) and ZeoSys Medical (Luckenwalde, Germany)).

Deltasorb utilises silica zeolites to function as a molecular sieve within a stainless steel canister placed between the anaesthetic machine and scavenging system. A preliminary evaluation used the Deltasorb apparatus to investigate the effectiveness of silica zeolites in mitigating isoflurane emissions in a simulated clinical environment [9]. This time-limited study of 18 h identified the point of volatile agent breakthrough (8–10 h) and found an in vitro mass transfer of 74% for isoflurane and saturation point of 18 h. The authors concluded their scavenging method was feasible for use in a clinical environment. More recently, a single-centre observational clinical pilot study funded by the manufacturer was presented in a non-peer reviewed promotional piece [10]. The concentrations of volatile agents at both the inlet and outlet of the capture canister were measured by infrared spectroscopy, whilst humidity was monitored solely on the inlet. Of the 32 surgical cases investigated, 25% (8/32) demonstrated breakthrough mid-surgery (defined as > 0 ppm) and the data from these cases were excluded. Vaporisers and capture canisters were weighed pre- and post-use for each case, and canisters

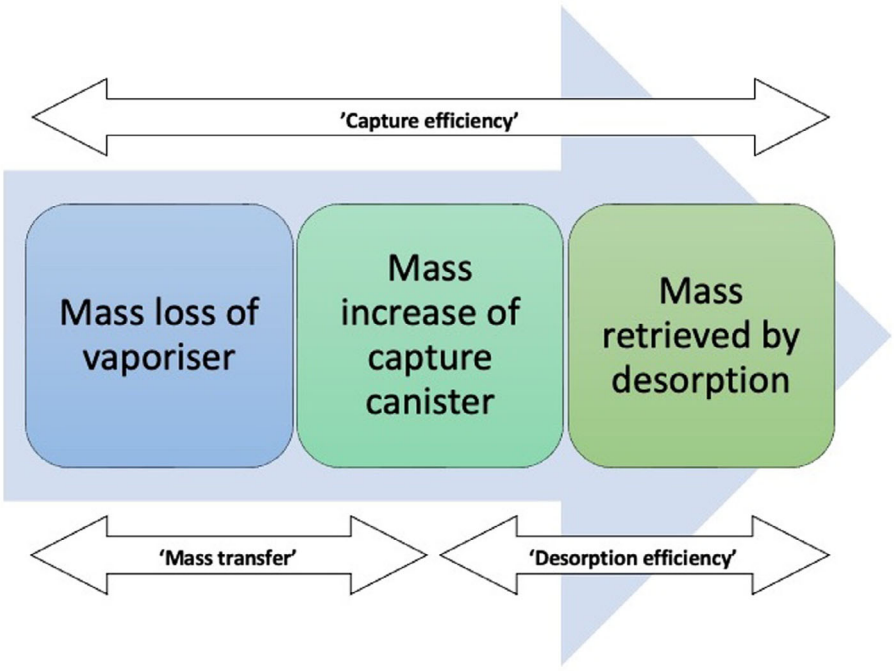

Figure 1 Suggested taxonomy of volatile capture metrics. Mass transfer can be further broken down into in vitro mass transfer reflecting the ability of the medium to bind the volatile anaesthetic with no compounding variables other than water vapour, and in vivo mass transfer where factors such as leak from airway, circuit breaks and residual agent in patient tissues influence the result.

were designated for either sevoflurane or desflurane, with results suggesting an in vivo mass transfer of 92%. However, in 25% of cases, the canister gained more mass than was lost by the vaporiser. This is likely attributable to adsorption of water vapour, but no attempt was made to quantify this in detail. Desorption data were presented for 9/32 (28%) of cases using two canisters, showing 65.8% and 73.3% capture efficiency for sevoflurane.

The SID-Dock VCT system uses activated carbon to bind sevoflurane, isoflurane and desflurane (SID). This device is inserted in series between the anaesthetic machine and the AGSS. Vaghela et al., investigated the SID-Dock VCT system in vitro by using a test lung connected to the ventilator, set with a minute volume of 6 l using various end-tidal sevoflurane concentrations (2–8%) and fresh gas flow rates (0.5–15 $l.min^{-1}$). The mass of the capture canisters and vaporisers was recorded pre- and post-test. They found that the in vitro mass transfer was 94.8%; of the total mass captured, 6.9% was water. The investigators found higher amounts of water were potentially captured at lower flow rates, with the mass gain of the capture canisters consistently greater than the mass of sevoflurane vapourised [11]. Gandhi et al. published a single-centre observational study of the SID-Dock in a real-world setting across 10 days with 50 elective patients for whom anaesthetists were requested not to alter their routine practice [12]. Forty-three patients received general anaesthesia and were included in the study. Patients' airways were managed by both tracheal intubation (20/44) and supraglottic airway devices (23/44). This pilot study utilised a capture device in both the anaesthetic room and operating theatre. Like previous study designs, the mass of the vaporiser and capture canisters were recorded pre- and post-study days. Desorption from 11 canisters was undertaken at the end of this period; however, one was damaged during the extraction process preventing analysis of its contents. The authors found that the capture efficiency of sevoflurane and isoflurane was 51%. Of the mass captured, 5.4% was water. This is in keeping with a more recent but unpublished study conducted at Guy's and St Thomas' NHS Foundation Trust (London, UK), in which sevoflurane capture efficiency by the same SID-Dock system was measured in routine unmodified clinical practice across 2 months (M Vaghela, personal communication). A similar method was used at NHS Lothian (Edinburgh, Scotland), which showed comparable capture efficiency to that shown by Gandhi et al. [12]. Following this, clinical staff were coached with suggested interventions to minimise volatile system loss, (e.g. pausing of gas flow during airway manoeuvres, rapid establishment of minimal flow, etc.) and a subsequent analysis showed an increase in capture rate in the anaesthetic room but not the operating theatre (S Cross and A Goddard, personal communication). These small changes to anaesthetic machine and circuit use may offer some way of bringing clinical capture efficiency closer to in vitro mass transfer rates.

The above pilot studies focused on capturing sevoflurane and isoflurane with the SID-Dock, but an additional study evaluated the applicability of VCT when desflurane was used [13]. This laboratory-based investigation aimed to evaluate the mass transfer of desflurane from vaporiser to capture device and measure breakthrough. The SID-Dock was sited in series between the anaesthetic ventilator and AGSS, with an infrared spectrometer positioned on the SID-Dock outlet. Nine combinations of volatile concentration (3–9%) and fresh gas flow (5–15 $l.min^{-1}$) were studied. As per previous designs, the mass of the vaporiser and canisters were measured pre- and post-test combination. The mean in vitro mass transfer of desflurane from vaporiser to the SID canisters was 94% [13], similar to the results for sevoflurane [11].

The CONTRAfluran system uses a capture medium composed of activated charcoal, and like the Deltasorb is designed to work with both passive and active scavenging systems. This differs from the SID-Dock, which is designed to work in series within the AGSS. Hinterberg et al. assessed the capture efficiency of the CONTRAfluran device in a passive system [14]. This observational study of 80 patients undergoing desflurane anaesthesia via tracheal tube found the capture efficiency for desflurane to be 25%. Of this, 70% was reported to be desflurane, with the remaining mass gain likely to be water. The protocol of this study had limitations, in particular, the utilisation of a new capture canister for each patient rather than mimicking normal clinical practice [15].

A potential environmental benefit of VCT systems that do not require an active AGSS is the energy (and hence carbon dioxide) savings that could be achieved by switching off the AGSS. This is only possible if nitrous oxide, which is not captured by VCT, is not used. The UK's Control of Substances Hazardous to Health (COSHH) regulations [16], developed in the 1980s in response to nitrous oxide exposure within theatres, influence the Health Technical Memoranda (HTMs, or SHTMs in Scotland) that govern operating theatre design [17]. However, considering changes in clinical practice and new technology, it may be appropriate to revise these regulations. Work is currently progressing in NHS Scotland investigating the relevance of AGSS in modern theatre spaces, given that theatre ventilation systems achieve air changes at a rate greater to

those available when the COSHH regulations were developed. Beyond the environmental savings from no longer requiring an AGSS, there would be a reduction in electricity, maintenance and capital expenditure when future procurement takes place for new hospitals or to replace aging equipment.

Resources are available to evaluate the energy consumption of current active scavenging systems [18], but to illustrate the potential savings in this review, we have used the example of the Cheshire and Merseyside Surgical Centre (Clatterbridge, UK). Currently, across 10 theatres that do not have nitrous oxide, the continual operation of nine AGSS consumes 12.75 kWh. With a current electricity tariff of £0.37 (US$0.45, €0.42) per kWh (September 2023) and the UK's average carbon factor of 0.207 $kgCO_2e.kWh^{-1}$ [19], the annual electricity costs are approximately £40,000 (US$48,880; €45,750), and the emissions from electricity are 22 tCO_2e. If the AGSS was de-activated due to the implementation of a passive VCT system, a cost saving of £23,000 (US$29,000, €26,210) would be realised in the first year, and £28,500 (US$35,930, €32,980) thereafter (Table 1). Although it should be noted that this does not include any costs for converting anaesthetic machines to work with passive scavenging systems, which is required by some manufacturers. However, if active scavenging remains a necessity, VCT will result in additional expenditure.

Discussion

The VCT systems available currently have shown wide-ranging results and fundamentally, based on these small studies, the 70% capture efficiency hypothesised by Hu et al., appears to be an overestimation [8].

Single-centre clinical studies investigating mass transfer and capture efficiencies of individual VCT systems are of limited value. However, they do highlight practices that prevent maximal capture of anaesthetic agents, particularly in `real-world´ scenarios. Unquantifiable losses to the surrounding environment due to leaks from sub-optimal airway management (e.g. difficult facemask ventilation, ineffective tracheal tube cuff seal, poorly seated supraglottic airway devices) can negatively impact capture efficiency. In some cases, anaesthetists opt to use higher than usual fresh gas flow rates, for example, when rapid changes in anaesthetic depth may be required or to compensate for leaks [20], hypothetically resulting in a greater amount of volatile anaesthetic entering effluent waste streams. Somewhat paradoxically, however, the capture efficiency of VCT systems may appear to be higher when high fresh gas flow rates are used because of the increased proportion of anaesthetic agent that enters the effluent gas stream [21]. This could create a perverse incentive if percentages of mass transfer or overall capture efficiency are used as the only metrics of interest.

The primary focus should be to prevent waste and greenhouse gas emissions through good practice, by reducing the amount of volatile anaesthetic used in the first place. Minimal flow practices are promoted not only by enthusiasts, but also by anaesthetic machine manufacturers who have indirectly developed additional methods of producing environmental savings. In comparison with traditional plenum vaporisers, electronically controlled variable bypass vaporisers and direct injection vaporisers deliver volatile agents into circle systems accurately with minimal fresh gas flows [22]. An automated version of this technique, in the form of end-tidal target control of volatile concentration, is now offered on some anaesthetic machines with the benefit of further promoting efficiency [23]. Each of these factors have the potential to significantly reduce the amount of volatile anaesthetic used, therefore limiting the available amount to be captured.

Other sources of volatile loss include being absorbed by, or leaking though, the plastic and rubber within the internal circuitry of anaesthetic machines, whilst soda lime canisters have the capacity to act as large reservoirs [24–26]. The remaining volatile loss is likely to be the percentage that remains in the patient's tissues after they leave the operating theatre – the recovery room loss. Depending on the drug used, duration of surgery and patient factors, a variable (but unknown) portion of volatile will remain, being liberated from tissues and expired for a variable length of time in

Table 1 Cost breakdown for implementing passive volatile capture technology (VCT) using CONTRAfluran and deactivating the anaesthetic gas scavenging system (AGSS). Costs are based on quote provided by Baxter directly to one Trust, which may not be applicable to other organisations.

	Price**
20 VCT systems – initial purchase	£5500 (US$6940, €6360)
20 VCT systems – annual service	£3500 (US$4410, €4050)
Consumable cannisters – annual purchase	£8000 (US$10,090, €9260)
Current cost of running AGSS – annual electricity costs*	£40,000 (US$50,440, €46,290)
Annual saving (year of purchase)	£23,000 (US$29,000, €26,210)
Annual saving after initial purchase	£28,500 (US$35,930, €32,980

*Based on estimated use; **estimates from August 2023.

transport to the post-anaesthesia care unit and during recovery. This was shown by Talent et al. [27], and consequently whole PACU capture has been mooted as an adjunct to current systems.

The results of this review have been limited by the small number of studies identified, and there were two papers excluded due to their non-English language scripts that have the potential to add to this knowledge base [28, 29]. There are also limitations due to the nature of the research conducted to date. Of the two studies using Deltasorb, one was a 20-year old preliminary investigation, whilst the second study has not been subjected to peer review. Only one study was identified for CONTRAfluran. The SID-Dock was evaluated in three published peer-reviewed studies, with two additional studies conducted but not yet published. All the studies identified for this review were single-centre small-scale studies, requiring the manufacturers to analyse and desorb the anaesthetic adsorption, therefore relying upon their integrity to accurately report the results.

Service evaluation studies of this nature will not be able to achieve the same rigour as randomised controlled trials but there are areas for future work that could be strengthened. Future research should look to standardise anaesthetic practice to make results more comparable, so findings could be combined. The projects suggested in Box 2 may require changes to anaesthetic practice and procedures, so research ethics committee approval may be required.

To minimise bias and improve applicability, we suggest that future work should be multi-centre, and to maximise accuracy, vaporisers and capture canisters should be weighed daily and desorption of captured contents should occur at the end of each study day rather than after each case. Additional monitoring including an analyser sited at the inlet and outlet of the VCT to monitor for humidity and breakthrough would further add to our understanding. In vitro mass transfer appears to be high across different manufacturers, but as noted above, clinical variables can have large impacts in vivo, thereby affecting capture efficiency. Ascertaining the differences in confounding factors is important, including patient, surgical and anaesthetic factors. Concerns about bias could be mitigated by working with an independent laboratory/engineering team to undertake the desorption work, alongside the manufacturer.

Anaesthetic technique can influence the results and we recommend studies incorporate `good husbandry´ guidance. It could be assumed induction of general anaesthesia in the operating theatre would improve the efficiency of anaesthesia, by limiting the equipment required, reducing the number of breaks in the anaesthetic breathing circuit and minimising the need for periods of high fresh gas flow. Additionally, comparing traditional variable bypass vaporisers with newer electronically controlled vaporisers to ascertain the difference in capture efficiencies would add further understanding.

Ongoing capture of volatile anaesthetic agents once patients have left the theatre environment is a particular area of interest. Investigating this potential in PACU would require development and quality assurance of a proprietary system.

Surgical factors requiring exploration include the duration of procedures (short vs. long durations) and how different surgical specialities could influence outcomes. Investigation of patient factors could include understanding how body habitus plays a role in storing volatile anaesthetics once patients are transferred to PACU.

Another factor highlighted by Hinterberg et al. was when partially full canisters are returned to the manufacture for desorption [14]. This appears to have been done to simplify the analytical process, but may have introduced inefficiencies which were unrepresentative of `real-world´ use [15, 21]. This does not appear to have been the case in the small studies conducted with the SID-Dock system [11–13], which showed no distinguishable difference in the ability to desorb partially full vs. full canisters. In the study conducted by Gandhi et al., one canister out of the 11 was unable to be analysed due to a failure in the system, but the authors were assured all contents were desorbed and transferred to the volatile storage container [12]. Analysis showed when canisters were less than full, there was a

Box 2 Possible future directions for volatile capture technology (VCT) research.

Research study	Question addressed
Induction in theatre	Does avoiding the anaesthetic room increase the overall capture efficiency?
Emergence in theatre	How much volatile can be captured if the patient stays in theatre until emergence from general anaesthesia?
Recovery room capture	What is the effect on capture efficiency if this is continued into the recovery period; how might this be optimised?
Long case selection	Do long cases lead to a higher capture efficiency vs. fast turnover cases?

disproportionately greater volume of water present. This suggests water is present on the capture medium prior to and during use. It could, therefore, be hypothesised that theatre humidity or a saturated heat and moisture exchange filter could increase the water content in the capture devices. However, in the presence of halogenated volatile anaesthetics, water is displaced and removed from the capture medium due to the preferential affinity of halogenated agents to be adsorbed [13].

Once capture canisters are returned to the manufacturers, the desorption efficiency (amount desorbed/total amount adsorbed) should be close to 100% to maximise carbon savings, but there is limited evidence to validate these processes. In their respective life cycle assessments of carbon dioxide equivalent impacts, SageTech Medical claim a modest 1.6% loss of anaesthetic agent during the desorption and purification process (personal communication, SageTech Medical) whilst Bluezone claim a < 1% loss [30]. Baxter ZEOSYS provide no indication of their desorption efficiency.

This review has investigated the applicability of VCT in the real-world setting and ideally would have also focused on the overall reduction or prevented carbon emissions. The life cycle assessments for Deltasorb and SID-Dock were done following the international standards for lifecycle assessment (ISO 14040) [30]. The two, however, vary greatly in detail, with a more robust and comprehensive analysis evident for SID-Dock. Given the discrepancies in information provided between the two, a like-for-like comparison as to which system provides the greatest net reduction in CO_2e emissions is challenging. For the CONTRAfluran, beyond the commercially available literature on carbon emission savings [31], there is no lifecycle analysis to explore. Baxter were invited to produce a lifecycle analysis for discussion in this review in March 2023 and at the time of publication, this was still pending.

The results in previous studies used varying nomenclature for understanding the amount of anaesthetic drug captured vs. that used, resulting in inconsistencies between reported values. The in vitro mass transfer of the device is of initial concern and manufacturers should endeavour to make their devices as close to 100% efficient as possible. Each of the current manufacturers indicate they have a 99% in vitro mass transfer, but this is of limited value when it comes to real-world capture efficiencies. The limited studies in this review suggest up to 50% of the volatile anaesthetic could remain with patients once they have been disconnected from the anaesthetic breathing circuit, but it is unclear as to what proportion is exhaled whilst in PACU and whether this could be captured to further mitigate environmental burden. This highlights the requirement for further work to investigate the amount of volatile anaesthetic expired from patients in the immediate recovery period and whether VCT can continue to play a role in PACU.

The `triple bottom line´ approach is a well-established framework to consider sustainability in terms of environmental, financial and social (e.g. patient care) factors [32]. Utilising this approach to establish the value proposition of VCT will require more data on the lifecycle greenhouse gas emissions of the whole process, and consideration of the cost effectiveness of the solution.

Many unknowns remain and further studies are required to assess the clinical efficacy and cost effectiveness of VCT, but the potential of the technology is without doubt. Innovative manufacturers have developed a means to effectively capture used anaesthetic gases from effluent waste streams and make them available for potential re-use in human healthcare. The mantra behind sustainability: reduce resource use, before re-use and recycling, remains paramount, and any anaesthetic department considering VCT should first endeavour to achieve good volatile anaesthetic husbandry and then maximise potential recovery.

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