Research Square

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Real-world implementation of a ventilation feedback device during out-of-hospital cardiac arrest: a population-based observational study from a French prehospital system

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Research Article

Keywords: implementation, cardiopulmonary ventilation, medical device, out of hospital cardiac arrest, prehospital medicine, ventilation feedback devices

Posted Date: June 28th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9884365/v1

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Additional Declarations: Competing interest reported. Professor Khoury is the Medical Advisor for Archeon Medical and a patent holder for different medical devices.

Abstract

Background: Ventilation quality during cardiopulmonary resuscitation remains highly variable despite clear guidelines. Ventilation feedback devices (VFDs) have shown substantial improvements in simulated settings, but real-world implementation data remain limited. Importantly, the effectiveness of medical devices is strongly influenced by human, organisational, and environmental factors.

This study aimed to evaluate real-world implementation and utilisation of a VFD during out-of-hospital cardiac arrest (OHCA) management in a French prehospital system.

Methods: We conducted a retrospective, population-based observational study of adult OHCAs jointly managed by firefighters and Mobile Intensive Care Unit teams in the Doubs region. Cases from 2022 (pre-implementation) and 2024 (post-implementation) were analysed. The primary outcome was VFD utilisation. Secondary outcomes included ROSC, survival, and neurological status, reported descriptively and exploratorily.

Results: Among 756 OHCAs, 190 (2022) and 166 (2024) met the inclusion criteria. Despite a protocol mandating its systematic use, the device was used in 48/166 (28.9%) cases.

Baseline characteristics and resuscitation variables were comparable between groups. Exploratory analyses showed ROSC in 25.0% with VFD versus 16.1% without, and survival at day 30 in 10.4% versus 4.2%. Favourable neurological outcome at day 30 was observed in 10.4% versus 3.4%. Given the observational design and limited sample size, these findings should be interpreted as hypothesis-generating.

Conclusions: This study highlights a discrepancy between protocol and real-world use of a ventilation feedback device during OHCA. They underscore the need to better understand implementation factors to inform future studies evaluating clinical effectiveness. Future research should incorporate robust implementation strategies and standardised ventilation parameters.

Introduction

Out-of-hospital cardiac arrest (OHCA) is a leading cause of death and morbidity worldwide, causing approximately 400,000 deaths annually in the United States [1]. According to the 2020 International Liaison Committee on Resuscitation (ILCOR) registry report, survival to hospital discharge or 30-day survival after EMS-treated OHCA ranged from 3.1 to 20.4%, with favourable neurological outcome of 2.8–8.2% [2]. More recent international registry data indicate that bystander-witnessed shockable OHCA survival ranges from 19.9 to 44.4%, with favourable neurological outcome of 9.5–35.1% [3].

Among survivors, neurological outcomes are frequently poor when return of spontaneous circulation (ROSC) is delayed [4, 5] and OHCA remains among the top three causes of preventable years of life lost in developed countries [6, 7].

Effective management relies on early and high-quality cardiopulmonary resuscitation (CPR). CPR quality depends on both effective chest compressions to restore circulation and effective ventilation to ensure tissue oxygenation [8].

While decades of research have largely focused on optimising chest compressions [9–11], ventilation has received comparatively less attention, mainly due to technical limitations. Yet, effective ventilation is crucial to maintain gas exchange and prevent hypoxia during prolonged resuscitation, as compression-only CPR cannot provide adequate alveolar ventilation during prehospital care [12–16].

The ILCOR, American Heart Association (AHA), and European Resuscitation Council (ERC) recommend a ventilation rate (VR) of 8–10 breaths per minute (bpm) with a tidal volume (VT) of 6–8 mL/kg of predicted body weight [17–19].

Despite well-defined guidelines, delivering ventilation according to recommendations remains challenging, regardless of the level or amount of training received. This issue has been recognised for decades [20] and, despite advances in resuscitation science, remains unresolved.

Manikin studies continue to show poor adherence, with only 2.8–22% of ventilations meeting both rate and volume targets [21–23]. Even when considering individual parameters, adherence is limited, for example 22.7% of ventilations meeting volume targets and 51% meeting rate targets in the study conducted by Charlton et al. [24].

Real-world data reflect these findings: O'Neill and Deakin observed VT ranging from 374–923 mL (median 618.5 mL) and VR of 9–41 bpm (median 26) in 12 OHCA patients [25]. Drennan et al., in a before-and-after study, showed that only 7% of the ventilations met both rate and volume targets [26].

Various medical devices (MDs) have been developed to assist manual ventilation during OHCA, including metronomes [27] and impedance threshold devices [28, 29]. More recently, ventilation feedback devices (VFDs) have been introduced. They provide real-time feedback on VR and VT.

Manikin studies suggest that VFDs substantially improve ventilation quality. Our research group observed an increase in effective ventilation from 15% to 90% with a VFD [30]. Lyngby et al. reported an increase from 22.1% to 75.3% [22], and Charlton et al. found that the proportion of clinicians achieving guideline ventilation ≥ 50% of the time increased from 9% to 91% [24].

However, clinical evidence remains limited, partly because evaluating MDs poses inherent challenges. Unlike drugs, whose effects are largely determined by pharmacological properties, their use and effectiveness depend not only on their design but also on user skills, training, environmental conditions, and contextual factors such as workload, stress, fatigue, and noise. Learning curves [31] and organisational barriers [32] can also constrain their adoption and effectiveness.

Real-world observational data are therefore needed to assess and optimise VFDs. Such data are also crucial to inform future clinical studies. We aimed primarily to describe the real- word implementation and use of a VFD by firefighters and prehospital Mobile Intensive Care Unit (MICU) teams in a French region. A secondary objective was to explore associations with clinical outcomes to generate hypotheses for future research.

Methods

Study design and setting

This was a single-centre, retrospective, population-based observational study conducted in the MICU of the University Hospital of Besançon, covering all OHCAs in the Doubs region. The study was classified as not involving human participants under French Jardé law. As a result, neither institutional review board nor ethics committee approval was required. The study was performed in accordance with relevant guidelines: the Declaration of Helsinki, Good Clinical Practices, and national legislation.

System of care

OHCA is managed jointly by firefighters and a MICU team. Firefighters provide basic life support (BLS), whereas the MICU team, staffed by an emergency medicine physician and a nurse, provides advanced life support (ALS) or decides to terminate CPR.

In the Doubs department, firefighters have been equipped with a VFD (EOlife®) in all vehicles since 1 January 2023. The Doubs area covers 5,233 km² and has 550,000 inhabitants (2019).

Ventilation feedback device

EOlife® is a CE-marked medical device placed between the bag-valve-mask and the airway interface. The device provides real-time visual feedback on VR and VT, the latter being defined for this device as the volume of gas effectively delivered to the lungs during each ventilation cycle.

Teams received standardised manufacturer training with periodic refreshers. Firefighters are required to systematically initiate CPR using EOlife® in all OHCAs, after which the MICU team decides whether to continue or terminate resuscitation.

Study population

We included all adult OHCAs jointly managed by the Besançon MICU and the Fire and Rescue Service in 2022 (pre-implementation) and 2024 (post-implementation).

Exclusion criteria were pregnancy, labour, minors, persons deprived of liberty, individuals under compulsory psychiatric care, or adults under legal protection or unable to provide consent.

Outcomes

The primary objective was to describe the real-world use of the VFD.

Secondary objectives were to:

- Compare OHCA cases without VFD use in 2022 (all cases) versus 2024 (cases in which the device was not used) for:
    - Return of spontaneous circulation (ROSC) in the prehospital setting, at hospital arrival, and at day 30 (or at ICU discharge).
    - The proportion of patients with favourable neurological outcomes (cerebral performance category (CPC) score =1 or 2) assessed at day 1, and day 30 (or at ICU discharge).
- Compare OHCA cases with versus without VFD use in 2024 for the same outcomes.
- Provide exploratory outcomes on survival and neurological outcomes.

Statistical analysis

Data are presented as means ± standard deviations for continuous variables and as counts and percentages for categorical variables. Given the observational design and focus on implementation, analyses were not adjusted for confounders and are presented as exploratory. Qualitative variables were compared using Pearson's chi-squared test or Boschloo's exact test when expected frequencies were below 5. Continuous variables were compared using the Student's t-test or the Wilcoxon – Mann – Whitney test, as appropriate. Normality was assessed using the Shapiro–Wilk test.

Unadjusted odds ratios (ORs) and 95% confidence intervals (CIs) were calculated for ROSC, survival at day 1 and day 30, and neurological status at day 30.

Statistical analyses were performed using a custom Python script (SciPy and Statsmodels libraries) and SPSS (PASW Statistics version 18.0.0). The level of statistical significance was set at $p < 0.05$.

RESULTS

The MICU managed 404 OHCAs in 2022 and 352 in 2024, for a total of 756 OHCAs. Among these, 190 in 2022 and 166 in 2024 were managed jointly with firefighters (Fig. 1).

In 2024, 48 (28.9%) OHCAs were managed with the VFD, and 118 (71.1%) without (Table 1). No significant differences were observed between the groups for any of the analysed variables. Patients were predominantly male (71.7%), with a mean age of 67 ± 16.7 years. OHCAs occurred mainly at home (80.1%), with 18.1% in public places and 1.8% in healthcare facilities. Nearly half were witnessed by a bystander (39.1%), and 38.7% presented with an initial shockable rhythm.

Table 1: Out-of-hospital characteristics

	With VFD n=48	Without VFD n=118	Total n=166	p-value
Age (years) - mean (SD)	68.1 (15.4)	66.5 (17.2)	67.0 (16.7)	0.627
Sex - n (%)				
Female	11 (22.9%)	36 (30.5%)	47 (28.3%)	0.385
Male	37 (77.1%)	82 (69.5%)	119 (71.7%)	
Total	48 (100.0%)	118 (100.0%)	166 (100.0%)	
No flow duration (minutes) - mean (SD)	8.6 (12.8)	7.3 (10.1)	7.7 (11.0)	0.893
No flow - n (%)				
< 5 minutes	12 (46.2%)	27 (49.1%)	39 (48.1%)	0.805
≥ 5 minutes	14 (53.8%)	28 (50.9%)	42 (51.9%)	
Total	26 (100.0%)	55 (100.0%)	81 (100.0%)	
Low flow duration (minutes) - mean (SD)	28.2 (10.9)	27.3 (15.0)	27.6 (13.6)	0.776
Shockable rhythm - n (%)				
No	26 (70.3%)	39 (56.5%)	65 (61.3%)	0.166
Yes	11 (29.7%)	30 (43.5%)	41 (38.7%)	
Total	37 (100.0%)	69 (100.0%)	106 (100.0%)	
Location of OHCA - n (%)				
Home	41 (85.4%)	92 (78.0%)	133 (80.1%)	0.547
Public place	7 (14.6%)	23 (19.5%)	30 (18.1%)	
Healthcare facility	0 (0.0%)	3 (2.5%)	3 (1.8%)	
Total	48 (100.0%)	118 (100.0%)	166 (100.0%)	
Bystander-witnessed cardiac arrest - n (%)				
No	29 (61.7%)	69 (60.5%)	98 (60.9%)	0.889
Yes	18 (38.3%)	45 (39.5%)	63 (39.1%)	
Total	47 (100.0%)	114 (100.0%)	161 (100.0%)	
Aetiology - n (%)				
Hypoxic	6 (24.0%)	15 (26.3%)	21 (25.6%)	NA
Cardiovascular	7 (28.0%)	12 (21.1%)	19 (23.2%)	
Palliative	1 (4.0%)	2 (3.5%)	3 (3.7%)	
Suicide (intoxication by medication/defenestration)	1 (4.0%)	4 (7.0%)	5 (6.1%)	
Hanging	5 (20.0%)	10 (17.5%)	15 (18.3%)	

Haemorrhagic	1 (4.0%)	3 (5.3%)	4 (4.9%)
Weapon-related	0 (0.0%)	1 (1.8%)	1 (1.2%)
Traumatic	3 (12.0%)	6 (10.5%)	9 (11.0%)
Septic	0 (0.0%)	1 (1.8%)	1 (1.2%)
Neurological	1 (4.0%)	1 (1.8%)	2 (2.4%)
Toxic	0 (0.0%)	2 (3.5%)	2 (2.4%)
Total	25 (100.0%)	57 (100.0%)	82 (100.0%)

Abbreviations: OHCA, out-of-hospital cardiac arrest. SD, standard deviation VFD, ventilation feedback device.

Missing data: we provided the total for each variable to allow the identification of the missing data. For “No flow”, 22 (45.8%) data were missing in the group with VFD and 63 (53.4%) in the group without VFD.

For low flow duration, 16 (33.3%) data were missing in the group with VFD and 60 (50.8%) in the group without VFD.

Table 2 presents the comparison of CPR characteristics in 2024. Only the number of shocks differed significantly between groups. CPR was initiated by bystanders in one third of cases (36.1%); of whom 34.4% were trained in CPR. In nearly half of the cases, the MICU team did not perform CPR (47.3%).

Table 2: cardiopulmonary resuscitation characteristics

	With VFD n=48	Without VFD n=118	Total n=166	p-value
Bystander CPR - n (%)				
No	13 (31.0%)	39 (38.2%)	52 (36.1%)	0.408
Yes	29 (69.0%)	63 (61.8%)	92 (63.9%)	
Total	42 (100.0%)	102 (100.0%)	144 (100.0%)	
CPR by trained bystander - n (%)- n (%)				
No	2 (20.0%)	9 (40.9%)	11 (34.4%)	0.425
Yes	8 (80.0%)	13 (59.1%)	21 (65.6%)	
Total	10 (100.0%)	22 (100.0%)	32 (100.0%)	
CPR provided by MICU - n (%)				
No	18 (38.3%)	60 (50.8%)	78 (47.3%)	0.145
Yes	29 (61.7%)	58 (49.2%)	87 (52.7%)	
Total	47 (100.0%)	118 (100.0%)	165 (100.0%)	
Epinephrine dose - n (%)				
< 5 mg	18 (64.3%)	36 (63.2%)	54 (63.5%)	0.919
≥ 5 mg	10 (35.7%)	21 (36.8%)	31 (36.5%)	
Total	28 (100.0%)	57 (100.0%)	85 (100.0%)	
Amiodarone administered - n (%)				
No	47 (97.9%)	106 (89.8%)	153 (92.2%)	0.111
Yes	1 (2.1%)	12 (10.2%)	13 (7.8%)	
Total	48 (100.0%)	118 (100.0%)	166 (100.0%)	
Number of shocks delivered - n (%)				
< 5	10 (100.0%)	20 (66.7%)	30 (75.0%)	0.043
≥ 5	0 (0.0%)	10 (33.3%)	10 (25.0%)	
Total	10 (100.0%)	30 (100.0%)	40 (100.0%)	
$EtCO_2$ at intubation - n (%)				
≤ 10 mmHg	0 (0.0%)	1 (2.3%)	1 (1.5%)	1
> 10 mmHg	24 (100.0%)	42 (97.7%)	66 (98.5%)	
Total	24 (100.0%)	43 (100.0%)	67 (100.0%)	
LUCAS device used - n (%)				
No	3 (27.3%)	5 (21.7%)	8 (23.5%)	1

Yes	8 (72.7%)	18 (78.3%)	26 (76.5%)
Total	11 (100.0%)	23 (100.0%)	34 (100.0%)

Abbreviations: CPR, cardiopulmonary resuscitation. $ETCO_2$, End Tidal CO_2. OHCA, out-of-hospital cardiac arrest. SD, standard deviation VFD, ventilation feedback device. LUCAS, mechanical chest compression device used.

Missing data: we provided the total for each variable to allow the identification of the missing data.

Table 3 presents survival outcomes, neurological status, and causes of death.

In 2024, 31 patients (18.7%) achieved ROSC: 19 (16.1%) without VFD and 12 (25.0%) with VFD. Survival at day 1 was 18 (10.8%), including 10 (8.5%) without VFD and 8 (16.7%) with VFD. Survival at day 30 was 10 (6.0%), with 5 (4.2%) in the no-VFD group and 5 (10.4%) in the VFD group. Among survivors, 9 (5.4%) had a favourable neurological outcome (CPC 1): 4 (3.4%) without VFD and 5 (10.4%) with VFD (p = 0.049) (Table 3).

In 2022 (pre implementation), 33 (17.4%) patients attained ROSC. Survival at day 1 was 24 (12.6%) and survival at day 30 was 9 (4.7%), with 6 (3.2%) patients having a good neurological status (CPC1). No statistically significant differences were found when comparing OHCAs in 2022 and the 118 OHCAs in 2024 managed without VFD (Table 4).

Although the VFD provides real-time feedback, objective ventilation data (tidal volume, ventilation rate, and leak magnitude) were not recorded in the database. Therefore, we were unable to assess ventilation quality or adherence to guidelines, limiting interpretation of the relationship between VFD use and clinical outcomes.

Table 3: Outcomes and aetiologies

	With VFD	Without VFD	Total	Odds Ratio	p-value
	n=48	n=118	n=166	(CI 95%)	
ROSC - n (%)					
No	36 (75.0%)	99 (83.9%)	135 (81.3%)	1.74	0.1
Yes	12 (25.0%)	19 (16.1%)	31 (18.7%)	[0.77; 3.93]	
Total	48 (100.0%)	118 (100.0%)	166 (100.0%)		
Survival at day 1 - n (%)					
No	40 (83.3%)	108 (91.5%)	148 (89.2%)	2.16	0.07
Yes	8 (16.7%)	10 (8.5%)	18 (10.8%)	[0.80; 5.86]	
Total	48 (100.0%)	118 (100.0%)	166 (100.0%)		
Survival at day 30 - n (%)					
No	43 (89.6%)	113 (95.8%)	156 (94.0%)	2.63	0.077
Yes	5 (10.4%)	5 (4.2%)	10 (6.0%)	[0.72; 9.53]	
Total	48 (100.0%)	118 (100.0%)	166 (100.0%)		
Neurological status at day 30 - n (%)					
CPC = 1	5 (10.4%)	4 (3.4%)	9 (5.4%)	3.28	0.049
CPC ≠ 1 or missing	43 (89.6%)	113 (96.6%)	156 (94.5%)	[0.84; 12.81]	
Total	48 (100.0%)	117 (100.0%)	165 (100.0%)		
Aetiology - n (%)				Not applicable	
Post-anoxic encephalopathy	2 (50.0%)	4 (50.0%)	6 (50.0%)		0.697
Multiorgan failure	1 (25.0%)	2 (25.0%)	3 (25.0%)		
New cardiac arrest	0 (0.0%)	2 (25.0%)	2 (16.7%)		
Hypoxic cause	1 (25.0%)	0 (0.0%)	1 (8.3%)		
Total	4 (100.0%)	8 (100.0%)	12 (100.0%)		

Abbreviations: CPC score, cerebral performance category score. OHCA, out-of-hospital cardiac arrest. ROSC, return of spontaneous circulation. VFD, ventilation feedback device.

Missing data: we provided the total for each variable to allow the identification of the missing data.

Table 4: Outcomes and aetiologies for OHCAs managed without VFD in 2022 and 2024

	OHCAs in 2022 n=190	OHCAs in 2024 n=118	TOTAL n=308	p-value
ROSC - n (%)				
No	157 (82,6%)	99 (83,9%)	256 (83,1%)	0,773
Yes	33 (17,4%)	19 (16,1%)	52 (16,9%)	
Total	190 (100,0%)	118 (100,0%)	308 (100,0%)	
Survival at day 1 - n (%)				
No	166 (87,4%)	108 (91,5%)	274 (89,0%)	0,258
Yes	24 (12,6%)	10 (8,5%)	34 (11,0%)	
Total	190 (100,0%)	118 (100,0%)	308 (100,0%)	
Survival at day 30 - n (%)				
No	181 (95,3%)	113 (95,8%)	294 (95,5%)	0,838
Yes	9 (4,7%)	5 (4,2%)	14 (4,5%)	
Total	190 (100,0%)	118 (100,0%)	308 (100,0%)	
Neurological status at day 30 - n (%)				
CPC = 1	6 (3,2%)	4 (3.4%)	10 (3,2%)	1
CPC ≠ 1	184 (96,8%)	113 (96.6%)	296 (96,1%)	
Total	190 (100,0%)	118 (100.0%)	308 (100,0%)	
Cause of death - n (%)				
Post-anoxic encephalopathy	10 (5,3%)	4 (3,4%)	14 (4,5%)	
Multiorgan failure	5 (2,6%)	2 (1,7%)	7 (2,3%)	
New cardiac arrest	4 (2,1%)	2 (1,7%)	6 (1,9%)	
Hypoxic cause	0 (0,0%)	0 (0,0%)	0 (0,0%)	
Total	19 (100,0%)	8 (100,0%)	27 (100,0%)	

Abbreviations: CPC score, cerebral performance category score. OHCA, out-of-hospital cardiac arrest. ROSC. return of spontaneous circulation;

Missing data: we provided the total for each variable to allow the identification of the missing data.

Discussion

This study provides a real-world evaluation of the implementation of a VFD within a mature prehospital system, revealing a clear divergence between protocolised recommendations and actual clinical practice, with utilisation remaining below 30% despite mandatory deployment. Among 166 consecutive OHCA managed jointly by firefighters and the MICU in 2024, the VFD was applied in only 48 cases (28.9%). These findings underscore that

the implementation of VFDs is shaped by multifactorial barriers that must be systematically identified and addressed in the design of future clinical efficacy studies to ensure both feasibility and methodological robustness. In keeping with established evidence on the adoption of novel technologies in emergency and prehospital care, this gradual uptake likely reflects a complex interplay between human factors, training exposure, operational workload, and broader system-level constraints.

Importantly, this study was designed as an implementation-focused evaluation rather than a clinical effectiveness trial. From this perspective, the observed utilisation rate is itself a key outcome, reflecting the real-world integration of the device into clinical workflows.

Exploratory outcome analyses suggested potential differences in ROSC and neurological outcomes. However, these findings are constrained by limited sample size, absence of covariate adjustment, and the observational nature of the study design, and should therefore be interpreted strictly as hypothesis-generating. Notwithstanding these limitations, a key strength of the study lies in its population-based design within a well-defined prehospital system, offering a comprehensive real-world assessment of device adoption under routine operational conditions. Moreover, the baseline comparability between groups supports the internal consistency and robustness of the dataset.

VFD use was not randomly assigned and may therefore reflect underlying differences in provider characteristics rather than a true device effect. Firefighters who utilised the VFD may have demonstrated higher protocol adherence, more recent training exposure, or greater engagement with high-quality CPR delivery. This form of selection bias is inherent to real-world implementation research and highlights the need for complementary randomized controlled evaluations to establish causal inference. Nevertheless, baseline patient characteristics and OHCA circumstances were broadly comparable between groups. In addition, survival rates in the non-VFD group were consistent with pre-implementation rates in 2022, with no major changes in prehospital practice over the study period (Table 4; Supplementary Tables 1 and 2).

In addition, VT and VR were not recorded, preventing assessment of guideline adherence. CPR duration, response times, and other prehospital interventions could not be evaluated due to a lack of data in this retrospective collection. User perceptions, device usability, and training coverage were also not formally assessed, which may have influenced adoption and effectiveness.

The interpretation of the utilisation rate is challenging, as no clear benchmarks exist for the adoption of MDs. It likely corresponds to the early stage of the S-shaped adoption curve [33–35].

In OHCA studies, full compliance is rarely achieved. For example, In a randomised trial of the LUCAS-2 device, only 60% of patients received mechanical CPR [36], despite typically higher adherence in trial settings [37]. In real-world settings, the use of mechanical CPR devices is more limited (<10%) with only modest increases over time [38].

The observed utilisation rate likely reflects an intermediate stage of adoption, in which the device is increasingly used but not yet fully integrated into routine practice, although direct comparisons remain limited. Identifying and addressing barriers to implementation is critical to ensure adequate adoption and valid evaluation. Failure to anticipate them may impede participant recruitment, compromise study feasibility, and bias assessment of the device's effectiveness.

Incomplete adoption results from the interaction of multiple determinants, from device-related factors to broader user-, environmental-, and organisational-level factors.

Regarding the device, deployment appeared feasible in a wide range of prehospital situations. No statistically significant differences in patient or scene characteristics were observed between CPR with or without the VFD. This suggests that obvious contraindications or systematic operational constraints are unlikely to explain the utilisation rate. However, this study was not designed to formally assess ergonomic or operational barriers. With respect to training, previous simulation-based studies indicated that the EOlife® VFD could be learned and operated rapidly [30]. Nevertheless, despite implementation one year earlier and standardised training with annual refreshers, some users may not have been trained, especially due to staff turnover.

Skill transfer from simulation to real-life resuscitation is complex. Adoption of new technologies is often slow, even when they have the potential to improve patient outcomes. This phenomenon is particularly pronounced in emergency medicine [39], and even more so in prehospital settings where environments are challenging and uncontrolled [40]. CPR is associated with substantial cognitive workload. Real-time feedback devices for ventilation or chest compressions can improve the quality of CPR but also increase cognitive load [41], which can represent a significant barrier to adoption of new technologies. In addition, behavioural responses and beliefs, such as avoidance or delayed initiation, rank among the top four factors influencing the implementation of new technologies and should be taken into account [40]. In prehospital settings with limited resources and challenging conditions, introducing new tools requires a careful, progressive implementation strategy.

Organisational factors such as system context, resource availability, and communication may also influence adoption of new practices and technologies [40].

These factors likely contributed to the utilisation rate observed here, despite prior implementation and training efforts.

Regarding the exploratory analysis, our results suggested a possible signal of clinical benefit. We observed an association that reached statistical significance for survival with a favourable neurological outcome ($p = 0.049$) although uncertainty remained due to wide confidence intervals. This imprecision likely reflects limited statistical power, and the findings should therefore be interpreted with caution and not as evidence of effectiveness. They highlight trends that could inform the design of future studies.

Idris et al., assessing ventilation quality using thoracic bioimpedance, reported a significant association between higher-quality ventilation and clinical outcomes in 1976 OHCA cases (a survival to hospital discharge of 13.5% versus 4.1% ($p<0.0001$), and a survival with favourable neurological outcome of 10.6% versus 2.4% ($p<0.0001$)) [42]. In our study, we did not have access to ventilation parameters and therefore could not assess the relationship between VFD use and ventilation quality.

Future studies should aim to simultaneously assess VFD use, ventilation quality, and clinical outcomes, as this represents a key methodological challenge. In a before-and-after study including 412 patients, Drennan et al. observed an improvement in the proportion of ventilation within recommended targets. However, they found no corresponding improvement in patient outcomes [26].

This challenge may be partly explained by the lack of standardization in key definitions and measurement techniques. Ventilation quality is generally defined as adherence to recommended VT and VR. However,

definitions vary across studies, with some considering both parameters simultaneously and others focusing on only one [22,24,30]. In addition, VT is often reported with or without accounting for mask leakage and is sometimes incorrectly equated with insufflated volume, which may substantially alter the estimation of effective ventilation.

How hyperventilation is defined might also be unclear. Hyperventilation is frequently reported in manikin [22,24,30] and in clinical studies [43–45]. Several factors have been associated with hyperventilation [46]. Hyperventilation, whether due to excessive pressure, volume, or rate, can induce gastric insufflation and increase intrathoracic pressure, leading to decreased venous return and cardiac output. It also causes hypocapnia and subsequent cerebral vasoconstriction, further reducing cerebral perfusion, and may be associated with worse outcomes [19,43,47–50].

However, hyperventilation is not always associated with adverse effects. A retrospective study of 337 adult patients resuscitated in a prehospital setting reported that hyperventilation occurred in 85.2% of cases but was not associated with outcomes [51].

Several mechanisms may explain this discrepancy. First, reduced lung compliance and alveolar collapse during CPR have been reported in both animal and clinical studies [52–54], which may influence the relationship between delivered and effective ventilation.

Technical factors should also be considered. In a prospective observational study examining ventilation during 30:2 CPR performed by BLS teams, the authors reported leakage with a median of 222 [160–261] mL [55]. Such leaks may partially reduce effective alveolar ventilation, suggesting a distinction between measured hyperventilation and effective alveolar ventilation.

Finally, as current guidelines are largely based on observational studies and expert consensus, thresholds for VT and VR remain not well defined. In addition to providing feedback, VFDs can record ventilation parameters, which may help refine ventilation targets [56].

In conclusion, this study highlights both the challenges and the potential value of evaluating medical devices in prehospital resuscitation. A medical device faces multiple barriers to implementation and use, and once adopted, its performance depends not only on its intrinsic properties but also on user skills, training, and care context, with additional constraints in time-critical settings such as OHCA.

The observed uptake, although incomplete, suggests that integration of the VFD into routine OHCA management is feasible and relatively substantial compared with other devices in similar settings. This may reflect both favourable device-related characteristics, such as ease of use and limited logistical burden, and growing awareness of the importance of ventilation quality during resuscitation.

Importantly, adherence to interventions is typically higher in prospective and randomised studies. Therefore, our results may represent a conservative estimate of the potential clinical impact of VFD use. Supported by robust implementation strategies and standardised ventilation assessment, future studies may better define whether VFDs can translate improved ventilation quality into meaningful clinical improvements.

Abbreviations

ALS: advanced life support.

AHA: American Heart Association.

BLS: basic life support.

Bpm: breaths per minute.

CI: confidence interval.

CPC: cerebral performance category.

CPR: cardiopulmonary resuscitation.

ERC: European Resuscitation Council.

$EtCO_2$: End Tidal CO_2.

ILCOR: International Liaison Committee on Resuscitation.

LUCAS: Lund University Cardiopulmonary Assist System.

MICU: Mobile Intensive Care Unit.

MD: medical device.

OHCA: out-of-hospital cardiac arrest.

OR: odds ratios.

ROSC: return of spontaneous circulation.

SD: standard deviation.

VFD: ventilation feedback device.

VR: ventilation rate.

VT: tidal volume.

Declarations

Ethics approval and consent to participate: the study was classified as not involving human participants under French Jardé law. As a result, neither institutional review board nor ethics committee approval was required. The study was performed in accordance with relevant guidelines: the Declaration of Helsinki, Good Clinical Practices, and national legislation.

Consent for publication: Not applicable.

Availability of data and materials: The data in this study are not publicly available, but reasonable requests can be made to the corresponding author.

Competing interests: Professor Khoury is the Medical Advisor for Archeon Medical and a patent holder for different medical devices.

Funding: none.

Authors' contributions: JBP: conceptualization, methodology, data curation, formal analysis, writing – original draft, writing – review and editing. MDC: investigation, data curation. SHI: writing – review and editing. LEP: investigation. AK: conceptualization, methodology, writing – review and editing, supervision.

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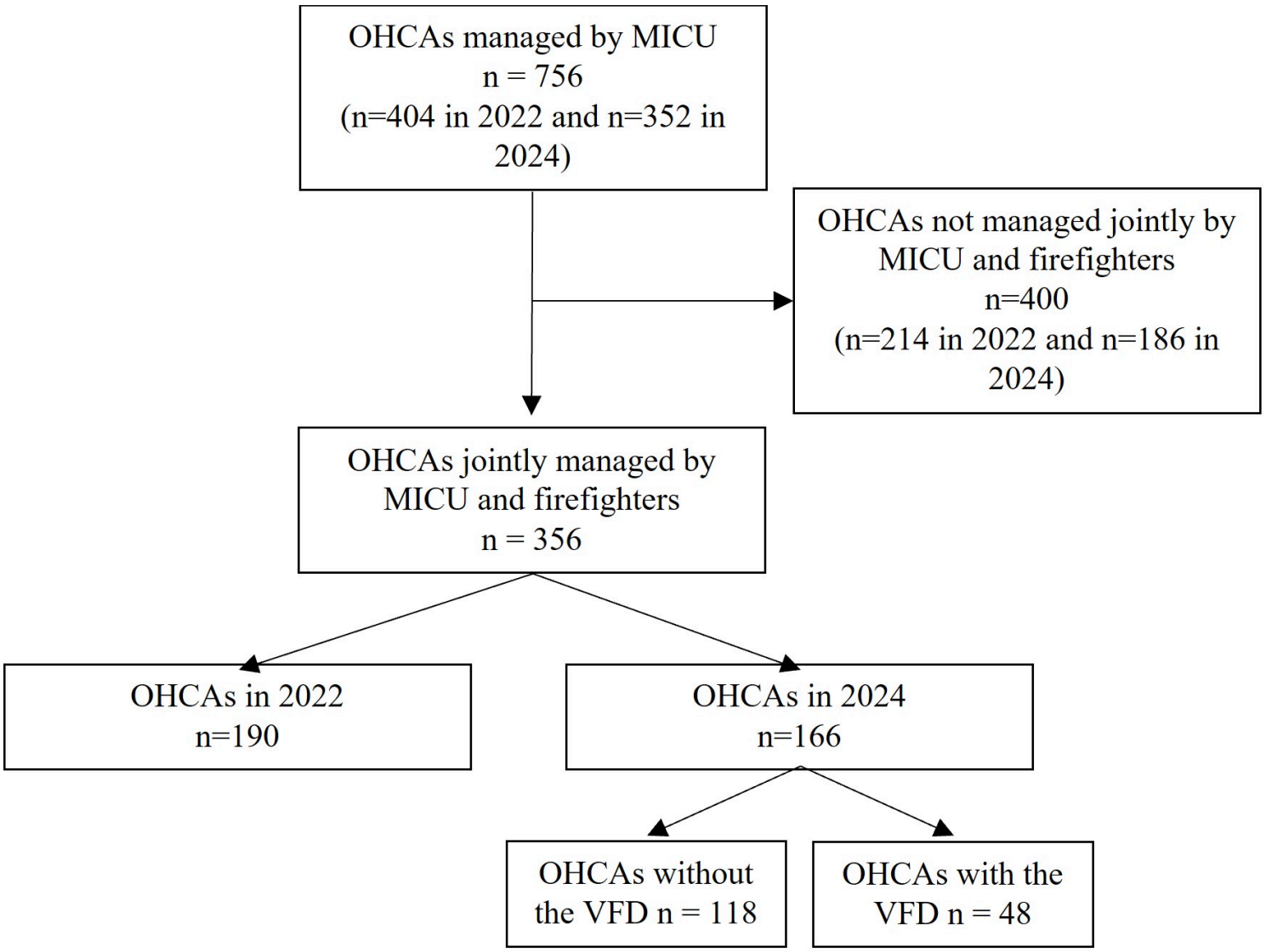
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Figures



Abbreviations: OHCAs, out-of-hospital cardiac arrest; MICU, mobile intensive care unit; VFD, ventilation feedback device

Figure 1

inclusion flowchart