Continuous Monitoring of Respiratory Rate with Wearable Sensor in Patients Admitted to Hospital with Pneumonia Compared with Intermittent Nurse-Led Monitoring in the United Kingdom: A Cost-Utility Analysis

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Abstract

Background Respiratory rate (RR) is one of the most important physiologic measures for predicting patients' deterioration of clinical condition and final prognosis. In several studies, RR has been the most important predictor of patients' prognoses.

Objectives The objective of this study was to conduct a cost-utility analysis to estimate the cost and effectiveness of automatic respiratory rate monitoring (ARRM) with a non-invasive sensor (RespiraSense™) plus intermittent nurse-led RR monitoring (ARRM strategy) compared with intermittent nurse-led RR monitoring (IM strategy) in patients admitted to hospital in the UK with pneumonia.

Methods A decision analytic model was developed based on a hypothetical cohort of patients who were admitted to hospital with pneumonia. After admission, the patients could be monitored with either ARRM or IM strategies. The outcomes of interest included total costs and total effectiveness of each strategy, including length of stay (LoS) in hospital, LoS in intensive care unit, quality-adjusted life-years (QALYs), deaths, and incremental cost per QALY gained. An incremental cost of £20,000 or less per QALY gained was considered cost effective. A lifetime time horizon (38 years) was used to capture the long-term benefits. Probabilistic and deterministic sensitivity analyses were performed.

Results Total costs of patient care in ARRM and IM strategies were £1986.9 million and £2079.4 million, respectively. Total incremental QALYs lived were 3548 higher in the intervention arm (ARRM), meaning that the ARRM strategy was dominant (i.e., less costly [£92.6 million less] and more effective). The results were stable in probabilistic and most of the deterministic sensitivity analyses. Results from threshold analysis indicated that a minimum of 7 and 10% improvement in percentage of early detection of respiratory compromise is required for ARRM to become cost effective and cost saving, respectively.

Conclusions Our results indicate that ARRM using RespiraSense, in addition to intermittent nurse-led monitoring of RR, in patients admitted to the hospital with pneumonia could be a cost-saving and cost-effective intervention if the minimum clinical thresholds are met.

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Key Points for Decision Makers

Conducting a clinical trial on automatic respiratory rate monitoring (ARRM) is recommended to narrow the gap in clinical evidence.

Our results indicate that ARRM in addition to nurse-led intermittent monitoring of respiratory rate is likely to be a cost-saving intervention compared with nurse-led intermittent monitoring alone.

Results from threshold analysis indicate that a minimum of 7 and 10% improvement in percentage of early detection of respiratory compromise is required for ARRM to become cost effective and cost saving, respectively.

1 Introduction

Lower respiratory infection (LRI) is one of the important contributors to mortality and morbidity in the UK. In 2019, around 42,000 deaths (more than 6.7% of all deaths) were due to LRIs [1]. Based on the global burden of disease study, the annual incidence of LRIs in the UK was around 4.1% in 2019 [2]. Among individuals who present to general practitioners with symptoms of LRI, 22–42% are admitted to hospital [3], and pneumonia is the most prominent LRI [4]. Between 1.2 and 10% of adults admitted to hospital with community-acquired pneumonia are managed in intensive care units (ICUs) and experience a high risk of fatality [3]. On the other hand, at any time, 1.5% of hospitalized patients in England have a hospital-acquired respiratory infection, more than half of which are hospital-acquired pneumonia [3].

Measuring vital signs is an important part of any physical examination, and monitoring of vital signs has been a standard practice for all patients admitted to hospitals to detect any deterioration of clinical condition [5]. This monitoring is conventionally a nurse-led intermittent measurement of vital signs through non-invasive devices. ‘Track and trigger’ systems, such as the National Early Warning Score (NEWS) are recommended for an appropriate response to important changes in the physiologic status of patients [6]. Although earlier detection and response to deteriorating conditions may lead to better clinical outcomes, it is affected by the quality and frequency of measurements of physiologic vital signs [7]. Alternative options for continuous physiologic monitoring, including bedside monitors and wearable sensors with wireless monitors, have been suggested to address the issues with frequency and quality of intermittent

monitoring [8, 9]. Wearable sensors for monitoring of vital signs are still developing. Most of the current devices are in different stages of validation and undergoing feasibility study [8, 10]. Based on a recent systematic review, clinical data are sparse, and cost data are lacking [8].

Respiratory rate (RR) is one of the most important physiologic measures for predicting patients’ deterioration of clinical condition and final prognosis. In several studies, RR has been the most important predictor of patients’ prognoses [11, 12]. As one of the criteria to stratify risk of mortality in patients with pneumonia, RR is used in risk stratification systems such as CURB65 and as a criterion for their safe discharge [13]. RespiraSense™ is a non-invasive, wireless, body worn, motion-tolerant, and continuous respiratory rate monitor [14]. It measures the mechanics of breathing by analysing the movements of the chest and abdomen using proprietary piezo film sensors [15].

The objective of this study was to conduct a cost-utility analysis to estimate the cost and effectiveness of automatic respiratory rate monitoring (ARRM) with RespiraSense plus intermittent nurse-led RR monitoring compared with intermittent nurse-led RR monitoring in patients admitted to hospital with pneumonia.

2 Methods

A decision analytic model was developed to assess the cost and effectiveness of each strategy. The model was built in Microsoft Excel and was based on a hypothetical cohort of patients who were admitted to hospital with the primary diagnosis of pneumonia. After admission, the patients could be monitored with either (1) intermittent nurse-led monitoring of RR and other physiologic vital signs in conjunctions with NEWS (comparator [IM strategy]) or (2) ARRM with RespiraSense (PMD Solutions, Cork, Ireland) in addition to the intermittent nurse-led monitoring of physiological vital signs in conjunction with NEWS (intervention [ARRM strategy]). The outcomes from the model included total cost and effectiveness of each strategy, including length of stay (LoS) in hospital, LoS in ICU, quality-adjusted life-years (QALYs), deaths, and incremental cost per QALY gained. A lifetime time horizon (38 years, from starting age [62 years] until age 100) was used in the model to capture the long-term benefits [16]. The incremental cost-effectiveness ratio (ICER) was compared with the cost-effectiveness threshold in the UK (i.e., £20,000 per QALY). The cost-effectiveness threshold is the maximum amount a decision maker is willing to pay for a unit of health outcome (QALY).

2.1 Model Structure

The decision analytic model comprised a decision tree followed by a Markov model with two health states: alive and dead. The model structure was informed by the available evidence, including the impact of respiratory compromise (RC) and its early detection and response on in-hospital and life-long mortality. The intra-hospital costs and benefits were estimated using the decision tree, and the long-term survival after discharge was estimated by the Markov model. The model structure is presented in Fig. 1. The cycle length in the Markov model was 1 year, and a half-cycle correction was implemented to estimate the outcomes.

Morris et al. [17] described RC as deterioration in respiratory function with a high probability of decompensation into respiratory failure or death; timely specific interventions in patients with RC might prevent or mitigate decompensation. The high mortality in patients with respiratory failure highlights the importance of planning for the detection of RC and instigating appropriate interventions before the development of respiratory failure [17]. Acute RC is defined as “absent, agonal or inadequate respiration that requires emergency assisted ventilation.” This assisted ventilation might be non-invasive (e.g., mouth-to-mouth, mouth-to-barrier

device, bag-valve-mask, continuous positive airway pressure or bi-level positive airway pressure) or invasive positive pressure ventilation through endotracheal or tracheostomy tube or laryngeal mask airway [18].

Patients with pneumonia entered the model after admission to hospital and are stratified to one of the two monitoring strategies (i.e., intervention or comparator). Patients with RC might be detected and managed rapidly or experience a delayed detection and response. Patients discharged alive then entered a Markov model, and the lifetime benefits and QALYs were estimated. The risk of death per cycle in the Markov model was estimated using UK life tables after adjustment for additional mortality among patients with a history of severe pneumonia [19].

2.2 Model Inputs

The main inputs in the model were incidence rate of RC, probability of early detection of RC in each arm, LoS in ICU and non-ICU wards, mortality rates without incidence of RC and with incidence of RC but with early or late detection, as well as the associated healthcare resource use and the health-related quality of life (i.e., health utility values) associated with different states in the model.

Fig. 1 Model structure; effects of continuous and intermittent monitoring of respiratory rate on respiratory compromise, early detection and response and mortality. IM intermittent nurse-led monitoring, NEWS national early warning system

2.2.1 Clinical Effectiveness Parameters

A targeted review was performed to collect evidence on the efficacy or effectiveness of using wearable sensors to monitor respiratory rates in patients with pneumonia. The references and citations of the included sources were also manually checked for relevant papers.

Table 1 summarizes the epidemiologic and clinical input parameters used in the model and their sources. We considered any adverse change that requires acute medical treatment as a sign of late detection and response; based on the study by Cavallini et al. [20] and our calculations, 70.3% of ‘late diagnosis and response’ in the IM group are attributable to the IM approach compared with the ARRM strategy as the counterfactual:

$$\text{Attributable fraction} = \frac{R_0 - R_1}{R_0} = \frac{0.64 - 0.19}{0.64} = 70.3\%$$

Based on our analysis of National Health Service (NHS) data, there is a 65.3% early detection of RC and response in the IM strategy (or 34.7% late detection and response). The late detection rate, which is attributable to using IM (and is preventable by using ARRM) = $(100\% - 65.3\%) \times 70.3\% = 24.4\%$

The early detection of RC and response in the ARRM strategy would be 89.7% (65.3% + 24.4%).

This is also aligned with a study that used RespiraSense in a group of patients with infectious respiratory disease in a tertiary hospital in Dublin (Ireland). The study showed that an increased RR had a hazard ratio of 1.8 (95% confidence interval 1.05–3.70) for desaturation in the next 12 h [15]. Because of the limited clinical data for effectiveness of ARRM (and RespiraSense) compared with IM, an effectiveness threshold analysis was performed to understand the robustness of results based on variation in the effect size.

There is no specific code for RC in the *International Classification of Diseases, Tenth Edition* (ICD-10) or previous versions, and it is a relatively new concept in the management of respiratory conditions [17]. We used a combination of Office of Population Censuses and Surveys (OPCS) [21] interventions or procedures as a surrogate for RC in patients with pneumonia. There might be arguments against this method, but we tried to choose all codes that reflected any response (early or delayed) to “absent, agonal or inadequate respiration”; although a patient with RC may be missed in the early stages, eventually they will need emergency assistance. It appears unlikely that a hospitalized patient with RC would proceed to death without receiving any of the interventions/procedures listed in our definition. There might be mild cases who get better without any medical intervention.

Table 1 Summary of epidemiologic and clinical input data

Epidemiologic and clinical input data settings	Value	95% CI	Distribution	References
Total number of pts (admitted to hospital with pneumonia)	418,113		Fixed	[26]
Incidence of RC in target population	7.3%	7.2–7.4	Beta	[26]
% of early detection of RC and response—ARRM strategy	89.70%	88.98–90.48	Beta	[20, 26]
% of early detection of RC and response—IM strategy	65.3%	64.7–65.8	Beta	[26]
In-hospital mortality among pts with pneumonia and no RC	15.8%	15.7–15.9	Beta	[26]
In-hospital mortality in case of delayed detection of RC and response	29.8%	28.9–30.7	Beta	[26]
In-hospital mortality in case of early detection of RC and response	24.0%	23.4–24.6	Beta	[26]
LoS in hospital ward (day) with pneumonia and no RC	6.7	6.7–6.8	Gamma	[26]
LoS in ICU (day) with pneumonia and no RC	0.9	0.9–0.9	Gamma	[26]
LoS in hospital ward (day) in case of delayed detection of RC and response	17.4	16.9–17.8	Gamma	[26]
LoS in ICU (day) in case of delayed detection of RC and response	13.4	13.0–13.8	Gamma	[26]
LoS in hospital ward (day) in case of early detection of RC and response	16.5	16.2–16.9	Gamma	[26]
LoS in ICU (day) in case of early detection of RC and response	5.7	5.6–5.8	Gamma	[26]
Post-discharge SMR ^a —male	2.9	2.1–3.7	Lognormal	[19]
Post-discharge SMR ^a —female	2.1	1.3–2.8	Lognormal	[19]
Health utility pre discharge (pts with ARDS in the UK using EQ-5D)	0.56	0.52–0.61	Beta	[27]
Health utility in ICU	0.00	0.0–0.0	Beta	Assumption
Health utility post-discharge (pts with pneumonia in the Netherlands using EQ-5D)	0.74	0.67–0.89	Beta	[23]

ARDS acute respiratory distress syndrome, ARRM automatic respiratory rate monitoring, CI confidence interval, ICU intensive care unit, IM intermittent nurse-led RR monitoring, LoS length of stay, NHS national health service, *pt(s)* patient(s), RC respiratory compromise, RR respiratory rate, SMR standardized mortality ratio

^aAssumed similar in intervention and comparator groups

We defined acute RC as the presence of at least one of the following OPCS codes in patients with pneumonia: E85.1 (invasive ventilation, including endotracheal intermittent positive pressure ventilation), E85.2 (non-invasive ventilation), E85.3 (improving efficiency of ventilation), E85.4 (bag-valve-mask ventilation), E85.5 (nebuliser ventilation), E85.8 (other specified), E85.9 (unspecified), E89 (other respiratory support), X52.1 (hyperbaric therapy), X52.8 (other specified oxygen therapy), X52.9 (unspecified oxygen therapy), X56 (intubation of trachea), X56.1 (nasotracheal intubation), X56.2 (endotracheal intubation, excluding endotracheal intubation as part of general anaesthesia), X56.3 (tracheal intubation using laryngeal mask airway), X56.8 (other specified intubation of trachea), X56.9 (unspecified intubation of trachea), and E58.1 (extracorporeal membrane oxygenation).

We assumed that E85.1, X56, X56.1, X56.2, X56.3, X56.8, X56.9, and X58.1 are procedures that represent a delayed response to RC. The delay might be due to late referral of the patient to hospital, delayed in-hospital detection of RC, or delayed response. Other OPCS codes reflect an early detection and response of RC unless they are accompanied with one of the delayed response codes.

For effects of the intervention on reducing percentage of delayed detection and response of RC, we used the study by Cavallini et al. [20], which is related to effects of continuous monitoring on patients admitted with stroke. We assumed that continuous monitoring of respiratory rate in patients

admitted with pneumonia through our intervention would have the same effect on reducing delayed detection.

There is no report of any moderate or severe adverse events associated with using RespiraSense for patients; therefore, we assumed no adverse events in our analysis.

2.2.2 Health Utilities

The health utility weights used in the model were based on published values and are summarized in Table 1 [22, 23].

2.2.3 Costs

The following costs were included in the model: cost of the intervention (i.e., RespiraSense device), costs of inpatient care, and costs of management of RC with early and delayed response. Costs were measured in UK £ for the year 2019. All costs are considered from an NHS and Personal Social Services perspective. All information and costs associated with the RespiraSense were provided by the company who manufactures the technology [24]. Additional information on costs of staying in ICU and non-ICU wards and costs associated with delayed response to RC were derived from NHS reference costs [25]. Input data on unit costs and resource use are summarized in Table 2. The recommended discount rate in the UK (i.e., 3.5% per annum) was used for both costs and benefits [16].

Table 2 Unit cost and resource use input data for RespiraSense in patients with pneumonia admitted in UK hospitals

Cost and resource use inputs	Value	95% CI	Distribution	Reference
Unit cost of excess days in general wards	290	261–319	Gamma	[25]
Unit cost of hospital stay in ICU per day	1958	1878–2039	Gamma	[27] ^a
Unit cost of delayed detection and response	1290	1161–1419	Gamma	[25]
Estimated average cost of RespiraSense per pt	76	76–76	Fixed	[24]
Number of hospitals	152	152–152	Fixed	NHS
Number of disposable sensors per pt (at any time of monitoring)	1	1–1	Fixed	[24]
Number of lobe(s) required for each pt (at any time of monitoring)	1	1–1	Fixed	[24]
Sensor life before requiring replacement (h)	168	168–168	Fixed	[24]
Disposable wearable sensor cost	35	35–35	Fixed	[24]
Average used lobes (at any time of installation of programme)	80%	80–80	Fixed	[24]
Kit (lobes) list price	5000	5000–5000	Fixed	[24]
Number of lobes per each kit	6	6–6	Fixed	[24]
Minimum use life of lobes (year)	5	5–5	Fixed	[24]
Amortization rate	20%	20–20	Fixed	[24]
Installation and test (server) per hospital	4800	4800–4800	Fixed	[24]
Local bluetooth network and server connection cost per hospital	7200	7200–7200	Fixed	[24]

Costs and resource use inputs are presented as £ unless otherwise indicated

CI confidence interval, ICU intensive care unit, NHS National Health Service, pt patient

^aInflated to 2019 values

2.3 Analysis

Considering our model structure (Fig. 1), the cumulative costs and effectiveness were estimated for each of the two strategies. Both probabilistic and deterministic sensitivity analyses (PSA and DSA, respectively) were conducted to explore uncertainty in input data and other forms of uncertainty surrounding the estimates from the base-case analysis. We conducted DSA to investigate the impact of key assumptions and parameter values used in the base-case analysis and how the results and conclusions changed when the values of these parameters were varied.

We conducted PSA using Monte Carlo simulation to estimate the parameter uncertainty. Probabilistic distributions were assigned to each input variable in the model and were used to randomly select a new plausible value in each iteration. Each new sampled value was applied in the model, and the new results of the model were recorded. This process was repeated for 10,000 iterations to produce an uncertainty interval for the outputs. The 250th and 9750th ranked outputs were used as the lower and upper limit of the interval, respectively.

Results are presented in the form of a cost-effectiveness plane, and the probability of each option being cost effective across a range of willingness-to-pay values is explored via cost-effectiveness acceptability curves (CEACs). Cost-effectiveness threshold analysis showed the minimum effect size of ARRM to be a cost-effective or cost-saving strategy compared with IM.

3 Results

Considering 418,113 adult patients admitted to NHS hospitals with pneumonia (2018–2019 cohort), total costs of patient care in ARRM and IM strategies were £1986.9 million and £2079.4 million, respectively. Total incremental QALYs lived were 3548 higher in the intervention arm (ARRM), meaning that the intervention was a dominant strategy (i.e., less costly [£92.6 million less] and more effective). The results were stable in PSA and most of the scenarios in the DSA. Table 3 summarizes the different cost items and clinical effects and consequences under the two different strategies.

To assess the effects of uncertainty in input data, we performed both DSA and PSA. Figure 2 demonstrates the cost-effectiveness plane and CEAC; the probability of being cost effective for a willingness to pay of £20,000 per QALY is 100%.

The most important drivers of cost effectiveness were the percentage of early detection of RC and response among the comparison groups. This is the only input that could change the incremental cost to a positive number, i.e., higher costs in the ARRM strategy (Figs. 3 and 4). Results from the cost-effectiveness threshold analysis indicated that a minimum of 7 and 10% improvement in percentage of early detection of RC would be required for ARRM to become cost effective and cost saving, respectively (Table 4). Figure 4 shows the net monetary benefit in

Table 3 Costs and clinical effects/consequences of using ARRM strategy compared with IM strategy in patients admitted to hospital with pneumonia

	IM strategy ^a	ARRM strategy ^b	Incremental Δ
Cost items ^c			
Cost of RespiraSense	0.0	31.7	31.7
Total costs of ICU stays	1159.1	1046.3	−112.8
Total costs of non-ICU ward stays	906.6	904.8	−1.8
Total costs delayed detection and response	13.7	4.1	−9.6
Total costs	2079.4	1986.9	−92.6
Total costs per patient (£)	4973.4	4752.0	−221.4
Clinical effects/consequences			
Total deaths	69,180	68,747	−433
Total LoS in ICU	592,129	534,494	−57,635
Total number of delayed detection and response	10,604	3144	−7461
Total life-years lived	3,921,669	3,926,464	4795
Total QALYs lived	2,892,263	2,895,811	3548
Total life-years lived per patient	9.379	9.391	0.011
Total QALYs lived per patient	6.917	6.926	0.008

ARRM automatic respiratory rate monitoring, ICU intensive care unit, IM intermittent monitoring, LoS length of stay, QALY quality-adjusted life-year

^aIM + NEWS

^bARRM + IM + NEWS

^cCost items are presented in millions of £ unless otherwise indicated

Fig. 2 Incremental costs (£) per QALY and cost-effectiveness acceptability curve: ARRM + IM vs. IM in patients admitted to hospital with pneumonia, probabilistic sensitivity analysis. *ARRM* automatic

respiratory rate monitoring, *IM* intermittent monitoring, *NEWS* National Early Warning System, *QALY* quality-adjusted life-year, *WTP* willingness to pay

Fig. 3 Incremental costs of using ARRM + IM vs. IM in patients admitted to hospitals with pneumonia; deterministic sensitivity analysis. *ARRM* automatic respiratory rate monitoring, *ICU* intensive care

unit, *IM* intermittent monitoring, *LoS* length of stay, *NEWS* National Early Warning System, *RC* respiratory compromise, *SpO₂* oxygen saturation

different scenarios in the DSA. We also ran the model having changed the probability of early detection and response in the comparator group to 50.0% (based on a different data source) [28] and 74.4% in the intervention group. In this scenario, the incremental costs changed to -£92.3 million, and the ICER was still dominant in favour of the ARRM strategy.

4 Discussion

In this study, the costs and clinical effectiveness of the current strategy of nurse-led intermittent monitoring of respiratory rates (IM strategy) were compared with a new strategy of adding RespiraSense for continuous monitoring

Fig. 4 NMB (£) of using ARRM + IM vs. IM in patients admitted to hospitals with pneumonia; deterministic sensitivity analysis. *ARRM* automatic respiratory rate monitoring, *ICU* intensive care unit, *IM*

intermittent monitoring, *LoS* length of stay, *NEWS* National Early Warning System, *NMB* net monetary benefit, *RC* respiratory compromise, *SpO₂* oxygen saturation

of RR in patients admitted to hospital with pneumonia (ARRM strategy). Based on our model, the new strategy (ARRM) was less costly and more effective and could be considered a dominant strategy with current estimations of clinical effectiveness. The extra cost of RespiraSense (£31.7 million for the total target population) would be compensated through reducing the direct costs of patient care, especially costs associated with ICU admissions. The effectiveness threshold analysis indicated that a minimum of absolute 7 and 10% improvement in percentage of early detection of RC would be required for ARRM to become cost effective and cost saving, respectively. These thresholds could be used to design subsequent clinical studies to measure the effects of ARRM compared with the IM strategy.

Delayed detection and response to clinical deterioration of patients admitted to hospital wards and emergency care units is common [29]. Faster response to deteriorating patient conditions reduces severe outcomes such as cardiopulmonary arrest and death [30]. The new strategy would help healthcare staff recognize early changes in respiratory rate [14, 29], which is the most important indicator for predicting patients' outcomes [12]. Rapid response teams are usually fed by information from the traditional intermittent monitoring systems and NEWS; using devices such as RespiraSense for continuous monitoring could provide extra time for healthcare staff and rapid response teams to intervene more quickly in earlier stages to increase their efficiency.

In addition to the studies that we used to source the input data, other studies have demonstrated the clinical efficacy

of continuous monitoring in different settings and different clinical outcomes [31–33]. Also, other economic studies have supported using portable sensors as a cost-effective intervention for continuous monitoring of vital signs in patients in other settings, such as surgical wards [34].

Watkinson et al. [35] used a portable multiparameter monitor device for mandated electronic physiologic monitoring (including RR and respiratory pattern) of a high-risk group of medical and surgical patients. Although the device detected physiologic abnormalities, the study did not show any benefit from the mandated monitoring compared with usual monitoring.

The authors concluded that when detecting an abnormal physiology does not instigate an appropriate and effective intervention (for any reason, such as shortage of healthcare staff), we would not be able to gain the benefits [35]. When early detection of deteriorating clinical conditions through continuous monitoring is not accompanied by planned responses, it does not necessarily translate into reductions in ICU transfers, LoS, or incidence of other in-hospital adverse events [9, 35]; proper responses should be planned in advance (i.e., through local protocols and patient pathways) to gain the most benefit from implementing continuous monitoring devices such as RespiraSense.

The coronavirus disease 2019 (COVID-19) pandemic and surge of respiratory cases around the world, including in the UK, revealed the vulnerability of hospital systems, even in high-income countries. Interventions such as ARRM, with effects on reducing the LoS in hospital and ICUs, could increase the efficient use of finite health resources. In addition to appropriate respiratory monitoring of multiple

Table 4 Incremental cost and incremental cost-effectiveness ratio based on the effectiveness threshold analysis (early detection and response using IM = 65%)

	Improvement in early detection and response (%)	Early detection and response using ARRM (%)	Incremental cost per patient	Total incremental cost	ICER
1	66	66	67.8	28,359,452	299,348
2	67	67	59.9	25,042,571	132,169
3	67	67	52.0	21,725,689	76,442
4	68	68	44.0	18,408,807	48,579
5	69	69	36.1	15,091,926	31,861
6	69	69	28.2	11,775,044	20,715
7	70	70	20.2	8,458,163	12,754
8	70	70	12.3	5,141,281	6784
9	71	71	4.4	1,824,400	2140
10	72	72	-3.6	-1,492,482	Dominant
11	72	72	-11.5	-4,809,364	Dominant
12	73	73	-19.4	-8,126,245	Dominant
13	74	74	-27.4	-11,443,127	Dominant
14	74	74	-35.3	-14,760,008	Dominant
15	75	75	-43.2	-18,076,890	Dominant
16	76	76	-51.2	-21,393,772	Dominant
17	76	76	-59.1	-24,710,653	Dominant
18	77	77	-67.0	-28,027,535	Dominant
19	78	78	-75.0	-31,344,416	Dominant
20	78	78	-82.9	-34,661,298	Dominant
21	79	79	-90.8	-37,978,180	Dominant
22	80	80	-98.8	-41,295,061	Dominant
23	80	80	-106.7	-44,611,943	Dominant
24	81	81	-114.6	-47,928,824	Dominant
25	82	82	-122.6	-51,245,706	Dominant
26	82	82	-130.5	-54,562,587	Dominant
27	83	83	-138.4	-57,879,469	Dominant
28	84	84	-146.4	-61,196,351	Dominant
29	84	84	-154.3	-64,513,232	Dominant
30	85	85	-162.2	-67,830,114	Dominant

ARRM automatic respiratory rate monitoring, ICER incremental cost-effectiveness ratio, IM intermittent monitoring

patients with COVID-19, RespiSense reduces the need for personal protective equipment, as stated by the Ireland Health Service [36].

4.1 Limitations

Studies on the efficacy and effectiveness of continuous monitoring of RR in general and for RespiSense, specifically, are limited. We used currently available evidence to inform the model; however, the analysis will benefit from more original studies, especially clinical trials. We used NHS real-world data as the source of frequency of early or delayed detection and response to RC. We had to use some assumptions for this purpose; however, we tested different options in the sensitivity analysis, and the results were not game changing in most of the scenario analyses. To make the results from this study

more informative, we conducted an effectiveness threshold analysis to identify the minimum improvement in early detection rate of RC that would make ARRM a cost-effective or cost-saving strategy. Results from any new potential clinical studies could be compared with our findings to inform future decision making.

We did not include indirect costs such as costs of productivity loss and litigation costs, which means the estimated cost savings could be higher. We also did not include electricity costs for charging RespiSense lobes, as we found them negligible compared with the other costs.

5 Conclusion

Our results indicated that ARRM using RespiraSense, in addition to intermittent nurse-led monitoring of RR, in patients admitted to hospital with pneumonia could be a cost-saving and cost-effective intervention if the minimum clinical thresholds are met. Further clinical studies could reduce the uncertainty around the estimated cost-effectiveness results.

Declarations

Funding This analysis was funded by PMD Solutions. Apart from its role in providing unit cost data regarding the RespiraSense and sharing some of the information on similar products, the funder did not have any role in the identification, design, conduct, or reporting of the analysis.

Conflicts of interest Optimax Access (MML, MJ, and AM) and Device Access Ltd (JA) received funds from PMD solutions during the conduct of the study.

Author contributions MML and MJ were responsible for developing and populating the economic model and drafting the first version of the manuscript. All authors provided inputs for the model and read and approved the final draft of the manuscript.

Availability of data and material All of the data supporting the findings of this study are available within the article.

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent to publication All authors provided inputs for the model, read, and approved the final draft of the manuscript.

Code availability The model was submitted to the reviewers during the review process and could be available through direct contact with PMD Solutions.

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