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Multi-criteria risk evaluation model for developing ventilator-associated pneumonia

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Abstract

Ventilator-associated pneumonia is a hospital-acquired infection of the lungs occurring in mechanically ventilated patients. An active risk management approach can prevent the occurrence of the disease and promote positive organizational changes, subsequently decreasing mortality and hospitalization costs. Using scientific and clinical practice knowledge, a risk evaluation model was developed to identify patients more at risk of developing the disease. For this purpose, a Decision Expert qualitative multi-criteria decision method was used, in which alternatives are evaluated according to predetermined hierarchically arranged criteria. Characteristics of each evaluated alternative are described by the members of an interdisciplinary expert team and are represented by the values of the basic criteria. Values of hierarchically higher aggregated criteria are computed in an upwards fashion according to utility functions, which are defined as simple logical rules. This method is integrated into a software solution, DEXi. The approach is applicable to vastly diverse decision problems and has been successfully used before for health-related decision support. The designed model was tested using actual clinical data. Evaluations of alternatives that most distinctly demonstrated the functionality of the evaluation model were selected and are presented in the results. The evaluation model is intended to assist a holistic evaluation of the risk of developing ventilator-associated pneumonia, by considering patient-related risk factors and the use of preventive measures. The model incorporates nursing-specific data that have hitherto been poorly utilized in preventing ventilator-associated pneumonia and promotes the active engagement of nurses in confronting this interdisciplinary healthcare problem, which has gained more prominence with the onset of COVID-19 disease.

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1 Introduction

Ventilator-associated pneumonia (VAP) is one of the most common infections in intensive care units, followed by urinary tract infections and bloodstream infections associated with central venous catheters (Dasgupta et al. 2015). An infection of the lungs that develops at least 48 h after endotracheal intubation is classified as VAP (Gupta et al. 2018; Feng et al. 2019). It is a serious complication of treatment, associated with increased mortality of intubated patients. A large-scale record analysis study that included 4479 patients estimated that, in intensive care units, somewhere between 1.6 and 7.0% of deaths on day 30 and between 2.5 and 9.1% of deaths on day 60 could be attributed to VAP (Bekaert et al. 2011). Estimated reports of mortality attributed to VAP range from 20 to 76%, while VAP mortality related to resistant bacteria is estimated even higher. Reasons for the discrepancies could be a lack of uniform methodological research approaches and of rigorous diagnosis protocols (Joseph et al. 2010). Additionally, VAP infections contribute to higher costs, associated with prolonged stay in intensive care units of about five to 7 days (Hillier et al. 2013).

Besides clinical examination, the monitoring of specific biomarkers such as C-reactive protein (CRP) and procalcitonin (PCT) (Póvoa et al. 2016; Luyt et al. 2008) has been employed in VAP surveillance for accurate and timely diagnosis. Analysis of the data gathered by electronic documentation systems offers a novel approach to monitoring various hospital-acquired infections (Cato et al. 2015). Parameters such as minute-to-minute ventilator settings, antibiotic use, microbiology data and clinical characteristics can be used in electronically supported VAP surveillance (Klein Klouwenberg et al. 2014).

The usefulness of clinical data could be maximized with data-driven active risk management in VAP prevention, since a comprehensive evaluation of risk could contribute to lowering the incidence of the illness. The management of risk and resulting decisions must be derived from the existing evidence and knowledge (Aven 2016), which in our case represents a multi-criteria decision problem. To estimate the risk of developing VAP, patient-related factors and environmental factors need to be considered. This is typically a daily decision made by healthcare workers, but is based on non-systematized knowledge, is not reliable and is hard to justify. Furthermore, a holistic evaluation of risk is a complex process, to the extent that evidence-based, reliable and continuous risk management is normally beyond the capabilities of individual healthcare workers. A decision support system could help them improve the quality, consistency and transparency of decisions.

In this study, we used multi-criteria knowledge modelling to tackle this decision problem. Multi-criteria decision making is a widely applicable approach in operational research. In this method, a decision model is used to evaluate, rank and/or compare alternatives based on predetermined criteria (Korhonen et al. 1992). Because of the qualitative nature of our decision problem and our familiarity with the methodological approach, the Decision Expert (DEX) (Bohanec et al. 2013) method, integrated into

a software solution, DEXi (Bohanec 2008), was used to create a decision model to provide complete and transparent support to the decision-maker. This approach and the software solution have been used before for nursing-related patient health evaluation (Šušteršič et al. 2009) and were also successfully utilized for diverse decision situations in other fields (Pavlovic et al. 2011; Čampelj et al. 2019).

This study aims to present a decision model that combines clinical and contemporary scientific knowledge. Using clinical data, this study also illustrates how the model can be implemented and demonstrates the potential utility of this type of approach in various clinical environments. Additionally, the decision model incorporates previously poorly utilized nursing-specific data, to promote cooperation between nursing science, respiratory physiotherapy and medical science professionals in VAP prevention. In so doing, we hope to encourage the interdisciplinary cooperation that is needed for tackling complex modern healthcare problems.

2 Methods

A literature review was conducted to identify the most important preventive measures and risk factors related to VAP. Using the review results and knowledge from clinical practice, a risk evaluation model based on the DEX method was developed by a five-member research group consisting of intensive care nurse practitioners, nursing science experts and DEX method experts.

The DEX method follows the multi-attribute utility theory. It is based on resolutions of multiple small problems to resolve a far more complex decision problem (Greco et al. 2016). The set of attributes $X = \{x_1, x_2, \ldots, x_n\}$ is a finite set of n attributes. The decision model can be represented as a hierarchical structure of attributes of two kinds, namely basic and aggregated. Basic attributes have no sub-attributes, whereas each aggregated attribute has two or more sub-attributes. The highest aggregated attribute represents the final evaluation of each alternative.

The DEX method is characterized as qualitative multi-attribute decision support with rule-based utility functions. Both of these characteristics are crucial for addressing the VAP issue.

The characteristics of alternatives are evaluated according to attributes with qualitative–descriptive discrete valued domains. D_i represents a domain value of attribute x_i. It is a finite set of two or more discrete values $D_i = \{d_{i1}, d_{i2}, \ldots, d_{ij}\}$. Its values are arranged from the most to the least desirable, according to the nature of the decision problem: $\forall\, p<q,\ d_{ip}\ P\ d_{iq}$, where P is the preference function of two parameters, so that $d_{ip}\ P\ d_{iq}$ indicates that d_{ip} is preferred to d_{iq}. Because elements in a set D are arranged according to preference, attributes can be called criteria.

The set of alternatives $A = \{a_1, a_2, \ldots\}$ is potentially infinite and alternatives may be added after the model construction is finished. This means that the model may be used to assess new alternatives that were not known during the model construction phase.

An alternative $a \in A$ is described by a vector of n values, where each value corresponds to a different criterion from X:

$$\vec{a} = (d_1, d_2, \ldots, d_n)$$

where $d_i \in D_i$.

Each alternative is assessed by experts according to the basic criteria—criteria in a tree of criteria that do not have any sub-criteria. On the other hand, values of other criteria—aggregated criteria—are computed following predetermined utility functions, which are defined by a set of if–then rules for each aggregated criterion separately. To illustrate these rules, let us consider an aggregated criterion x_1, which has two sub-criteria x_2 and x_3 with their respective domain values D_1, D_2 and D_3, with their cardinalities x, y and z respectively. There are $y * z$ combinations and each is represented by a simple if–then rule in the form:

$$IF\ value(x_2) = d_2\ AND\ value(x_3) = d_3\ THEN\ value(x_1) = d_1$$

where $d_i \in D_i$.

Such rules are simple to understand and cover all combinations of domain values of sub-criteria. This differs from the usual weighting sum models in that the weights of the criteria are not fixed but may depend on the values of the criteria. This means that, if one sub-criterion has a large negative value, its weight may be 100%, whereas its weight may be far less in other combinations. In the present proposed solution, this was achieved by defining individual decision rules by experts expressing their scientific and practical knowledge of relationships among criteria. The software solution used aids experts by suggesting outcomes of rules and by underlining logically mismatched rules, based on the fact that all criteria have sorted domain values from the best to the worst (Mihelčić and Bohanec 2016).

Similarly, the values of the aggregated criteria of the higher order are computed towards the root of the tree, based on the values of subordinated criteria.

The method described is included in a Microsoft Windows-based software called DEXi, which was downloaded from the author's website to use in our study (Bohanec 2017).

For the study, empirical data were collected to aid experts in determining the utility functions of the evaluation model and to identify any design flaws. At the model testing stage, the required data for the VAP risk evaluation of 19 patients were collected, to analyse the functioning of the model in an actual clinical environment. Data were gathered in five intensive care units. The complete intensive nursing care records included all data necessary for the evaluation of VAP risk according to the model here presented. However, to avoid obtaining any superfluous patient data, only the necessary data were duplicated, documented separately and forwarded for analysis. This was done on a two-page form, which contained no personal patient data. Ethical approval for the conduct of this study was obtained beforehand.

Criterion	Domain Values
RISK OF VAP	***Min Susc***; Less susc; Susceptible; More susc; High susc; **V-High susc**
├─**PREVENTIVE MEASURES**	***Min Susc***; Less susc; Susceptible; More susc; **High susc**
│ ├─**Cuff leakage prevention**	***Min Susc***; Less susc; Susceptible; More susc; **High susc**
│ │ ├─Subglottic drainage	***Min Susc***; Less susc; More susc; **High susc**
│ │ ├─Cuff pressure management	***Less susc***; Susceptible; **More susc**
│ │ └─Oral care	***Min Susc***; Less susc; Susceptible; More susc; **High susc**
│ ├─**Gastroesophageal reflux prevention**	***Min Susc***; Less susc; Susceptible; More susc; **High susc**
│ │ ├─Enteral feeding protocol	***Less susc***; Susceptible; **More susc**
│ │ └─Patient positioning	***Min Susc***; Less susc; More susc; **High susc**
│ └─**Airway management**	***Min Susc***; Less susc; Susceptible; More susc; **High susc**
│ ├─Endotracheal aspiration	***Less susc***; Susceptible; **More susc**
│ └─Respiratory physiotherapy	***Less susc***; Susceptible; More susc; **High susc**
└─**PATIENT RELATED CRITERIA**	***Min Susc***; Less susc; Susceptible; More susc; **High susc**
├─**Intubation**	***Min Susc***; Less susc; Susceptible; More susc; **High susc**
│ ├─Number of days intubated	***Min Susc***; Less susc; Susceptible; More susc; **High susc**
│ └─Intubation circumstances	***Less susc***; Susceptible; **More susc**
├─**Microaspiration susceptibility**	***Min Susc***; Less susc; Susceptible; More susc; **High susc**
│ ├─**Oral health**	***Min Susc***; Less susc; Susceptible; More susc; **High susc**
│ │ ├─Oropharyngeal aspirate	***Less susc***; Susceptible; More susc; **High susc**
│ │ ├─Oral cavity status	***Less susc***; Susceptible; More susc; **High susc**
│ │ └─Oral care conditions	***Less susc***; Susceptible; More susc; **High susc**
│ └─**Cuff leakage**	***Min Susc***; Less susc; Susceptible; More susc; **High susc**
│ ├─Tube irritation	***Less susc***; Susceptible; More susc; **High susc**
│ ├─Subglottic secretions	***Less susc***; Susceptible; **More susc**
│ └─Gastroesophageal reflux	***Min Susc***; Less susc; Susceptible; More susc; **High susc**
└─**Health status**	***Min Susc***; Less susc; Susceptible; More susc; **High susc**
├─Age	***Min Susc***; Less susc; Susceptible; More susc; **High susc**
├─Gender	***Less susc***; **More susc**
└─Immunodeficiency	***Less susc***; Susceptible; **More susc**

Fig. 1 Tree of criteria for evaluating VAP risk for a specific patient, with assigned domain values

3 Model description

The evaluation model consists of 18 basic and 11 aggregated criteria. The hierarchical structure of the proposed model, which takes the form of a tree, with assigned domain values for individual criteria, is presented in Fig. 1.

The multi-criteria evaluation model consists of two sections. One section describes preventive measures that should be employed to lower the risk of VAP according to contemporary guidelines and recommendations. The other section of the model is focused on a patient and covers risk factors that, according to the scientific literature, contribute to an increased risk of developing VAP. A holistic evaluation of both the implemented preventive measures and the risk factors associated with an individual patient delivers a general estimation of the risk of developing VAP.

3.1 Criteria selection

Preventing cuff leakage is vital for the minimization of micro-aspirations and is therefore mentioned in numerous recommendations and VAP prevention care bundles (Hellyer et al. 2016). Commonly recommended strategies include subglottic drainage, cuff pressure monitoring (Akdogan et al. 2017) and comprehensive oral care. Oral care with antiseptics is a well-established strategy in VAP prevention that aims to minimize the chance of oropharyngeal aspiration (Haghighi et al. 2017). Similarly, the possibility of aspirating gastric secretions needs to be minimized. The scientific literature

suggests that the likelihood of gastric reflux can be lowered with early and safe enteral feeding protocols (Elke et al. 2019). Another fundamental measure in VAP prevention is patient positioning, with the suggested head-of-bed elevation between 30° and 45°, unless medically contraindicated (Álvarez Lerma et al. 2014; Najafi Ghezeljeh et al. 2018). Additional measures for preventing lung infections in intubated patients customarily include recommended airway management practices such as endotracheal aspiration using closed suction systems, respiratory physiotherapy, cuff shape, hand hygiene and appropriate endotracheal tube materials (Álvarez Lerma et al. 2014; Kučan et al. 2015), although in-depth research into the effectiveness of some of these measures is lacking (Coppadoro et al. 2019).

The other section of the evaluation model focuses on patient-related criteria. The risk of developing VAP is strongly associated with the duration of mechanical ventilation (Kock and Maurici 2018). If re-intubation is required, the risk of developing VAP increases (Gao et al. 2016), while initial intubation circumstances can also contribute to the risk of infection. Pre-hospital intubation is considered to be a risk factor for developing VAP (Arumugam et al. 2018), some evidence additionally pointing to a possible association between pre-hospital endobronchial intubation and the early onset of VAP (Padilla et al. 2019). Male gender, immunodeficiency and old age are also linked with an increased incidence of VAP, according to the recent literature (Kock and Maurici 2018; Timsit et al. 2017).

In our evaluation model, the criteria focusing exclusively on nursing care are represented in the aggregated criterion 'micro-aspiration susceptibility'. The amount and content of oropharyngeal aspirate resulting from an infection of the upper airway or excessive salivation can increase the volume of subglottic secretion and consequently the possibility of oropharyngeal micro-aspiration. Similarly, poor oral hygiene or certain health conditions before or during hospitalization can lead to plaque, inflammations and bacterial or fungal infections, resulting in poor oral health. Both salivatory volume and poor oral health are associated with a higher incidence of VAP (Munro et al. 2006) and are continuously monitored by nurses performing regular oral care.

The abovementioned risk factors were gathered solely from the literature review. Our model additionally includes patient-related risk factors specific to nursing care, which were selected by clinical experts in our team. In intensive care units, oral care is performed by experienced nurses; however, factors such as the patient's health, mental state and medications can increase the difficulty of oral care, thereby negatively impacting its quality. Therefore, it is clearly a risk factor for developing VAP, despite the lack of research in the field. Similarly, tube irritation, the volume of subglottic aspirate and gastric reflux contribute to the possibility of micro-aspirations. Excessive tube irritation negatively impacts the effectiveness of cuff pressure monitoring, which is especially important when larger amounts of secretions are collected. As mentioned above, preventing gastric reflux is an important measure for preventing VAP, but in some cases it proves ineffective, which is why vomiting and regular reflux of the patient are included in our risk evaluation model. These criteria are closely connected with well-established risk factors and preventive measures. The proposed criteria are also regularly monitored by nurses but have not yet been adequately addressed in contemporary VAP prevention strategies.

Table 1 Domain values with descriptions of a basic criterion, 'oral care conditions'

	Domain value	Description
1.	***Less susc***	Patient actively participates in oral care
2.	Susceptible	Deeply sedated patient
3.	More susc	Moving patient (not cooperative)
4.	**High susc**	Resistant patient—oral care is hard or nearly impossible to conduct

3.2 Domain values

The criteria in the DEX method have qualitative domain values for describing the characteristics of alternatives. In our evaluation model, the criteria represent preventive measures and patient-specific risk factors related to VAP, while an alternative represents an individual patient being evaluated by our model.

In the present model, the domain values are arranged from the most to the least desirable. Their values correspond to their impact on VAP risk. They are defined as different levels of susceptibility and are hierarchically ranked on a scale from 'minimally susceptible' to 'very highly susceptible'. The number of domain values used depends on the nature of the criterion or, more specifically, on the number of plausible levels of susceptibility related to the criterion. Susceptibility evaluation of the implementation of preventive measures and relevant patient-related risk factors are combined in an evaluation susceptibility for a specific patient in a specific clinical environment and depict the evaluated overall VAP risk.

Precise descriptions for all basic criteria domain values are crucial. The decision-maker will use this description to enter the initial data needed for evaluation and describe the evaluated patient. Domain values of aggregated criteria, on the other hand, do not necessarily require descriptions, since their values are defined by their utility functions. As an example, the domain values of a basic criterion 'oral care conditions' with descriptions are presented in Table 1.

Because the DEX method uses qualitative domain values, the categories of the basic criteria were carefully assigned in a way that most accurately depicted their real impact on the risk of developing VAP. For example, the 'number of days intubated' is a criterion in which risk increases with time, but only up to a certain point. Research shows that the hazard rate for VAP increases at first and peaks about 5–6 days after intubation. Following the peak, the hazard rate drops and reaches a plateau phase after being intubated for about 2 weeks (Forel et al. 2012; Wolkewitz et al. 2019). Assessment of the risk was therefore achieved with appropriate description and arrangement of domain values, which was done in our model according to the results of Wolkewitz et al. (2019). This is shown in Table 2, which presents the domain values of a basic criterion 'number of days intubated' with corresponding descriptions.

Appropriate criteria arrangement, suitable domain values and knowledge about their relationships and effects on the overall risk of developing VAP were vital to determine the decision rules of the proposed model.

Table 2 Domain values and descriptions of a basic criterion 'number of days intubated'

	Domain value	Description
1.	***Min susc***	Less than 1 day
2.	Less susc	2–4 days
3.	Susceptible	More than 15 days
4.	More susc	7–14 days
5.	**High susc**	5–7 days

3.3 Decision rules

In the risk evaluation process, we aim to evaluate the overall risk for a specific patient of developing VAP. Since not all criteria contribute to the estimated risk equally, utility functions for individual aggregated criterion are assigned. To demonstrate this, we present the aggregated criterion 'health status' as an example. This criterion is derived from three basic criteria: age, gender and immunodeficiency. Although all three criteria contribute to the risk of developing VAP, the scientific literature suggests that their impact differs. According to a study that analysed the correlation between immunosuppression and age and the development of VAP, both had a significant impact on the hazard ratio of developing VAP, but immunosuppression was found to have the greater impact (Moreau et al. 2018). On the other hand, gender was identified as a risk factor for developing VAP in some cases (Kock and Maurici 2018) but in some other studies was not significantly correlated with increased risk of developing the infection (Chang et al. 2017; Arumugam et al. 2018). Accordingly, the utility function was adjusted so that the basic criterion 'immunodeficiency' had the greatest impact on evaluated VAP risk, followed by age and then gender. This, however, is an estimate, and all utility functions are meant to be adjusted in the future in response to new empirical research findings.

In some situations, fixed weights are inadequate for computing the values of aggregated criteria, because the appropriate weight is dependent on the values of the criteria themselves. This means that a value 'highly susceptible' influences the value of the aggregated criterion differently from a value 'less susceptible' of the same criterion. For example, in our evaluation model, the criteria 'subglottic secretions' and 'tube irritation' had a synergetic effect on overall risk. When a significant amount of secretions was present in the subglottic area, tube irritation had a greater likelihood of leading to the micro-aspiration of bacteria. The individual rules within the evaluation model were therefore adopted to achieve an appropriate evaluation of the aggregated criterion 'cuff leakage'.

Determination of individual rules was done to ensure the accuracy of the evaluation model. Weighted sum models commonly use fixed weights when aggregating sub-criteria into an aggregated criterion. On the other hand, DEX uses if–then rules, which enables defining utility functions, taking into account that weights may depend on the values of alternatives for given criteria. For example, a very negative value may have a greater weight on the overall score than a positive value. Therefore, its weight is value-dependent. Determination of individual rules is done to ensure the accuracy

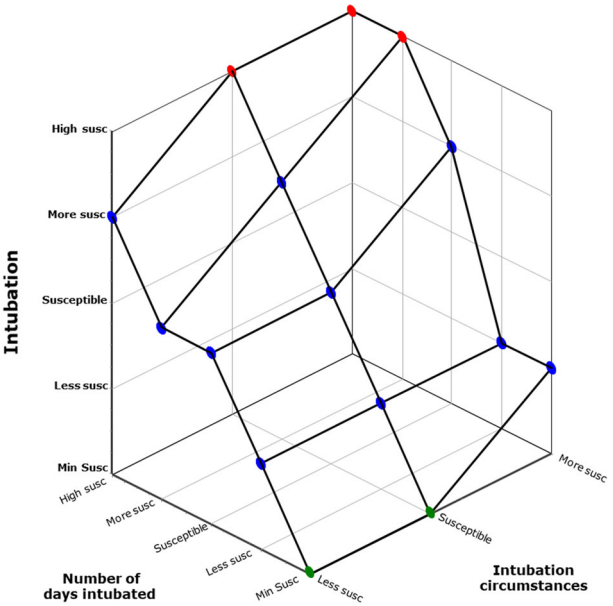

Fig. 2 Graphical representation of a utility function of the aggregated criterion 'intubation'

of the evaluation model. Furthermore, qualitative domain values are similar to everyday terminology and are collectively easier to understand than numerical scales. For easier visualization, utility functions can be represented in a multi-dimensional graph as points in several dimensions, where each rule is represented by a single point. Figure 2 represents a utility function of the aggregated criterion 'intubation'. Two of its axes represent the basic criteria 'intubation time' and 'intubation circumstances'. The vertical axis refers to the computed value of the aggregated criterion 'intubation'. Points on the chart are defined by three axes and represent all possible outcomes in accordance with the decision rules.

4 Results

We obtained and analysed data for evaluating the VAP risk of 19 intubated patients. In addition to the data necessary for the evaluation of risk, prior or present diagnosed lung infection during mechanical ventilation was noted. In this section of the paper, we present the VAP risk evaluations for four patients. These patients were purposely chosen because their results most clearly demonstrate the interrelations among the criteria of the presented evaluation model.

DEXi offers a graphical visualization of evaluation results to support decision-makers. For the representation of selected patients, we used a polar chart with seven axes. Each axis represents a single criterion. For the holistic representation of alternatives, all aggregated criteria from the third level of the hierarchy were selected. The value of overall VAP risk evaluation is the main result of the decision process and

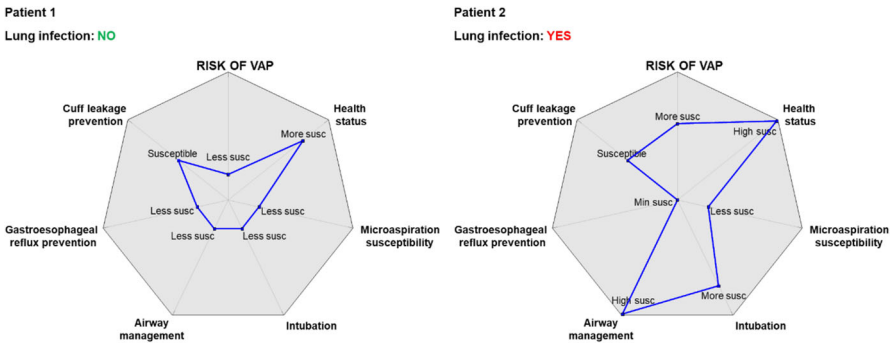

Fig. 3 Polar charts of two patients with different evaluation of VAP risk

is displayed on the central top axis. Arrangement of criteria corresponds to the two sections of our model. Patient-related criteria are presented on the right-hand side of the chart and criteria related to preventive measures are presented on the left-hand side.

First, we present data for two patients, who, according to our model, have overall different levels of VAP risk. Patient 1 was evaluated as 'less susceptible', while patient 2 was evaluated as 'more susceptible' to the development of VAP. Evaluations for these two patients are presented graphically in the form of polar charts in Fig. 3.

Patient 1 was not diagnosed with VAP (no lung infection) and his VAP risk was assessed as 'less susceptible'. Patient 2 was diagnosed with VAP and his VAP risk was evaluated as 'more susceptible'. Thus, our model successfully evaluated a patient with a diagnosis of lung infection as being more susceptible. We would like to use the results of our model to analyse the underlying reasons for differences in overall risk evaluation. A high risk of acquiring VAP is a result of criteria that were assessed as 'more susceptible' or 'highly susceptible'. There are three such criteria in the polar chart: 'health status','intubation' and 'airway management'. The first two of these three criteria are patient-related characteristics, but the last criterion is related to preventive measures used on the ward. Attention should be paid to these three criteria in order to lower the risk level, whereas the other three criteria in the chart are less crucial in the current situation. Such an analysis reminds us of the priorities in the treatment of Patient 2.

Patient 1 was evaluated as 'less susceptible' to developing VAP. The chart in Fig. 3 shows that the criterion 'health status' contributes the most to the evaluation of the overall risk for VAP. Criterion 'health status' combines three criteria—'age', 'gender' and 'immunodeficiency'. The patient is male and aged between 50 and 65 years. This means that little can be done to additionally lower the risk of developing VAP, since age or gender cannot be changed. Although the overall estimation of risk was evaluated as 'less susceptible', these patient characteristics could significantly contribute to a higher estimation of risk if adequate preventive measures are discontinued or if additional patient risk-related factors occur during hospitalization.

Besides analysing the explanations for differences in final evaluations, the transparency of our approach also enables an in-depth comparison of seemingly equally

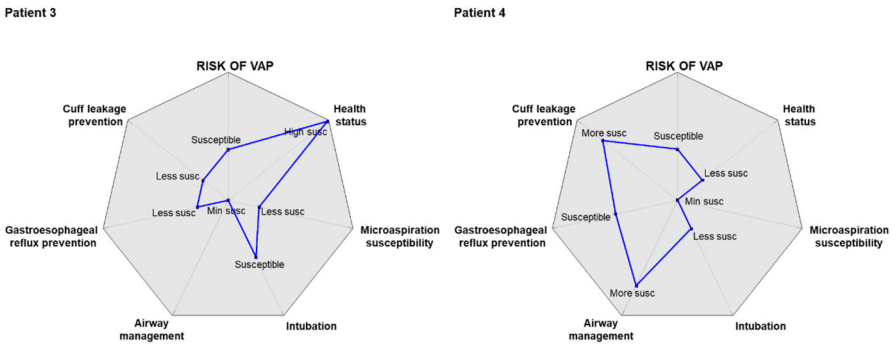

Fig. 4 Polar charts of two patients with equal evaluation of VAP risk

susceptible patients. Figure 4 presents two patients, who, according to the final evaluation, have an equal risk of developing VAP but differ in their characteristics and in various aspects of VAP susceptibility.

Patient 3 was evaluated as 'highly susceptible', according to the criterion 'health status', and 'susceptible', according to the criterion 'intubation'. This resulted in an evaluation of patient-related criteria as 'more susceptible'. However, strict preventive practices resulted in a 'less susceptible' evaluation of criteria related to preventive measures, thus leading to an overall evaluation of the patient's risk as 'susceptible'.

In comparison, Patient 4 presented patient-related risk factors lower than or equal to 'less susceptible'. Nevertheless, poor implementation of preventive measures on the ward shifted the overall estimation of risk to 'susceptible'. Healthcare professionals should be alerted to such factors and adequately adapt their preventive practices to lower the chance of infection. Poor preventive measures can drastically increase the risk of developing VAP, especially if a patient has additional patient-related risk factors or requires mechanical ventilation for a longer period.

5 Discussion

Contemporary approaches in VAP prevention focus on a bundle implementation approach that promotes the strict implementation of preventive measures (Okgün Alcan et al. 2016). Although maximizing preventive behaviour among staff is crucial, low adherence is relatively common. Education can lead to better adherence, but its effects may be limited, especially when nurses' workloads are not adequately controlled (Aloush 2017).

Preventing and monitoring VAP in intensive care units is vital for decreasing patient mortality and preventing avoidable costs. As we expect the numbers of patients on ventilators to rise, as a consequence of COVID-19, it is vitally important to reduce VAP. Our model represents a novel approach for active risk management in preventing VAP. To the best of our knowledge, this is the first integrated and systematic modelling of such a quantity of interdisciplinary data for the prevention of VAP. Furthermore, the designed decision model assimilates nursing-specific observations and practices,

which provide an important source of clinical data and strategies to lower the risk of developing infection. The DEX method used in the present study enables a selective explanation of the role of specific critical healthcare factors and promotes interdisciplinary cooperation.

Factors contributing to the overall risk of developing VAP are numerous and diverse. In our evaluation model, they are represented as basic criteria. The model enables a comprehensive evaluation of the risk of developing VAP for a specific patient on two levels. First, the section covering the preventive measures implemented can be used to evaluate staff's compliance with best practices. The estimated risk according to our evaluation model may subsequently decrease for the same patient if stricter preventive measures are implemented. Second, when identical preventive measures are implemented on the entire ward, the patient-specific section of the evaluation model will distinguish patients who are more at risk of developing VAP. When comparing two patients with a different overall evaluation of VAP risk, our model correctly flagged Patient 2, who had previously been diagnosed with an infection of lungs, as 'more susceptible'. Patient 1 was not diagnosed with a lung infection and was evaluated as 'less susceptible'. The prediction of future infection is one of the desired main benefits of our approach; however, determining the prediction effectiveness is beyond the scope of this study, since it requires a longitudinal methodological strategy.

Our results suggest that the present model, when applied in clinical settings, should be focused on systematic screening and targeted interventions to reduce the risk of developing VAP for a specific patient. The interdisciplinary knowledge integrated within the model can be utilized systematically for the reliable and efficient evaluation of risk, in order to identify more susceptible patients. In a case where the overall risk is believed to be high, an in-depth analysis will throw light on the reasons for the increased risk and indicate possible means for decreasing it. If a decision was impacted by poor implementation of preventive measures, additional measures can be employed. Similarly, if the overall risk is a consequence of patient-specific criteria, additional patient-centred measures can be taken to decrease the overall risk. For example, if the overall risk is estimated to be high because of excessive salivation and a subsequent larger amount of oropharyngeal aspirate, measures can be taken to either decrease salivation or employ continuous subglottic aspiration to counteract its negative impact. Thus, an in-depth analysis of the risk evaluation can form the basis for appropriate adaptation of the treatment plan and the nursing care plan.

Although this study demonstrates how the proposed model could be implemented in a clinical environment, the lack of substantial empirical testing is a notable limitation, which must be overcome in order to develop the model. New empirical data will allow us to modify the design of the model for a better estimation of risk. Our model uses exclusively qualitative criteria. Future findings will identify whether the implementation of numerical criteria could bring additional benefits (Trdin and Bohanec 2018). The second limitation of this study is the monocentric collection of data, which resulted in homogeneity of the patient data, in particular in relation to the implementation of preventive measures. Although five different intensive care units were included in the study, all wards belong to the same hospital. The inclusion of data from more diverse clinical environments would result in the detection of greater disparity in preventive measures. Therefore, the model should be tested extensively in more diverse

intensive care units. Additionally, this study does not take into account the long-term mechanical ventilation treatment that is prevalent in hospital environments as well as home care; nor does it indicate how the model can be effectively integrated into an actual clinical environment. These issues need to be considered in future research and redesigns of the proposed model.

VAP prevention is an interdisciplinary field that should include the diligent efforts of nurses, medical professionals, respiratory physiotherapists and other healthcare professionals to ensure optimal results. This study shows that the use of multi-criteria decision modelling allows a vast quantity of interdisciplinary knowledge to be systematically organized and used effectively. The study has further illustrated that the integration of operational research methods in healthcare is beneficial, especially for solving complex problems that require diverse knowledge and an interdisciplinary approach. The main strength of the present model is the utilization of previously poorly acknowledged nursing-specific data. Implementation of the model will, therefore, promote better integration of nursing science into VAP prevention and could provide a starting point for researching undiscovered factors that contribute to the development of VAP. Additionally, the data required for risk evaluation using our model can be collected daily with minimal additional effort, since the model is heavily reliant on medical and nursing records. As such, the model promotes continuous alertness to the possibility of VAP.

6 Conclusion

The multi-criteria evaluation model encompasses nursing-specific data, thereby presenting a novel approach in the oversight of VAP. Multi-criteria decision modelling was used to summarize the most important clinical and scientific knowledge for VAP prevention. Using the DEXi software, we were able to accurately represent the knowledge base, enable future modifications according to new empirical findings and ensure a reliable and transparent evaluation of the risk of developing VAP. Data gathering was made simple by including only data already documented in contemporary clinical practice. The software used demonstrated the benefits of modern information and communication technology, without which the proposed approach for decision-making and identifying risk would not be possible.

Authors' contribution All authors contributed to the study conception and design. Data collection and analysis were performed by RD and MMK. The first draft of the manuscript was written by RD and all authors contributed to writing the manuscript. All authors read and approved the final manuscript.

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Data availability The collected data and the signed informed consent forms are securely stored in paper form by the first author. All stored documents will be destroyed within a year of publication. The evaluation model used in this study is saved in electronic form by all authors.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval Ethical approval for the conduct of this study was obtained from the ethical committee of the University of Maribor, Faculty of Organizational Sciences. All the procedures involving human participants were in accordance with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Consent to participate and consent for publication Participants signed a form giving their consent to participation and for publication prior to the beginning of the study.

Code availability The software used, DEXi, was not customized and is freely available at: https://kt.ijs.si/MarkoBohanec/dexi.html.

References

Akdogan O, Ersoy Y, Kuzucu C, Gedik E, Togal T, Yetkin F (2017) Assessment of the effectiveness of a ventilator associated pneumonia prevention bundle that contains endotracheal tube with subglottic drainage and cuff pressure monitorization. Braz J Infect Dis 21:276–281. https://doi.org/10.1016/j.bjid.2017.01.002

Aloush SM (2017) Does educating nurses with ventilator-associated pneumonia prevention guidelines improve their compliance? Am J Infect Control 45:969–973. https://doi.org/10.1016/j.ajic.2017.04.009

Álvarez Lerma F, Sánchez García M, Lorente L et al (2014) Guidelines for the prevention of ventilator-associated pneumonia and their implementation. The Spanish 'Zero-VAP' bundle. Med Intensiva 38:226–236. https://doi.org/10.1016/j.medin.2013.12.007

Arumugam SK, Mudali I, Strandvik G, El-Menyar A, Al-Hassani A, Al-Thani H (2018) Risk factors for ventilator-associated pneumonia in trauma patients: a descriptive analysis. World J Emerg Med 9:203–210. https://doi.org/10.5847/wjem.j.1920-8642.2018.03.007

Aven T (2016) Risk assessment and risk management: review of recent advances on their foundation. Eur J Oper Res 253:1–13. https://doi.org/10.1016/j.ejor.2015.12.023

Bekaert M, Timsit J-F, Vansteelandt S et al (2011) Attributable mortality of ventilator-associated pneumonia. Am J Respir Crit Care Med 184:1133–1139. https://doi.org/10.1164/rccm.201105-0867OC

Bohanec M (2008) Program for multi-attribute decision making. User's manual. Institut "Jožef Stefan" Ljubljana, Slovenia. http://kt.ijs.si/MarkoBohanec/pub/DEXiManual30r.pdf. Accessed 26 January 2020

Bohanec M (2017) DEXi: a program for qualitative multi-attribute decision modelling. Jožef Stefan Institute. https://kt.ijs.si/MarkoBohanec/dexi.html. Accessed 25 January 2020

Bohanec M, Žnidaržič M, Rajkovič V, Bratko I, Zupan B (2013) DEX methodology: three decades of qualitative multi-attribute modeling. Inform 37:49–54

Čampelj B, Karnet I, Brodnik A, Jereb E, Rajkovič U (2019) A multi-attribute modelling approach to evaluate the efficient implementation of ICT in schools. Cent Eur J Oper Res 27:851–862. https://doi.org/10.1007/s10100-018-0595-y

Cato KD, Cohen B, Larson E (2015) Data elements and validation methods used for electronic surveillance of health care-associated infections: a systematic review. Am J Infect Control 43:600–605. https://doi.org/10.1016/j.ajic.2015.02.006

Chang L, Dong Y, Zhou P (2017) Investigation on risk factors of ventilator-associated pneumonia in acute cerebral hemorrhage patients in intensive care unit. Can Respir J 2017:7272080. https://doi.org/10.1155/2017/7272080

Coppadoro A, Bellani G, Foti G (2019) Non-pharmacological interventions to prevent ventilator-associated pneumonia: a literature review. Respir Care 64:1586–1595. https://doi.org/10.4187/respcare.07127

Dasgupta S, Das S, Chawan NS, Hazra A (2015) Nosocomial infections in the intensive care unit: incidence, risk factors, outcome and associated pathogens in a public tertiary teaching hospital of Eastern India. Indian J Crit Care Med 19:14–20. https://doi.org/10.4103/0972-5229.148633

Elke G, Hartl WH, Kreymann KG et al (2019) Clinical nutrition in critical care medicine—guideline of the German society for nutritional medicine (DGEM). Clin Nutr ESPEN 33:220–275. https://doi.org/10.1016/j.clnesp.2019.05.002

Feng DY, Zhou YQ, Zou XL et al (2019) Differences in microbial etiology between hospital-acquired pneumonia and ventilator-associated pneumonia: a single-center retrospective study in Guang Zhou. Infect Drug Resist 12:993–1000. https://doi.org/10.2147/IDR.S204671

Forel JM, Voilet F, Pulina D et al (2012) Risk factors for death among critically ill patients with ventilator-associated pneumonia and ICU mortality in severe ARDS patients ventilated according to a lung-protective strategy. Crit Care 16:2–10. https://doi.org/10.1186/cc11312

Gao F, Yang LH, He HR et al (2016) The effect of reintubation on ventilator-associated pneumonia and mortality among mechanically ventilated patients with intubation: a systematic review and meta-analysis. Hear Lung J Acute Crit Care 45:363–371. https://doi.org/10.1016/j.hrtlng.2016.04.006

Greco S, Ehrgott M, Figueira JR (2016) Multiple criteria decision analysis: state of the art surveys, 2nd edn. Springer, New York

Gupta R, Sharma S, Parwez SaxenaS (2018) Changing panorama for surveillance of device-associated healthcare infections: challenges faced in implementation of current guidelines. Indian J Med Microbiol 36:18–25. https://doi.org/10.4103/ijmm.IJMM_18_50

Haghighi A, Shafipour V, Bagheri-Nesami M, Gholipour Baradari A, Yazdani Charati J (2017) The impact of oral care on oral health status and prevention of ventilator-associated pneumonia in critically ill patients. Aust Crit Care 30:69–73. https://doi.org/10.1016/j.aucc.2016.07.002

Hellyer TP, Ewan V, Wilson P, Simpson AJ (2016) The intensive care society recommended bundle of interventions for the prevention of ventilator-associated pneumonia. J Intensive Care Soc 17:238–243. https://doi.org/10.1177/1751143716644461

Hillier B, Wilson C, Chamberlain D, King L (2013) Preventing ventilator-associated pneumonia through oral care, product selection, and application method. AACN Adv Crit Care 24:38–58. https://doi.org/10.1097/NCI.0b013e31827df8ad

Joseph NM, Sistla S, Dutta KT, Shankar BA, Parija SC (2010) Ventilator-associated pneumonia: a review. Eur J Intern Med 21:360–368. https://doi.org/10.1016/j.ejim.2010.07.006

Klein Klouwenberg PM, van Mourik MS, Ong DS et al (2014) Electronic implementation of a novel surveillance paradigm for ventilator-associated events. Feasibility and validation. Am J Respir Crit Care Med 189:947–955. https://doi.org/10.1164/rccm.201307-1376OC

Kock KS, Maurici R (2018) Respiratory mechanics, ventilator-associated pneumonia and outcomes in intensive care unit. World J Crit care Med 7:24–30. https://doi.org/10.5492/wjccm.v7.i1.24

Korhonen P, Moskowitz H, Wallenius J (1992) Multiple criteria decision support: a review. Eur J Oper Res 63:361–375. https://doi.org/10.1016/0377-2217(92)90155-3

Kučan M, Djekić B, Ravljen M (2015) The influence of the endotracheal tube cuff on the occurrence of ventilator-associated pneumonia. Slov Nurs Rev 49:222–232. https://doi.org/10.14528/snr.2015.49.3.52

Luyt CE, Combes A, Reynaud C et al (2008) Usefulness of procalcitonin for the diagnosis of ventilator-associated pneumonia. Intensive Care Med 34:1434–1440. https://doi.org/10.1007/s00134-008-1112-x

Mihelčić M, Bohanec M (2016) Approximating incompletely defined utility functions of qualitative multi-criteria modeling method DEX. Cent Eur J Oper Res 25:627–649. https://doi.org/10.1007/s10100-016-0451-x

Moreau AS, Martin-Loeches I, Povoa P et al (2018) Impact of immunosuppression on incidence, aetiology and outcome of ventilator-associated lower respiratory tract infections. Eur Respir J. https://doi.org/10.1183/13993003.01656-2017

Munro CL, Grap MJ, Elswick RK, McKinney J, Sessler CN, Hummel RS (2006) Oral health status and development of ventilator-associated pneumonia: a descriptive study. Am J Crit Care 15:453–460. https://doi.org/10.4037/ajcc2006.15.5.453

Najafi Ghezeljeh T, Kalhor L, Moradi Moghadam O, Lahiji Niakan M, Haghani H (2018) The effect of head-of-bed elevation of 45 degree on the incidence of ventilator- associated pneumonia among hospitalized patients in intensive care units. Iran J Nurs 31:65–74. https://doi.org/10.29252/ijn.31.111.65

Okgün Alcan A, Demir Korkmaz F, Uyar M (2016) Prevention of ventilator-associated pneumonia: use of the care bundle approach. Am J Infect Control 44:e173–e176. https://doi.org/10.1016/j.ajic.2016.04.237

Padilla ACH, Trampont T, Lafon T et al (2019) Is prehospital endobronchial intubation a risk factor for subsequent ventilator associated pneumonia? A retrospective analysis. PLoS ONE 14(5):e0217466. https://doi.org/10.1371/journal.pone.0217466

Pavlovic M, Cerenak A, Pavlovic V, Rozman C, Pazek K, Bohanec M (2011) Development of DEX-HOP multi-attribute decision model for preliminary hop hybrids assessment. Comput Electron Agric 75:181–189. https://doi.org/10.1016/j.compag.2010.11.002

Póvoa P, Martin-Loeches I, Ramirez P et al (2016) Biomarker kinetics in the prediction of VAP diagnosis: results from the BioVAP study. Ann Intensive Care 6:32. https://doi.org/10.1186/s13613-016-0134-8

Šušteršič O, Rajkovič U, Dinevski D, Jereb E, Rajkovič V (2009) Evaluating patients' health using a hierarchical multi-attribute decision model. J Int Med Res 37:1646–1654. https://doi.org/10.1177/147323000903700544

Timsit J-F, Esaied W, Neuville M, Bouadma L, Mourvllier B (2017) Update on ventilator-associated pneumonia. F1000Res 6:2061. https://doi.org/10.12688/f1000research.12222.1

Trdin N, Bohanec M (2018) Extending the multi-criteria decision making method DEX with numeric attributes, value distributions and relational models. Cent Eur J Oper Res 26:1–41. https://doi.org/10.1007/s10100-017-0468-9

Wolkewitz M, Palomar-Martinez M, Alvarez-Lerma F, Olaechea-Astigarraga P, Schumacher M (2019) Analyzing the impact of duration of ventilation, hospitalization, and ventilation episodes on the risk of pneumonia. Infect Control Hosp Epidemiol 40:301–306. https://doi.org/10.1017/ice.2018.360