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Intensive Care Monitoring and Therapy Planning for Newborns

Silvia Miksch[1)], Werner Horn[1,2)], Christian Popow[3)], Franz Paky[4)]

[1)] Austrian Research Institute for Artificial Intelligence, Schottengasse 3, A–1010 Vienna, Austria
[2)] Department of Medical Cybernetics and Artificial Intelligence, University of Vienna, Austria
[3)] Neonatal ICU, Department of Pediatrics, University of Vienna, Austria
[4)] Department of Pediatrics, Hospital of Mödling, Austria
Email: silvia@ai.univie.ac.at

We developed a knowledge–based system, VIE–VENT, for monitoring and therapy planning of the artificial ventilation of newborn infants. Clinical and textbook knowledge were implemented in VIE–VENT's knowledge base. Therapy planning was based on transcutaneously and invasively determined blood gas measurements and on clinical observations. After the selection of appropriate input parameters, measured data were validated and transformed into qualitative values. If these values differed from target values, therapeutic actions were proposed according to heuristic clinical rules of artificial ventilation. VIE–VENT was specifically designed for practical use under real–time constraints in Neonatal Intensive Care Units (NICUs). VIE–VENT was applied to the ICU data set provided by the organizers of the AAAI–AIM–94 symposium and a neonatal data set, which covered a neonatal case of similar severity. It included all transcutaneous measurements and allowed to explore the full potential of VIE–VENT.

1. Introduction

During the past decade, several knowledge–based systems were introduced to support clinicians in the monitoring of critically ill patients and to assist the staff in diagnostic decision making and therapy planning (Uckun, 1993). These systems range from simple intelligent alarms (e.g., Beneken, et al. 1989) to sophisticated systems for anesthesia monitoring and management of artificial ventilation, e.g., VentPlan (Rutledge, et al. 1993), SIMON (Uckun, et al. 1993), GUARDIAN (Hayes–Roth, et al. 1992).

Closest to our approach is the SIMON project, a ventilator monitoring system for premature infants. We could not apply its knowledge base, because, firstly, SIMON's main issue is a context sensitive understanding of the patient's status related to the pathophysiology of existing disorders with no therapy planning component included. Secondly, SIMON analyses invasively determined blood gas measurements, which are only discontinuously and infrequently determined. Moreover, in modern ICUs therapeutic decisions are increasingly based on noninvasive continuous measurements of transcutaneous partial pressure of oxygen ($PtcO_2$), arterial oxygen saturation (SaO_2) and transcutaneous partial pressure of carbon dioxide ($PtcCO_2$). Thirdly, its knowledge base consists of data interpretation components which do not represent the clinical routine at our hospitals.

In this paper we present VIE–VENT's system architecture concentrating on our data interpretation and therapy recommendation components. Additionally, we apply the knowledge base of VIE–VENT to selected parts of the AAAI–AIM– 94 data set and to a second neonatal data set, which covers

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similar severe situations as the AAAI–AIM 94 sample, but deals with a neonate instead of a 8.5 months old child. We used this second data set to show the full functionality of our system, which was designed for neonates.

2. VIE–VENT's System Architecture

Our aim in developing VIE–VENT was to incorporate monitoring and therapy planning tasks. The architecture of VIE–VENT consists of several modules: data selection, data validation, data abstraction, data interpretation and therapy recommendations. All these steps are involved in a single cycle of data collection and interpretation from monitors. According to our aim to design a practically oriented knowledge–based system, we built the various module components in analogy to the clinical reasoning process. VIE–VENT represents a data–driven approach and is an open–loop system. A detailed description of VIE–VENT's system architecture is given in Miksch, et al. (1993).

2.1 Data Selection

The phase of data selection is the process of filtering out context–relevant data for further analysis. VIE–VENT's whole input data set is divided into continuous and discontinuous variables. VIE–VENT uses the following input parameters:

(a) *continuous* data:
- ventilator settings: F_iO_2, f, PIP, PEEP, t_I, t_E, v_i, v_e, V_T
- mode of ventilation: IPPV, IMV, CPAP
- transcutaneous blood gases: $PtcO_2$, $PtcCO_2$, SaO_2

(b) *discontinuous* data:
- neonate's personal description (e.g., name, sex)
- clinical parameters (e.g., weight, age, chest wall expansion, spontaneous breathing effort)
- invasively determined blood gases: pH, PO_2, PCO_2
- site of blood gas measurement: arterial, capillary, venous.

The continuous data are received every 10 seconds. The arithmetic means of the 10–second data are stored after every 10 minutes for further analyses and trend detection. At the onset of the monitoring and therapy planning process the neonate's personal description is entered. The other discontinuous data are either demanded from VIE–VENT depending on different conditions (e.g., critical ventilatory condition, elapsed time intervals) or entered by users without being requested.

The output parameters are primarily therapy recommendations. A therapy recommendation consists of the amount and frequency of the ventilator settings to be changed (e.g., "decrease PIP to 20"). Additionally, VIE–VENT prints information about detected invalid measurements and their transformations (e.g., "unplausible SaO_2, classified as unknown", "calibration of $PtcCO_2$ with factor 1.3 since 5 min. 30 sec."), comments and explanations about the health condition of the neonate (e.g., "respiratory acidosis", "$PtcCO_2$ is substantially below target range"), as well as warnings in critical situations (e.g., "extremely bad health condition, check perfusion").

2.2 Data Validation

The major aim of the data validation process is to arrive at reliable measurements. VIE–VENT combines different kinds of methods to detect faulty data. Firstly, the plausibility of the measurements is checked. We defined look–up tables for all input parameters, which cover the plausible measurements depending on additional attributes, e.g., (pCO_2, (arterial, IPPV), 15, 130). Secondly, we defined causal and functional dependencies of the measurements and the ventilator settings (e.g., causal dependencies of the chest wall expansion and the tidal volume; or a functional dependence: $AMV = V_T * f$, where AMV is the minute ventilation, V_T is the tidal volume and f is the frequency). Thirdly, we used reliability ranking which is derived from priority lists of the measurements (e.g., oxy-

genation: invasive PO_2 is more reliable than SaO_2 and SaO_2 is more reliable than $PtcO_2$). Fourthly, VIE–VENT has two options to deal with missing values: a simplified system model of neonatal respiration during the initial phase when the only reliable continuous measurement is SaO_2 and a set of context–dependent rules applying defaults.

2.3 Data Abstraction

Data abstraction is the process of transforming quantitative data of the observable system into qualitative values. In VIE–VENT, the basis for transforming blood gas measurements are schemata, which categorize the data in seven qualitative categories depending on the degree of the blood gas abnormalities (slightly/substantially/extremely *below* target range, target range, slightly/substantially/extremely *above* target range). These schemata are defined for all kinds of blood gases depending on the sampling site (arterial, capillary, venous, transcutaneous) and the mode of ventilation (IPPV, IMV).

2.4 Data Interpretation and Therapy Recommendations

Neonatal respiration in our system model is represented by two processes, ventilation (CO_2 elimination) and oxygenation (oxygen uptake). Ventilation is reflected by the blood tension of CO_2 (PCO_2 or $PtcCO_2$). Ventilation is increased (and PCO_2 or $PtcCO_2$ decreased) depending on an increase of the AMV ($AMV = V_T * f$). The V_T is strongly but not linearily related to the peak inspiratory pressure (PIP) and clinically to the extent of chest wall expansion. Independently of the ventilation process, the PCO_2 or $PtcCO_2$ may be increased due to a poor pulmonary perfusion or to right to left shunting. Oxygenation is reflected by the blood tension of O_2 (PO_2 or $PtcO_2$). Oxygenation is increased with a raising of the inspiratory oxygen concentration (F_iO_2) and of the mean airway pressure (MAP). The MAP increases with PIP, inspiratory time (t_I) and positive endexpiratory pressure (PEEP). Independently of the oxygenation, PO_2 or $PtcO_2$ may be decreased due to right to left shunting and an increased pulmonary vascular resistance, which itself at least partly depends on the PCO_2.

Depending on the course of the disease, the monitoring possibilities and the therapeutic goals of artificial ventilation, i.e., the target values of PCO_2 and PO_2, may change. We divided the whole period of artificial ventilation into four phases: an *initial* phase, a phase of *controlled ventilation* (IPPV), a phase of *weaning* (IMV) and a phase of *returning to spontaneous breathing*. Transition from one phase to the next is handled by rules depending on the amount of artificial ventilation (e.g., if F_iO_2 can be reduced to a value $\leq 50\%$ and PIP to ≤ 20 mbars IMV is recommended).

For every phase a set of target values and rules of therapy recommendations are formulated. No restrictions of the quantity of ventilator settings to be changed are defined if the amount of artificial ventilation must be increased for limiting an extremely severe health condition of a neonate. But VIE–VENT prunes the quantity of ventilator settings to be changed to a maximum of two parameters in case the artificial ventilation must be decreased. Context–dependent preference rules control the pruning process.

Additionally, we defined three types of users (aggressive, normal, conservative) to represent different kinds of therapeutic behavior of physicians in order to increase the acceptance of our system. The most important characteristics of the user model are the maximum of the allowed amount of change and the interval recommended between invasive blood gas analyses.

For example, no changes of the ventilator settings are recommended if pH, PCO_2 or $PtcCO_2$ are within target range during the phase of controlled ventilation. If $PtcCO_2$ is increasing—represented in VIE–VENT as slightly / substantially / extremely *below* target range—respiratory or metabolic acidosis is detected, and an increase of f or PIP is recom-

mended. Depending on the degree of abnormality of the blood gas measurement and the type of physician, a different amount of change is suggested (e.g., if $PtcCO_2$ is substantially *below* target range and the "normal" user type is active, then an increase of the PIP of 15% is recommended) .

VIE–VENT recommends changes of the ventilator settings as long as the conditions for the changes hold and the settings are not changed by the physician. If the physician changes the ventilator settings, her/his actions have highest priority. VIE–VENT accepts the changes as a correct decision and waits for 10 minutes adaptation time without giving any therapy recommendation. The other components of VIE–VENT are still active during this phase. After this delay time, VIE–VENT starts criticizing the ventilator settings again. Therefore, VIE–VENT recognizes a fruitless or even a wrong adjustment of the ventilator settings and forces to change them.

3. Applying VIE–VENT to Sample Cases

We applied VIE–VENT to the AAAI–AIM–94 ICU data set and a neonatal data set. We assumed a "normal" type of user in both cases.

3.1 Our Evaluation Conception

Our main issue was the evaluation of VIE–VENT's data interpretation and therapy recommendation components. Two domain experts participated in the evaluation. The physicians ranked VIE–VENT's therapy recommendations, warnings and explanations as "correct", "correct, but needs smoothing" and "incorrect" and the therapeutic actions of the provided cases compared to VIE–VENT's recommendations. They had to rank the decision steps in the AAAI–AIM–94 data set and in our neonatal data set.

3.2 Evaluating the Original AAAI–AIM–94 ICU Data Set

3.2.1 The Data Selection and Transformation

We used the following data subsets from the AAAI–AIM–94 sample: the continuous measurement of SaO_2 (during approximately 12 hours), the ventilator settings: F_iO_2, f, PIP, PEEP, V_T, arterial blood gases pH, PO_2, PCO_2 and the mode of ventilation CMV.

In our evaluation process we compressed the time axis by the factor of 6, resulting in one minute intervals of the data set. We added a default value of inspiratory time t_I of 0.7 and calculated the correspondent expiratory time t_E ($f = 60 / (t_I+t_E)$). The mode of ventilation CMV is equivalent to our phase of *controlled ventilation* (IPPV). We used four of the available five arterially determined blood gases. We stopped VIE–VENT after receiving the last continuous measurement of SaO_2 because the last blood gas analysis was available only 54 minutes later.

3.2.2 Results

We did not apply the restricted mode of the initial phase because there were arterially determined blood gases available since the beginning of the treatment and it was unrealistic that such a severely ill child would be monitored in a restricted way during approximately 12 hours. Moreover, we did not have any information about the chest wall expansion or the spontaneous breathing effort, which is temporally needed in the restricted mode. A problem of the AAAI–AIM–94 case was that PIP and PEEP were set extremely high and that VIE–VENT suggests changes to the ventilatory parameters mainly in relation to changes of the $PtcCO_2$. However, there were only four invasively determined blood gas analyses within 12 hours. Additionally, hand bagging for raising the PCO_2 is a rather unusual therapeutic action at both of our clinical departments. We enlarged our knowledge–base by recognizing hand bagging and classifying data values during this period as artifacts.

For VIE–VENT's therapy recommendations one

general trend was discovered: VIE–VENT recommended mainly a decrease of the PIP. However, the unusually high PIP was not changed in the sample case for more than 6 hours (6 hours 29 minutes). Moreover, within the next 6 hours, PIP was alternatively decreased and increased without any corresponding clinical information (43, 40, 43, 42, 43, 42, 41). The first arterial blood gas analysis (23:16), which was interpreted as hypoxemia and respiratory acidosis, forced VIE–VENT to recommend a decrease of the PIP. Oxygenation was worse than ventilation at a F_iO_2 of 50%. VIE–VENT therefore tried firstly to decrease the very high PIP and pruned the other therapy recommendations. In summary, VIE–VENT recommended decision steps 31 times: 16 times a decrease of PIP was recommended, once a decrease of the F_iO_2 and an increase of the f (as a response to the invasive blood gas analysis at 4:30). On 4 occasions, the ventialtor settings were kept and on 10 occasions, VIE–VENT only monitored the patient based on 10 minutes adapting time after a change of the ventilator settings or hand bagging.

Both physicians ranked 29 recommendations of VIE–VENT as "correct", two as "correct, but needs smoothing" because depending on the invasive blood analyses at 4:30 and 6:11 and in respect to the high PEEP (9 mbars), they additionally would have recommended to decrease the PEEP.

3.3 Evaluating our Neonatal Data Set

3.3.1 Case Description

We applied VIE–VENT to a historical case of comparable severity from one of our neonatal ICU's case base to demonstrate the full functionality of our system. We chose a male premature infant with a birth weight of 2,920g, who presented with a history of oligohydrammios, bilateral hydronephrosis due to an urethral valve. Moreover he had lung hypoplasia, massive ascites and was in circulatory shock. He was ventilated immediately after birth and received exogenous surfactant three and 12 hours after birth. Our input parameters are listed in chapter 2.1. Our therapeutic recommendations are based on the transcutaneous blood gases (SaO_2, $PtcO_2$, $PtcCO_2$) and on three capillary blood gas analyses ($PcCO_2$, PcO_2, pH). Figure 1 presents these values (upper two charts) and the ventilator settings (lower four charts) which show the physician's actions (by a — line) and VIE–VENT's recommendations (by a small ▲triangle). The acting physician's decisions and VIE–VENT's therapy recommendations were retrospectively analyzed by our two domain experts.

3.3.2 Results

In general, VIE–VENT anticipated the acting physician's decision. However, when the SaO_2 increased above the normal range, the physicians gave clinical priority to a reduction of the high PIP instead of a reduction of the high F_iO_2. Moreover, the physician was more conservative in reducing the F_iO_2 (steps of 5% compared to VIE–VENT's suggested 10%) as he was afraid to produce flip–flopping of the SaO_2 due to a too rapid reduction of the F_iO_2. Additionally, they criticized VIE–VENT's therapy recommendations for suggesting a too dramatic reduction of the F_iO_2. The evaluating experts criticized the acting physician for not increasing the rate (f) and the PEEP early enough in view of the high $PtcCO_2$. VIE–VENT recommended such changes several times.

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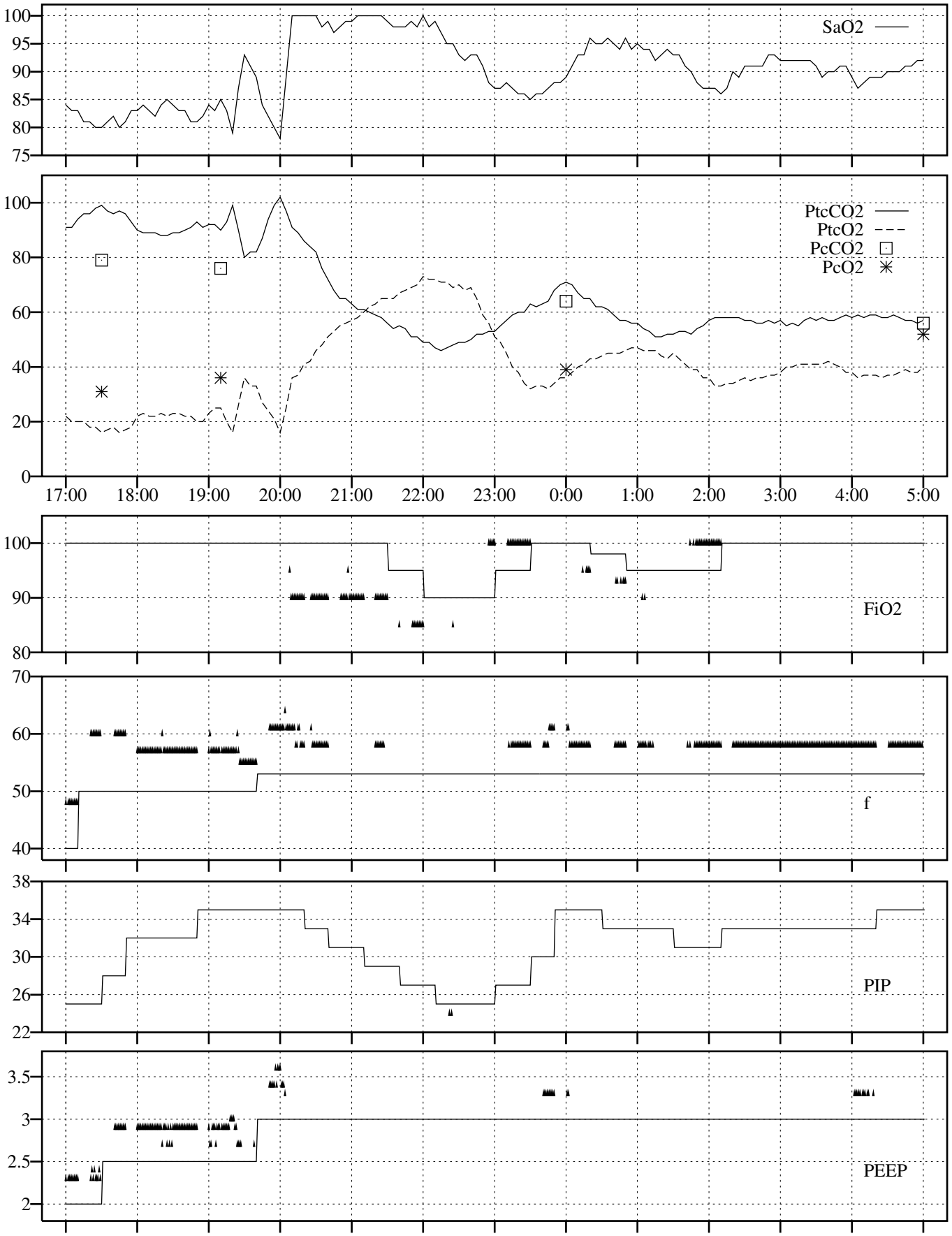

Figure 1: Blood gas measurements (top 2 charts) and therapy actions (physician — ; VIE–VENT's recommandations: ▲)