Metaphor graphics to visualize ICU data over time

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Abstract. The time-oriented analysis of electronic patient records at a (neonatal) intensive care unit is a tedious and time-consuming task. The vast amount of data available makes it hard for the physician to recognize the essential changes over time. VIE-VISU is a data visualization system which uses multiples to present the change in the patient's status over time in graphic form. Metaphor graphics is used to sketch the parameters most relevant in characterizing the situation of a patient.

1 Introduction

The intensive care unit (ICU) is a data rich environment. On-line monitoring produces a set of patient data every second. Moreover, clinical data (patient's state, lab values, diagnoses, medication, other therapeutic and nursing actions) are collected manually at various time intervals. A computer based patient data management system (PDMS) stores both types of data, on-line collected and manually entered data within a time frame.

Even if these electronic patient records are complete and correct, they are difficult to analyze because they contain so many data. The amount of data stored in electronic form outperforms by far the amount of data available in paper records. This should serve for an important function: the investigation of problems in great detail. However, the overall assessment of the situation of the patient becomes more difficult. Physicians have a hard job to select the relevant information from the vast amount of data available.

The monitoring devices of a modern ICU are usually optimized to support the recognition of instantaneous problems. Usually, only a limited amount of past data can be reviewed on the monitor itself. Sophisticated PDMS (such as HP's CareVue 9000) allow for a complete review of a patient's data for the entire period of her stay at the ICU. Such a typical view is given in Figure 1.

Most of the data are presented in form of a spreadsheet. A few parameters can also be displayed as X–Y plots. This kind of display makes it easy to find a specific value of a specific parameter at a specific point of a time scale. It is more difficult to extract a summary of a patient's condition at a specific time point. And it is even more complicated to find out the essential change(s) of a patient's state over a given time interval.

There are several reasons why spreadsheet tables and X–Y plots are difficult to use:

- there are too many parameters displayed for easy comprehension by humans;
- usually there is no comprehensive indicator for value ranges (normal, critical, or out of range). This would require a conceptual understanding of value ranges. Moreover, in medicine parameter ranges are context dependent: What is *normal* often depends on the patient's actual situation, i.e., on several other parameters;
- X–Y plots give the impression of a linear development of parameters between the tics shown. This is often misleading;
- the data shown have to be representative for the period of time they cover. A PDMS with time-stamped data usually shows the data value received at a fixed time point. No provisions are made to present the value most representative for a given time interval. This creates a severe problem when the time interval one data point covers is increased. Usually this happens by decreasing the resolution of the time axis in the display. Depending on the starting time of the time axis of the display quite different data values may be shown if the PDMS just picks out the values stored at the time of the axis tics.

As an aid to comprehension and analysis of data graphic representations are a proper tool [6]. We have developed a graphic visualization system (called VIE-VISU) which uses metaphor graphics. In the following section we present the design of the graphic objects and the display. Section 3 summarizes the components of our visualization system. A discussion of the design and its usability is given in section 4.

2 Metaphor graphics to visualize ICU data

Graphic representation offers a wide variety of methods to support humans in the easy integration of data [4, 5, 6, 7]. The method to choose depends mainly on what information you like to ease comprehension. In our domain—neonatal intensive care—we would like to be able to recognize changes in the status of the neonate over time. The most relevant parameters for such a view are circulatory, respiratory, and fluid balance data.

A good way to represent changes over time are small multiples [4]. They resemble the frames of a movie: the same graphical object changes its shape and color from frame to frame. The time steps between frames are fixed as is the basic design of the frame. The fixed design focuses attention to the shifts of the data over time.

Volume rectangles were used as a metaphor graphic by Cole and Stewart [1] to represent respiratory data. Breath rates and breath volumes are sketched by the size and volume of rectangles. Rectangles offer too few degrees of freedom for our problem. Our first goal was to combine the following parameters into one metaphor object:

- Circulatory data:
  - mean blood pressure (BP),
  - heart rate (HR), and
  - a catecholamines index (CI). The index gives the summarized (and weighted) administration of dopamine, dobutamine, epinephrine, and norepinephrine.
- Respiratory data:
  - spontaneous breathing frequency (f_{spont}),
  - oxygen saturation measured by pulsoximetry (S_pO_2),

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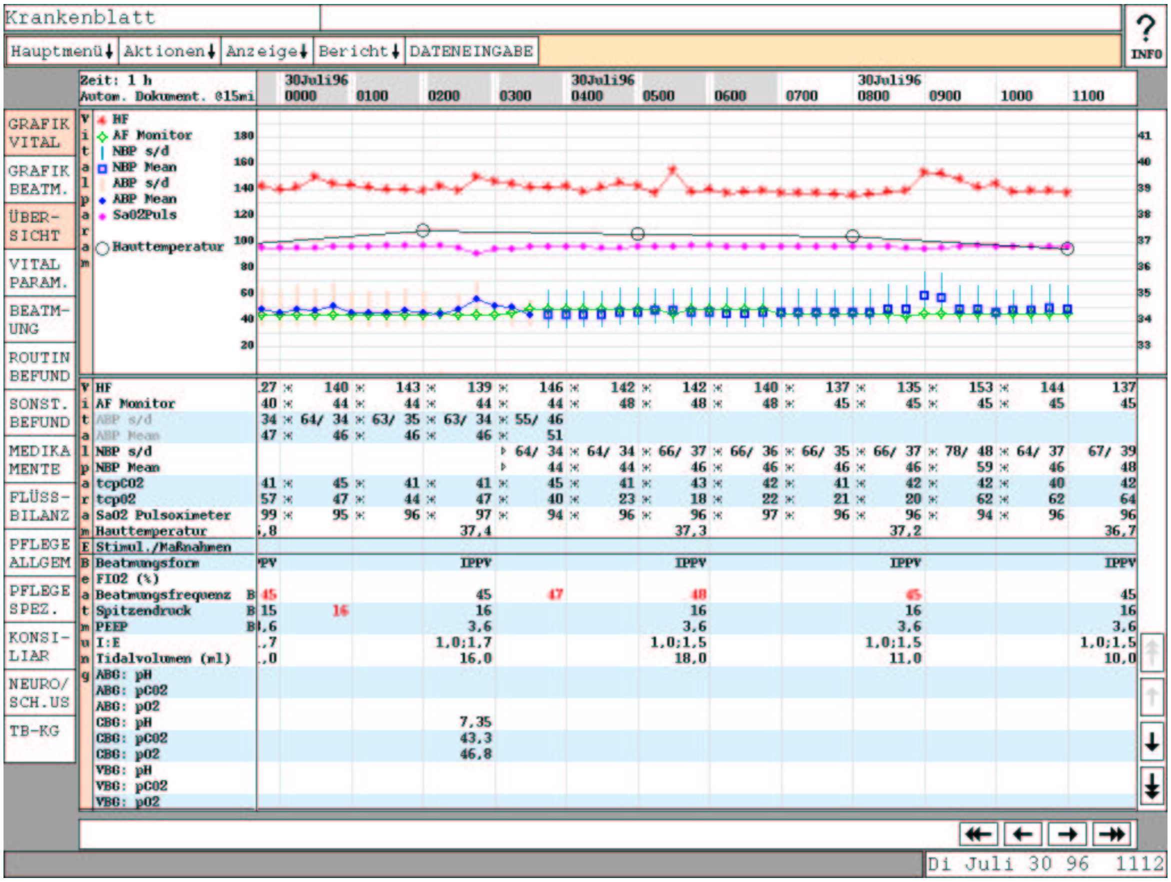

Figure 1. Sample data display of patient data management system

- fraction of inspired oxygen concentration (FiO_2)
- type of ventilation: none, continuous positive airway pressure (CPAP), high frequency ventilation (HFOV), or intermittent positive pressure/mandatory ventilation (IPPV/IMV). Depending on the type of ventilation:
- $CPAP\ level$ for CPAP ventilation;
- mean airway pressure (Paw) and
- pressure amplitude of the oscillator (ΔP) for HFOV;
- peak inspiratory pressure (PIP),
- positive end-expiratory pressure ($PEEP$), and
- mechanical ventilatory rate (f) for conventional mechanical ventilation.

- Fluid balance:
  - total fluid intake, and
  - total urinary output.

It took several design steps to find a metaphor graphic able to include most of these parameters in a way easy to comprehend. It is quite clear that such a graphic object has to be rather complex.

2.1 A first design: growing and shrinking circles

For our first design we used a very simple object: a circle with twelve sectors. Each sector represents one parameter. A "normal" circle represents the normal situation, i.e., all parameters are normal. The sectors grow or shrink in correspondence to the deviation from the normal value. The first implementation made transparent that twelve sectors were too much to be recognized. We reduced the number of sectors to eight. A sample graphic object is drawn in Figure 2. The parameters shown are (in clockwise order): HR, fluid balance (intake minus output), FiO_2, f_{spont}, f or ΔP, PIP or Paw, CI, BP. To separate sectors more clearly they are alternately colored light and dark blue. A dangerous increase is colored in red.

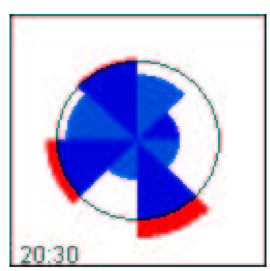

Figure 2. Circle sectors depict ICU parameters

The first use gave us a clear impression of the major flaws of this design: there is no overall impression how the situation of the patient "looks like". The physician is forced to isolate the sectors, which hinders from recognizing repetition and change over time. The design suffers further from learnability. It is hard to remember which parameter each sector shows.

The bad experience with a uniform object made us try a completely different approach using a highly structured object.

2.2 A structured metaphor graphic object

A highly structured object has the advantage of easy identification of several parameters. The object we designed is explained in Figure 3.

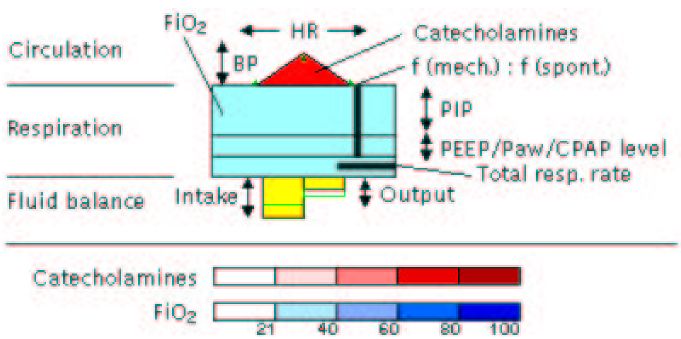

Figure 3. The metaphor graphic object

The actual value of a parameter is either depicted by the size of an object or by its color. The larger a value the larger the object, or the darker the color. Heart rate is the only parameter which varies the horizontal size (of the top triangle). Blood pressure, PIP, $PEEP$, Paw, fluid intake, and urinary output vary the vertical size of the drawn object. The total respiratory rate is given by a slider which increases from right to left. The relation between the mechanical ventilatory rate and the spontaneous breathing rate is depicted by a vertical slider which moves to the left the higher the spontaneous respiratory rate. FiO_2 is represented by the color of the respiration block. The higher the FiO_2 concentration supplied by the ventilator or by the incubator, the darker the blue of the respiration block. The color of the triangle changes in the intensity of red with increasing amounts of catecholamines applied. S_pO_2 and ΔP are not displayed.

The metaphor graphics differs depending on the type of mechanical ventilation. Figure 4 samples four different situations for each type of ventilation. The left column shows the graphic, the right column shows the corresponding data values. VIE-VISU is able to switch between alternate displays for graphics and for data values.

The four examples show (from top to bottom):

1. The ideal situation. Everything is normal. The neonate is not ventilated. The spontaneous breathing rate is normal (50/min). The FiO_2 is 21%. Intake of 5 ml/kg/h and (urinary) output of 3.5 ml/kg/h are as expected.
2. The neonate is on n(asopharyngeal)-CPAP. The CPAP level is 4 mbar ($PEEP$). The FiO_2 is slightly increased to 30%. The heart rate is elevated to 170/min. Intake and output are a bit above normal values (marked by green lines.)

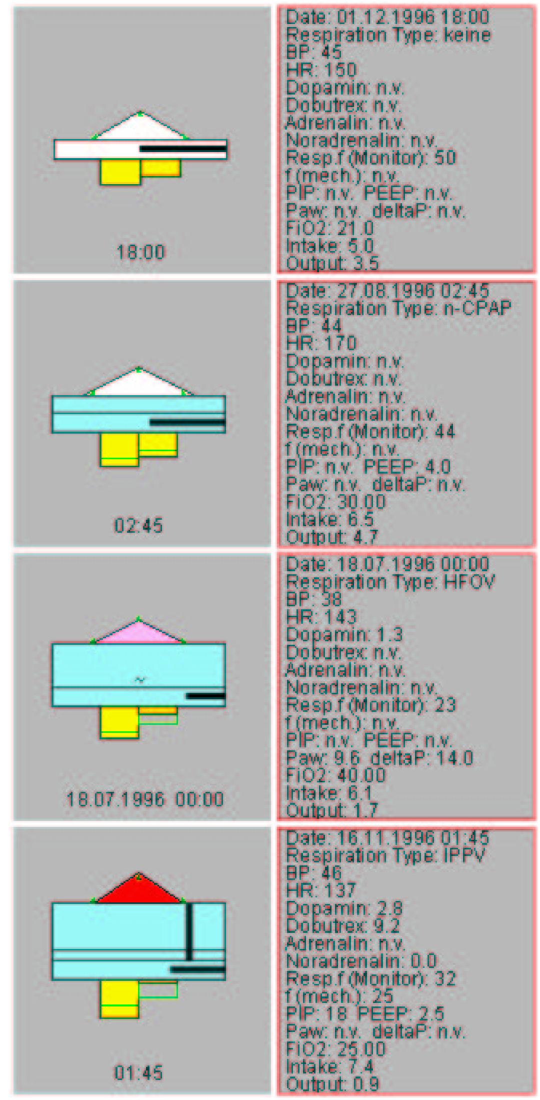

Figure 4. Four different ventilation situations

3. A high-frequency ventilated (HFOV) neonate with a Paw of 9.6 mbar (ΔP is not shown in the image.) To be able to distinguish CPAP and HFOV ventilation the HFOV graphics contains a "$\sim$" marker. The catecholamines index shows a light pink due to the delivery of dopamine at 1.3 μg/kg/min. The spontaneous breathing rate is a bit low (23/min). FiO_2 is light blue (40%). Intake is a bit increased, output is decreased.
4. An IPPV ventilated neonate with a PIP of 18 mbar and a $PEEP$ of 2.5. The mechanical ventilation rate is 25/min. The (total) breathing rate shows a reading of 32/min. As a result, the vertical bar showing the relation between the mechanical ventilatory rate and the spontaneous breathing rate is in a right sided position. FiO_2 is slightly increased to 25%. The catecholamines index is dark red due to 2.8 μg/kg/min dopamine and 9.2 μg/kg/min dobutamine. The mean blood pressure and the heart rate are quite normal. Intake (7.4 ml/kg/h) is considerably increased and output (0.9 ml/kg/h) is decreased.

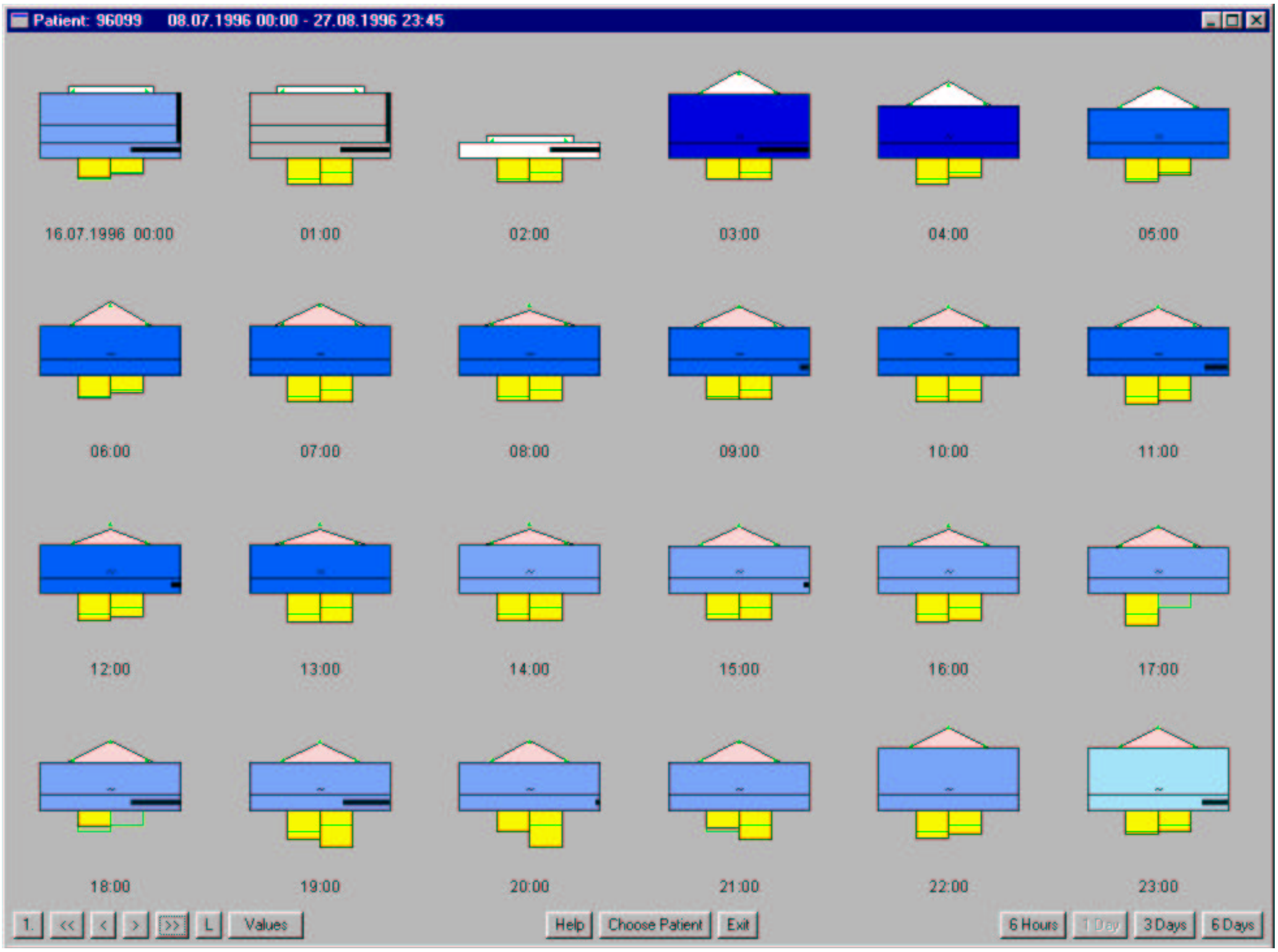

Figure 5. The 24 hours display of VIE-VISU

The graphic object is the basis for recognition of change over time. By repetition of the object in 24 frames (6x4) the situation of the ICU patient in the last 24 hours is presented in one display. Each multiple shows the situation at a specific hour. The multiples should enable the physician to focus on repetition and change. A sample display is shown in Figure 5.

The display draws attention to the change from IPPV ventilation (at 01:00) to HFOV ventilation (at 03:00; data are missing at 02:00). HFOV ventilation starts with high FiO_2 supply which decreases over time. Simultaneously Paw settings decrease over time until 22:00. At this time Paw is increased again. The circulation is quite ok. Fluid balance shows a considerably increased output most of the time.

The 24 hours display supports to focus on continuity and surprise. It is easy to recognize a stable patient. Continuous improvement is made transparent. Attention is directed toward critical situations in patient care: the change from IPPV to HFOV and the increase of Paw at 22:00 in our example. With respect to our initial goal, namely to ease the comprehension of the essential changes in the patient's status over time, the display fulfills its task.

3 The VIE-VISU display system

The VIE-VISU display system is a client-server application. It is embedded into the standard network of bedside and nursing PDMS workstations at two neonatal intensive care units at the Department of Neonatology, University of Vienna. VIE-VISU is activated by the PDMS using a special applications button. The graphic display is overlayed to the standard PDMS window. VIE-VISU is a Java based application. It communicates with a server providing the necessary data.

The Java client starts by showing the graphical display of the selected patient. The most recent 24 hours data received from the data server are displayed. The client offers a set of buttons for display management (bottom of Figure 5). This includes

- changing between the display of metaphor graphics and of data values;
- moving around on the time axis (scrolling the display);
- changing the time scale: the standard time scale is a 24 hours display with a graphic object drawn every hour. The scale may be changed to 6 hours (object distance is 15 minutes), 3 days (3 hours

between objects), or 6 days (4 objects per day);

- selecting a different patient to view.

The data server fulfills three tasks:

- *data selection*: the data required by VIE-VISU are collected over night from the PDMS. In principle this can be done online, but the time needed daily to collect and format the data is 22 minutes. This is prohibitive for online requests. Data selection uses an ODBC interface to the PDMS database. The data export queries are run at very low priority which causes the enormous time required. This problem disappears on a PDMS which uses state-of-the-art relational database technology.
- *data preprocessing*: the retrieved data are preprocessed by utilizing data validation methods [3]. Preprocessing further introduces a temporal validity interval for each parameter. E.g., fluid balance values are usually entered every three hours. As a consequence the same fluid balance value will be served for a maximum of three hours. After that time it will be a missing value if no real data value is available. Preprocessing further normalizes values. Fluid intake and output and catecholamines dosages are divided by the current body weight of the patient.
- *data service*: the server provides the Java client with the requested data. This process includes finding a representative value for each parameter for the time points requested. The current version uses the median of all valid data values available in the interval between a time point and the next one.

4 Discussion

Multiples directly depict comparison. They are well suited to reveal repetition and change, enabling the user to see patterns and surprise. A first evaluation of VIE-VISU has proven the 24 metaphor graphic objects are able to focus physician's attention toward critical situations in patient care. A very fast comprehension of the situation is supported. This is consistent with results from a human performance evaluation on the recognition of respiratory data [2].

However the goodness of metaphor is of essential importance to recognition. Cole and Stewart [1] used volume rectangles to represent two ventilatory parameters: breathing/ventilation rate and tidal volume. Width and height of the rectangles are modified in accordance to these two parameters. The size of the rectangle is a metaphor for the minute breathing volume of the patient.

Uniform objects do not seem to be adequate for helping to analyze the complex situation of a patient represented by a set of *different* parameters. A circle is not suitable for such a task. It is hard to learn—you often forget which parameter is to be found in which sector. It forces attention to the sectors instead of the change between frames. And it gives problems in establishing "normal values". A norm circle is inappropriate to do that. It is confusing. Some parameters may be lower or higher compared to normal (e.g., BP, HR), other values are never less than normal (e.g., FiO_2 is never less 21%), and others have a normal value of zero (e.g., PIP). As a result, some sectors never shrink and the display gets biased. The highly structured object we used in our second design avoids such a bias. It further supports learnability and orientation due to the different shapes and colors within one object.

Highly structured objects have one disadvantage: there is very limited space for each of the different parameters. This makes it nearly impossible to recognize subtle changes of a parameter's value. Inappropriate scales effectively hide the essentials [7]. We tried to avoid such hiding effects by carefully setting scales. In addition, we marked expected (normal) values by green dots and lines. This makes is easy to recognize deviations from the expected. An evaluation study should provide us with details about the accuracy a viewer is able to achieve. We can not expect great precision on recognizing slight modifications of individual parameters (the values display should serve for this task), but we expect high accuracy on recognizing essential changes.

Visualization of monitoring data invokes an additional problem: how to deal with missing and erroneous data. Monitoring suffers from holes in the data collection and from errors due to several other causes (e.g., sensor displacement, calibration procedures). Preprocessing tries to detect such problems. As a result several parameters will be missing over some periods of time. Visualization has to make transparent such missing values. Our metaphor object was designed with respect to the ability for displaying missing values. In principle we use four methods:

1. color becomes grey (FiO_2),
2. sliders disappear (ventilatory rate),
3. objects shrink to (near) zero size (heart rate, blood pressure, fluid balance),
4. blocks are drawn in the size of the normal value of a parameter, but the upper left edge is cut (PIP, $PEEP$, Paw, $CPAP\ level$).

All these four methods have qualified not to disturb the comprehension of the patient's situation. An example of missing blood pressure is given in the first three frames of Figure 5. The circulation triangle degenerates to a horizontal bar. Method (4) is the most drastic one: Drawing a block with default size is preferable to drawing a block of zero size. It has the advantage of keeping the image of the current ventilation method. But it may confuse due to a possible size change of the ventilation block. Specifically this will be a problem if ventilation data are missing for one or few time points only. However in practice this rarely happens. Ventilation parameters are not changed very often and they can be assumed constant between changes. As a result they are either missing for a long period of time or they will be filled in by the preprocessing. In effect continuity of object shape is guaranteed in practice.

A different and quite problematic question is the one about the representative value of a parameter over a certain interval of time. This becomes virulent if the resolution of the time axis of the display is less than the time resolution of the data collection process. We use the median value of all data values within the time interval as the representative value. This is somewhat consistent with data collection methods of the PDMS averaging data received every five seconds. However it is quite questionable. It looses extreme values which may be of specific importance for patient care. However, in practice, extreme values are very often artifacts. Data validation offers only very limited methods to recognize such artifacts if the data density is low and if the data has been already averaged by the PDMS preprocessing. The VIE-VISU server is confronted with such a situation. Therefore it serves the median value over an interval instead of the most severe value within that interval which may me more interesting.

The design of graphic displays for ICU data comprehension has to look for easy learnability, high accuracy, and increased speed in comprehension. We are preparing a clinical study which examines the usefulness of VIE-VISU both for expert neonatologists and for novice physicians. The result should provide us with detailed insight about the three criteria learnability, accuracy, and speed.

5 Conclusion

VIE-VISU is a visualization system for data collected at intensive care units. The change in the patient's status over time is depicted by 24 multiples. Each multiple is a highly structured metaphor graphics object. Each object visualizes important parameters from circulation, ventilation, and fluid balance. One display gives a metaphor graphics summary on a time scale of six hours to six days depending on the user's choice.

Fast comprehension and easy analysis of changes of the patient's situation by physicians was the primary goal of VIE-VISU. The design using multiples promotes to focus on stability and change. A stable patient is recognizable at first sight, continuous improvement or worsening is easy to analyze, drastic changes in the patient's situation get the viewers attention immediately. In summary VIE-VISU provides access to the complex without complicating the simple.

Metaphor graphics are quoted for easy learnability, long remembering periods, and good decision support when the task is finding patterns in a mass of data. A clinical study now at its beginning should justify these claims for VIE-VISU.

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