Benefits of a Knowledge-based System for Parenteral Nutrition Support: a Report after 5 Years of Routine Daily Use

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Abstract. Calculating the daily changing composition of parenteral nutrition for small newborn infants is troublesome and time consuming routine work in neonatal intensive care. The task needs expertise and experience and is prone to inherent calculation errors. In 1996 we introduced a knowledge-based system called VIE-PNN at the neonatal intensive care unit (NICU). It supports the daily calculation of nutrition plans for combined parenteral and enteral nutrition of newborn infants utilizing textbook knowledge and clinical rules of expert neonatologists. VIE-PNN uses a HTML-based client-server architecture and is integrated into the intranet of the local patient data management system (PDMS).

The system is now in daily routine use for more than 5 years at 2 NICUs. Its main benefits are considerable time savings for clinicians and an increased quality of care. The main factors for success are its ease of use, its robustness, the integration into the PDMS, and the maintainability by the clinical experts. Most important, physicians highly value the time savings the system provides.

1 Introduction

Neonatal intensive care units (NICU) care for small premature or sick newborn infants. They have either a low birth weight (400-1500 grams) and/or a serious medical problem and may not tolerate oral feeding. Thus, the planning and calculating of an adequate nutritional support for the sick newborn infants is daily routine work. Individual parenteral nutrition solutions (PNS) are calculated by the attending neonatologists according to the individual and changing needs, prepared by the nurses or pharmacists and administered continuously over 24 hours via infusion pumps. The healthier the newborn infant, the more oral nutrition may be tolerated and proportionally the daily PNS needs will be decreased. In addition, some drugs mainly those helping to maintain adequate tissue perfusion are supplied as bypass medication in parallel to the PNS. These bypasses contain the small amounts of the drug(s) usually dissolved in a glucose/water solution. Since this amount of glucose adds to the glucose and fluid load, it has to be taken into account when computing the daily PNS. Finally the nutrition supply should be optimized balancing the maximum individual nutritional and fluid allowance with the individual tolerance which increases with age and state of healthiness.

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These boundary conditions make evident that preparing PNS schedules is time consuming, needs practical expert knowledge and experience, and involves the risk of introducing possibly fatal errors [4, 7, 15, 16]. The daily time required per patient is approximately 10 minutes summing up to more than one hour for an eight beds NICU. Approximately 5–50% of all PNS sheets contain calculation or omission errors requiring recalculation or even remixture. This is costly and requires additional time of physicians and nurses.

A computer program which supports this planning task should overcome the problems inherent to the manual computation of the PNS schedule. Such a program has to combine standard textbook knowledge about neonatal nutrition with the practical knowledge of expert neonatologists. Being able to cover the clinical standards of a NICU it has to codify this knowledge and apply it to the data of the neonate.

The basic goals for creating such a knowledge-based system (KBS) are

- to interactively calculate the daily nutritional supply. As it is impossible to cover all clinical conditions for such a KBS the user must have a chance to adapt the programs recommendations to the actual condition and tolerance of the newborn infant,
- to reduce the daily workload associated with the calculation of PNS,
- to individually balance enteral and parenteral feedings,
- to use standardized PNS in case this is applicable to the newborn infant (usually about 50% will tolerate a standardized PNS, reducing the nurses or pharmacists workload),
- to include bypass medications for both, individual or standardized PNS,
- to allow daily increases or decreases of the nutrition and fluid supply. This requires reasoning methods taking into account the data of the previous days,
- to produce a printed PNS schedule output which will be used by the nurses or pharmacists to prepare the PNS and for the data archive.

Following the path to maintain an excellent quality of care such a system should be able to maintain the hospital's standard for neonatal nutrition management. It has to provide adequate control of fluids, electrolytes, fat, nitrogen, and caloric needs. This standard is defined in terms of rules of expert neonatologists. Finally, it is extremely important to allow the experts to keep the system up-to-date. Nutrition facts and products change quite often. Furthermore, new knowledge arising from a better understanding of the needs of low birth-weight neonates has to be integrated into the knowledge-base. This knowl-

edge maintenance aspect is essential for the longevity of such a routinely used medical system.

Computer programs supporting the calculation of parenteral nutrition plans are available at a few hospitals. Most of them are designed for adult or pediatric patients (e.g., [10, 14]) without giving specific consideration to the specific needs of newborn infants. There are a few pediatric programs for parenteral nutrition planning covering also the group of newborn and premature infants [6, 11, 12].

Such programs, however, do not cover the specific metabolic and nutritional needs of extreme low birth-weight newborn infants (birthweight 400–1000 grams). Only a few programs are specifically tailored to the needs of small newborn infants: there are simple calculation programs [2, 8, 11] and more complex rule-based systems [3, 6]. Both types of programs reduce the routine work load, and lead to a more optimized nutrition supply. None of these programs offers solutions to all requirements stated above. Specifically the support of both individualized and standardized [17] PNS in combination with bypass medication, the adaptability to different clinical standards, and the support for maintenance by clinical experts are critical points.

Our solution to the problem is presented in the next section. This is followed by a discussion of the lessons learned and the benefits of the system. This should lead towards a better insight under what circumstances knowledge-based systems are to be successfully applied in the clinical routine.

2 The VIE-PNN system

VIE-PNN consists of three main modules: patient administration, computation of the daily PNS schedule, and maintenance of the knowledge base.

Patient administration is needed for adding new patients (name, sex, date of birth, venous access) and for archiving the data of discharged infants. The maintenance module supports editing of nutrition rules, parameter limits, rounding factors, and updating of oral nutrition preparations and bypass medications. All these rules, parameters and components are revisable by the experts using an HTML browser.

The main module of VIE-PNN interactively calculates the daily PNS schedule. It starts with yesterday‘s PNS values of the infant (or plausible default values at the day of hospital admission). These values determine the input parameters of the system (see Table 1).

Table 1. Input and output parameters of VIE-PNN.

Input parameters	*Output parameters*	*Statistical measurements*
Body weight	Parenteral supply	Energy rates
Age	Enteral supply	Parenteral infusion rate
Total fluid allowance	Glucose	Fat infusion rate
Enteral products	Proteins / amino acids	
Drugs	Electrolytes	
Serum values	Vitamins	
Health condition	Trace elements	
	Fat	
	Bypass medication	

VIE-PNN determines the PNS schedule by

- applying rules for the daily increase of nutrition components,
- applying rules for nutrition needs based on today’s serum values,
- applying rules for adapting the nutritional requirements to the clinical problems of the infant,
- decreasing parenteral nutrition components by the ratio of enteral to total supply (for components which are contained in oral products),
- checking for range limits of the components,
- applying rounding methods based on knowledge about the precision needed for each component,
- combining drugs for bypass medication,
- solving the problem if the total fluid allowance is too small to cover the nutritional requirements.

The system’s knowledge is coded in PERL-like IF-THEN rules. A sample rule is given in Figure 1. It determines the daily prescription of sodium based on age, the current serum value and the clinical condition IADH. This is a rule of medium complexity. Protein and fat supply, e.g., need more complex, addition of trace elements, e.g., need a simpler rule. VIE-PNN’s rules are applied in a forward chaining manner to determine today’s values of all output parameters.

```
Targetvalue Na   = 137;
Targetvalue NaCl = 1.5;

if    (Na mmol/l > 145) { NaCl mmol/kg/d = 0; }
elsif (Na mmol/l > 142) { NaCl mmol/kg/d = 0.5; }
elsif (Na mmol/l > 139) { NaCl mmol/kg/d = 1.0; }
elsif (Na mmol/l > 135) { NaCl mmol/kg/d = 1.5; }
elsif (Na mmol/l > 130) { NaCl mmol/kg/d = 2.0; }
else  {
  if   (IADH eq 'yes') { NaCl mmol/kg/d = 0; }
  else {NaCl mmol/kg/d = Targetvalue NaCl
          + (Targetvalue Na - Na mmol/l) * 0.45; }
       }

if (Age == 1) { NaCl mmol/kg/d = 0; }
```

Figure 1. Sample VIE-PNN rule: daily sodium prescription.

Using eight HTML pages VIE-PNN asks for input and verification of the nutritional parameters. Minimal input is required from the physician. Manual input is mandatory for lab values (if new values are available), for changes in the amount or kind of oral feedings and for changes in bypass medication. If there are no changes the physician may accept all pages by clicking the `OK` button. The system recommends values for nutritional components based on its knowledge rules. The physician may change a value in case the nutrition requirements differ from standard rules due to a problem of the neonate which is not included in the knowledge base of VIE-PNN. For each component the user can request an information page. It gives an in-depth explanation about the computation of the recommended value (including basic values, rounding factors, and rules used). The final page shows the complete PNS schedule (see Figure 2). The user may accept it and print the PNS sheet or again modify single parameters.

3 Lessons learned

3.1 Physicians like HTML

Not a surprise today it became evident to us in 1996. The Web-Browser provides an intuitive interface to the user. This obviously reduces the need for training and the time required to adapt to the design of the user interface of a task-specific application.

We started with the project in 1991. The first four versions of VIE-PNN [9] were stand-alone PC versions. The initial three versions were implemented using an expert system shell (“Intelli-

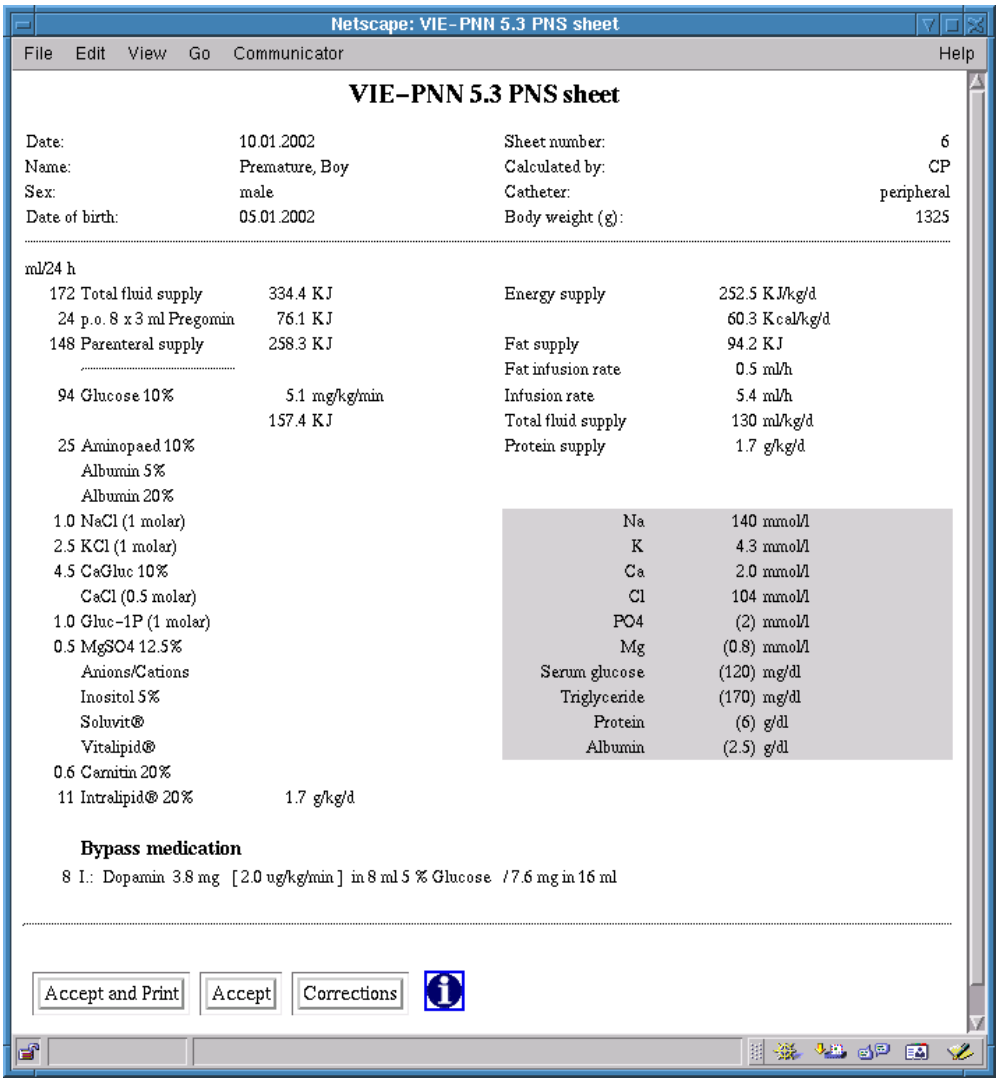

Figure 2. VIE-PNN's HTML page showing the final composition of the parenteral nutrition solution. The top part gives administrative data. The left column shows the components of the PNS. The right column lists statistics and actual lab values. If these were not determined, the calculation will be based on normal values (shown in parentheses).

gence/Compiler (I/C)"). These versions were too slow to be useful in the daily routine. The fourth version was a redesign in C++ with a user interface written in TurboVision. It was fast, but not enough flexible. Furthermore, it was impossible for the experts to adapt VIE-PNN's decision rules to changing nutritional standards. Such changes in the knowledge base required source code changes by the knowledge engineers and recompilation of the system. The system was introduced at the NICU including some initial training. It was evaluated successfully for its correctness [1] but was used only by a few physicians and then not on a regular basis. The main reasons were its inflexible user interface and its installation on a stand-alone PC: The PC was located in a room off-site and it was often used for other urgent tasks.

The negative experiences with the stand-alone version of VIE-PNN motivated us to try a completely different approach. The NICU is equipped with an intranet of workstations. The workstations (two mirrored servers, a bedside workstation for each bed, and several workstations in the nurses' and the physicians' rooms) run the patient data management system (PDMS) Hewlett-Packard CareVue 9000. All patient records are handled electronically by this PDMS. Our goal was to integrate VIE-PNN into this system. Unfortunately, HP CareVue at this time was a completely closed system. There was no possibility to integrate knowledge-based modules which would be the ideal solution for a parenteral nutrition support system. We were therefore forced to choose the second best solution: using the workstations as a display for our VIE-PNN system. We added an additional server to the intranet which runs VIE-PNN on request of any client workstation.

The redesign of VIE-PNN (version 5) for a client-server architecture is based on HTML. This makes it ideally suited for use from every workstation within the clinical intranet. Using this technology VIE-PNN has survived the replacement of the whole hardware equipment of the NICU.

The introduction of VIE-PNN version 5 in 1996 at the NICU was well appreciated by the clinical team. Obviously, the HTML interface and the integration into the standard PDMS environment made the system really comfortable to use. After a very short period nearly all neonatologists liked to work with the system. There were no more

PNS sheets calculated by hand.

Due to the success of VIE-PNN it was installed in 1998 at a second NICU. VIE-PNN is now in continuous operation at these two NICUs.

3.2 Physicians only use time-saving systems

The main reason for the success of VIE-PNN is the amount of time it saves for the physicians. Clinicians changing from the manual computation with the help of a hand-held calculator to the computation using VIE-PNN immediately experienced how fast they are able to do the nutrition planning. This was proved by the results of a questionnaire which was answered by all neonatologists at the NICU using the system: 73% used the system for its time-saving features.

To get a more objective view of the time saved, we performed a prospective study. In this study 50 routine PNS were calculated in parallel by using VIE-PNN or by the traditional way using a hand-held calculator. Both calculations were performed by various physicians in charge. The time needed to complete a PNS sheet was measured exactly.

The results proved significant time savings of a mean of 4.7 minutes per PNS prescription. The mean time needed to calculate a PNS was 2.4 minutes (VIE-PNN) vs. 7.1 minutes (hand-held calculator). This sums up to about $\frac{1}{2}$ to 1 hour daily time savings at the NICU [5].

For all PNS prescriptions collected at the two NICUs from 1996 to 2002 we analyzed the connect times (see Figure 3). The connect time is defined as the time between the begin of work with a patient sheet and the final printing of the completed PNS. Again we see the main peak at 3 minutes. But the average connect time is higher. This may be explained by the fact that physicians at the NICU only rarely can work uninterrupted: even while calculating the PNS they are distracted by urgent patients needs, telephone calls or requests from nurses, parents or others. From our data we may estimate that only about 60% of the PNS solutions were calculated without interruption. This adds to the importance of providing a robust and structured interactive program.

3.3 Physicians need accurate systems

Accuracy is a fundamental condition of a medical support system. However for KBS which always have the problem of limited knowledge there is the question whether the system behaves accurate in all situations. This was answered positively by the users. Our questionnaire showed that 73% of usage was motivated by VIE-PNN's accuracy improving features.

Again, our evaluation study proved the accuracy. The PNS sheets produced in parallel were later reviewed by a senior neonatologist who rated errors and omissions as potentially life threatening (like prescribing dangerous concentrations of potassium or bypass medication), major (e.g., prescribing too little amounts of calcium which is needed for bone mineralization) or minor or clinically not relevant (like forgetting to calculate the total energy supply).

The results showed that there were only little and no systematic differences in the composition of the PNS and no life threatening errors. There were less major (10% vs. 18%) and minor (12% vs. 66%) errors and omissions in the VIE-PNN calculated prescriptions. More details are to be found in [5].

Most interesting, all errors detected in the VIE-PNN calculated prescriptions were related to values that were interactively changed by the prescribing physician. The possibility to create nutrition plans

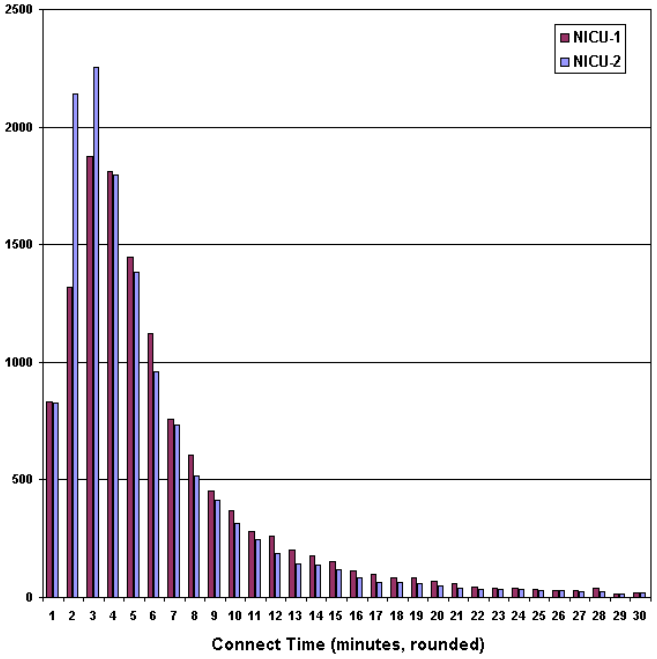

Figure 3. Number of PNS-Sheets completed within the specified connect time to VIE-PNN.

with (major or minor) errors is a consequence of the provided interactiveness. We are, however, convinced that this interactiveness is definitely required.

How does VIE-PNN prove to the user that its recommendations are accurate? The explanation page (activated by clicking the `i`(nformation) button) presents details about the computation of the parameter in question. Often a value looking unplausible appears correct after looking at the explanation page. Specifically the proportional subtraction of components from the parenteral nutrition which are contained in the enteral product subscribed is a complex procedure which is usually not done by hand or only roughly estimated. The explanation facility unveils these details and has an additional educational effect.

3.4 Knowledge maintenance: a job for medical experts

One of the most important features of knowledge-based systems is the ease of maintenance. Expert neonatologists must have good support to keep up-to-date the knowledge about oral products, drugs, plausible limits of parameters and prescription rules. This was essential during the development and life-time of the various versions of VIE-PNN. Most importantly, knowledge has to be readable, understandable, and modifiable by the experts. This gives basic trust in the system (essentially required in the field of medicine) and it allows to fulfill the required update tasks without intervention of a system's expert.

VIE-PNN has a HTML-based maintenance module which allows the supervising neonatologist to edit the knowledge. Using HTML-forms and a rule editor he/she may alter parameters, products and prescription rules. Such changed rules are checked for correct syntax and consistency. If the validation succeeds they are converted to PERL code and put in use immediately.

4 Benefits: a summary after 5 years of routine use

VIE-PNN is now in routine use for more than 5 years. It is installed at two NICUs. NICU-1 is an 8-bed unit close to the delivery room. It admits mainly very small premature infants immediately after birth. NICU-2 is a 16-bed unit, which covers a broad spectrum of premature and sick neonates. Only a portion of the babies at NICU-2 need parenteral feeding, but they usually stay longer. A statistical summary which characterizes the years of operation at these NICUs is given in Table 2.

Table 2. Characterization of VIE-PNN's performance at the two NICUs.

		NICU-1	*NICU-2*
Beds		8	16
Patients (with PNS-sheets)		1826	1344
Age at admission (days)	median	1	6
Age at admission (days)	avg	3.5	30
	min	429	415
Birth-weight (g)	avg	1602	1986
	max	4442	4200
Weight at admission (g)	avg	1634	2043
PNS-sheets		13060	13223
PNS-sheets/patient	avg	7.7	13.5
Days of operation		1696	980
PNS-sheets/day	avg	7.15	9.84

Summarizing this time of operation we are able to identify the following features of success. This may help to identify success conditions for future projects on bringing AI applications into clinical routine.

Time savings

The most visible benefit to the users is the amount of time it saves. Physicians save up to 1 hour per day if they use VIE-PNN. This is achieved by replacing a complex manual computation by an interactive system which knows about clinical prescription rules.

Quality of care

VIE-PNN considerably reduces errors of prescription. Its results are accurate and physicians trust in the results of the PNS computation (possibly after inspecting an explanation page giving in-depth details).

The essential knowledge contained in VIE-PNN is taken both from textbooks and from practical clinical experience. It encodes best practice standards of the clinic. The daily routine use of VIE-PNN makes clinical guidelines operational. As a consequence it helps to improve and maintain quality of care at a very high level.

On-line maintenance

Expert neonatologists are enabled to cope with the continuous change of knowledge about nutritional requirements. VIE-PNN supports the experts in maintaining its knowledge base. We would not have VIE-PNN running after 5 years without this maintenance tool. It is essential for longevity.

Practical knowledge made applicable

A system containing practical clinical knowledge can be a success even if physicians do have that knowledge at hand. Our experience shows that successful AI systems are not restricted to complex domains of application with very specialized knowledge. VIE-PNN is valuable in the hecticness of the clinical routine because it improves the accuracy and the quality of care.

Of essential importance is the smooth integration of VIE-PNN into the environment of the PDMS which results in all-time accessibility and routine use. Finally, the intuitive user interface of the HTML browser provides the necessary ease of use.

VIE-PNN is a superb tool to ensure quality of care by integrating an AI module into the daily working environment of physicians and nurses. Five years of continuous stable operation at two NICUs have demonstrated the beneficial effects of daily routine use. Further NICUs have shown their high interest in installing the system. The knowledge maintenance module simplifies the customization of VIE-PNN to the clinical standards of such new sites.

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