An Improved Intravenous Fluid Rate Determination Using Fuzzy Logic

Adesina Abdul Akeem Agboola
Department of Mathematics
University of Agriculture, Abeokuta, Ogun State, Nigeria
aaaola2003@yahoo.com

Misturah Adunni Alaran, Adio Taofiki Akinwale[1] and **Olusegun Folorunso**[2]
Department of Computer Science
University of Agriculture, Abeokuta, Ogun State, Nigeria
[1]atakinwale@yahoo.com
[2]folorunsolusegun@yahoo.com

Abstract

Recently, medical experts have shown that the determination of appropriate intravenous fluid rate (IFR) for intensive care unit (ICU) patient is not too efficient when based on Mean Arterial Pressure (MAP) and Hourly Urine Output (HUO) for an ideal clinical situation. This paper increased the parameters to four by including Heart Beat Rate (HBR) and Central Venous Pressure (CVP) to determine the exact value of IFR. A Mamdani fuzzy type model was employed to develop a reasoning mechanism for four input variables and the method of Centre of area was used to derive a better result. The input variables were formed on rule base system which resulted into 81 different combinations of all possible situations. The process was implemented with fuzzy logic toolbox 2.1 in MATLAB 6.5. An interactive graphical user interface was designed as front end to accept values and display results. The developed software permits the saving of information which could form a medical database for decision making by the medical experts. A series of data were collected and entered into the developed interface which generated output result. In comparing the two-parameter based technique (MAP, HUO) with the new four-parameter (MAP, HUO, HBR and CVP), it was found that there was discrepancy in the rate of the IFR such that most patients (92%) were not given appropriate intravenous fluid. It was also found that IFR values based on latter tested significantly better than IFR values based on the former when compared with human expert judgments.

***Keywords**: Fuzzy Logic, Mamdani model, Intravenous fluid rate, Fuzzy inference rule, Centre of area*

1 INTRODUCTION

Intensive care Unit of any clinic is where treatment involving rapid decisions on the basis of a large and disparate array of information are made. To make medical decisions, intensive care unit (ICU) physicians often rely on conventional wisdom and personal experience (tacit knowledge) to arrive at subjective assessments and judgments. This requires an intuitive, or non explicit weighting of various factors to achieve an optimal balance between clinical endpoints that are often competing [1]. Recently, there has been a great concern over the burden of unwanted variation in clinical practice [22] [12]. As a result, physicians are increasingly being asked to adhere to explicit guidelines that have been agreed on by the medical community at large [7]. Such guidelines often have a logical structure that makes them suitable for computer implementation. Consequently, there is an increasing interest in computer-based decision support tools to automate aspects of the medical decision making that takes place in complex clinical areas such as the ICU [9].

However, in ICU the rate at which intravenous (IV) fluids are administered to a patient is currently determined by the physician. Furthermore, medical experts have shown that the determination of appropriate intravenous fluid rate (IFR) for intensive care unit (ICU) patient is not too efficient when based on Mean Arterial Pressure (MAP) and Hourly Urine Output (HUO**)** for an ideal clinical situation. Multiple factors are weighed by the clinicians to determine the amount and rate of intravenous fluid administration that should be administered to a given patient [1]. The authors illustrated how fuzzy logic control works using only two variables: Mean Arterial Pressure **(MAP**) and Hourly Urine Output (**HUO**) to determine how intravenous fluid Rate (**IFR**) should be administered. This paper is increasing the parameters to four by including Heart Beat Rate **(**HBR**)** and Central Venous Pressure (CVP) to determine the exact value of IFR. A Mamdani fuzzy type model is to be employed to develop a reasoning mechanism for four input variables and the method of centre of area will be used to derive a better result.

The rest of the paper includes related works in section 2, description of fuzzy systems in section 3, a design methodology in section 4, section 5 discussed system implementation, section 6 on testing and evaluation while section 7 discusses the conclusion.

2 RELATED WORKS

Fuzzy logic has been used in variety of disciplines like Engineering [20] [21], Medicine and controlling a wide variety of devices [20]. It has been used in applications that are amenable to conventional control algorithms on the basis of mathematical models of the system being controlled such as the high-frequency mechanical ventilator of Noshiro and co-workers [16]. Medical areas where fuzzy logic has been applied are to analyze diabetic neuropathy [14], improve decision-making in radiation therapy [18], control hypertension during anaesthesia [19] and detect breast and prostrate cancer [10] [3]. It has also been successfully implemented to the problem of controlling fluid resuscitation [8].

However, fuzzy logic has a particular advantage in areas where precise mathematical description of the control process is impossible and is thus especially suited support medical decision making [9]. A fuzzy logic-based approach to automatic control of pressure support mechanical ventilation for Intensive Care Unit (ICU) patients has been developed [17] [20]. Hence, the utility of fuzzy in the ICU is by no means limited to this particular application.

In [1] algorithms were discovered to be too simple for an ideal clinical use and could be extended to include additional fuzzy variables such as Heart Beat Rate (**HBR**) and Central Venous Pressure (**CVP**). This would allow more precise control of fluid balance and maintain cardiac output so also to prevent renal failure. In view of these, this paper extends the work of Bates and Micheal (2003) to include Heart Beat Rate and Central Venous Pressure in determining IFR while employing the methods of fuzzy logic.

3 FUZZY RULE SYSTEM

A fuzzy set A in X is defined as

$$\mu_A : X \rightarrow [0,1]$$
$$A = \{ (x: \mu_A(n)) : x \in X \}$$

Where μ_A is the membership function and [0,1] is the membership space. $\mu_A(n)$ is the grade of membership of an element $x \in X$ in the fuzzy set A.

A rule-based system utilizes a model that represents human knowledge in the form of "IF-THEN" rules. This conventional approach has been adapted to build fuzzy rule-based systems. A simple fuzzy IF-THEN rule can be written in the form of " IF x is A THEN y is B" where A and B are fuzzy sets. This can be extended to more than two fuzzy sets resulting in *compound fuzzy propositions*. In general, fuzzy IF-THEN rules are production rules whose antecedents, consequences or both are fuzzy [6]. Mendel (2001) classified fuzzy rules into 6 different types, namely *Incomplete Rules, Mixed Rules, Fuzzy Statement Rules, Comparative Rules, Unless Rules and Quantifier Rules*. However there is no agreed classification of fuzzy rule models [6] and a single rule might involve a combination of several different classification types [15].

3.1 MAMDANI MODEL

This is the most widely used linguistic fuzzy model and has been used for various real-world applications. This model also has high interpretability [23]. The model has the following structure:

If X_1 is A_1 and,…, and X_n is A_n THEN Y_1 is B_1 and ,…, and Y_m is B_m……………………………………..(1)

where X_i are fuzzy input linguistic variables, Y_j are fuzzy output linguistic variables, and Ai and Bj are linguistic terms in the form of fuzzy sets that characterize Xi and Yj [11].

The Mamdani model is more suitable for use of fuzzy logic as a way for translating the application domain expert's experience into a computer algorithm by interviewing the experts and extracting the applicable rule base. [5]

4 DESIGN METHODOLOGY

4.1 THE FUZZY INFERENCE SYSTEM

The fuzzy inference system in the paper consists of fuzzification, fuzzy rule base and defuzzication as shown in figure 1. Fuzzification of variable is categorized as either input or output variables. The input variables used are **Mean Arterial Pressure (MAP), Hourly Urine Output (HUO), Central Venous Pressure (CVP) and Heart Beat Rate (HBR)**. In considering each of these it was observed that these quantities may either be too high, acceptable or too low. This divides the possible range of values into three corresponding fuzzy sets namely **HIGH, NORMAL and LOW**. These four variables were defined according to **trapezium function** which is the membership function used in defining the range of values that can belong to or not to belong to the set as follows.

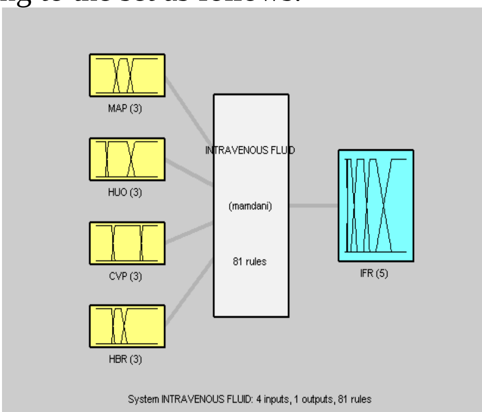


Fig. 1: Fuzzy Inference Engine for Intravenous fluid rate determination

Input variable MAP refers to the average pressure throughout each cycle of the heartbeat and it is measured in mm/hg

$$f(x) = \overset{Low}{\begin{pmatrix} 0 & , & x \geq 75 \\ \frac{75-x}{20} & , & 55 < x < 75 \\ 1 & , & 0 \leq x \leq 55 \end{pmatrix}} \overset{Normal}{\begin{pmatrix} 0 & , & x \leq 55,\ x \geq 120 \\ \frac{x-55}{20} & , & 55 < x < 75 \\ \frac{120-x}{20} & , & 100 < x < 120 \\ 1 & , & 75 \leq x \leq 100 \end{pmatrix}} \overset{High}{\begin{pmatrix} 0 & , & x \leq 100 \\ \frac{x-55}{20} & , & 100 < x < 120 \\ 1 & , & x \geq 120 \end{pmatrix}}$$

………..(1)

Input variable HUO measures the amount of urine passed out by the patient and is measured in ml/hr

$$f(x) = \overset{Low}{\begin{pmatrix} 0 & , & x \geq 40 \\ \frac{40-x}{10} & , & 30 < x < 40 \\ 1 & , & 0 \leq x \leq 30 \end{pmatrix}} \overset{Normal}{\begin{pmatrix} 0 & , & x \leq 30,\ x \geq 125 \\ \frac{x-55}{20} & , & 30 < x < 40 \\ \frac{120-x}{20} & , & 100 < x < 125 \\ 1 & , & 40 \leq x \leq 100 \end{pmatrix}} \overset{High}{\begin{pmatrix} 0 & , & x \leq 100 \\ \frac{x-100}{25} & , & 100 < x < 125 \\ 1 & , & x \geq 125 \end{pmatrix}}$$

…….…..(2)

Input variable CVP gives an indication of the amount of blood circulating within the body and is measured in cm of water

$$f(x) = \overset{Low}{\begin{pmatrix} 0 & , & x \geq 6 \\ \frac{6-x}{1} & , & 5 < x < 6 \\ 1 & , & 0 \leq x \leq 5 \end{pmatrix}} \overset{Normal}{\begin{pmatrix} 0 & , & x \leq 5,\ x \geq 15 \\ x-5 & , & 5 < x < 6 \\ 15-x & , & 14 < x < 15 \\ 1 & , & 6 \leq x \leq 14 \end{pmatrix}} \overset{High}{\begin{pmatrix} 0 & , & x \leq 14 \\ x-14 & , & 14 < x < 15 \\ 1 & , & x \geq 15 \end{pmatrix}}$$

………(3)

Input variable HBR is measured in beat per second

$$f(x) = \overset{Low}{\begin{pmatrix} 0 & , & x \geq 60 \\ \frac{60-x}{10} & , & 50 < x < 60 \\ 1 & , & 0 \leq x \leq 50 \end{pmatrix}} \overset{Normal}{\begin{pmatrix} 0 & , & x \leq 50,\ x \geq 100 \\ \frac{x-50}{10} & , & 50 < x < 60 \\ \frac{100-x}{20} & , & 80 < x < 100 \\ 1 & , & 60 \leq x \leq 80 \end{pmatrix}} \overset{High}{\begin{pmatrix} 0 & , & x \leq 80 \\ \frac{x-80}{20} & , & 80 < x < 100 \\ 1 & , & x \geq 100 \end{pmatrix}}$$

……..(4)

Output variable is referred to as Intravenous Fluid Rate (IFR) and is measured in ml/hr. It is the amount of the fluid to be given based on the four input variables. It has five fuzzy set of low, maintain, moderate, high and very high.

$$f(x)=\overset{Low}{\begin{pmatrix} 0 & , & x\geq 100 \\ \frac{100-x}{40} & , & 60<x<100 \\ 1 & , & 0\leq x\leq 60 \end{pmatrix}} \overset{Maintain}{\begin{pmatrix} 0 & , & x\leq 60,\ x\geq 400 \\ \frac{x-600}{40} & , & 60<x<100 \\ \frac{400-x}{200} & , & 200<x<400 \\ 1 & , & 100\leq x\leq 200 \end{pmatrix}} \overset{Moderate}{\begin{pmatrix} 0 & , & x\leq 200, x\geq 800 \\ \frac{x-200}{200} & , & 200<x<400 \\ \frac{800-x}{200} & , & 600<x<800 \\ 1 & , & 400\leq x\leq 600 \end{pmatrix}} \quad ..(5)$$

$$\overset{High}{\begin{pmatrix} 0 & , & x\leq 600,\ x\geq 1500 \\ \frac{x-200}{200} & , & 200<x<400 \\ \frac{800-x}{200} & , & 600<x<800 \\ 1 & , & 800\leq x\leq 1000 \end{pmatrix}} \overset{Very\ High}{\begin{pmatrix} 0 & , & x\leq 1000 \\ \frac{x-1000}{500} & , & 1000<x<1500 \\ 1 & , & x\geq 1500 \end{pmatrix}}$$

4.2 FUZZY RULE BASE

The rule base is defined according to experts' experience. As used in this research work the table 1 describes the action to be taken given the states of the four inputs as explained above. It contains 81 rules as there are four input fuzzy variables each of three instances of which when combined gives 3^4 = (81) different situations that can arise as shown sample in table 1.

Table 1: Determining IFR for given values of MAP, HUO, CVP and HBR

S/N	MAP	HUO	CVP	HBR	IFR
1.	Low	Low	Low	Low	High
2.	Low	Low	Low	Normal	Moderate
3.	Low	Low	Low	High	Very High
4.	Low	Low	Normal	Low	Moderate
5.	Low	Low	Normal	Normal	Maintain
6.	Low	Low	Normal	High	Low
.	.	.	.	.	.
63.	High	Low	High	High	Low
64.	High	Normal	Low	Low	High
.	.	.	.	.	.
.	.	.	.	.	.
79.	High	High	High	Low	Maintain
80	High	High	high	Normal	Low
81	High	High	High	High	low

According to rule 1 in table A:

If MAP is LOW and HUO is LOW and CVP is LOW and HBR is LOW, THEN IFR must be HIGH.

Also, according to rule 60 as formulated in table 1:

IF MAP is HIGH and HUO is LOW and CVP is NORMAL and HBR is HIGH, THEN IFR must be MAINTAIN.

For instance as illustrated in table 1 according to rule 81, IF MAP is HIGH and HUO is HIGH and CVP is HIGH and HBR is HIGH, THEN IFR must be LOW.

This is how the interpretation of any rule taken is expressed for all the 81 rules.

4.3 DEFUZZIFICATION

Defuzzification involves evaluating crisp output and the method of centre of area (COA) is used which is similar to the formula for calculating the center of gravity in Physics.

$$COA=\frac{\int_z \mu A(z)_{zdz}}{\int_z \mu A(z)_{dz}} \quad where\ \mu A(z)\ is\ the\ aggregated$$

$output\ of\ membership\ function\ (MF).$

5 SYSTEM IMPLEMENTATION

This work was implemented on a computer system with AMD Athlon(tm) 64X2 Dual Core Processor TK-53 1.78GHz 604MB RAM, running on Microsoft XP Professional Version 2002 Service Pack 2. MATLAB 6.5 was used to implement the system design. The Fuzzy Logic Toolbox was developed based on the 81 rules as illustrated in table 1 and the centre of area was used as the defuzzification method. The tool has main window to key in patient identification and the two or four input variables. On pressing compute button, the tool displays IFR result and membership function. Pressin graph button would provide the rule viewers picture of the four variable values to generate IFR output value. Save button assists to save the output results with the current date and time at entry to a window into patient database records. The print button permits to print the whole process for doctor analysis. Figure 2 illustrates a sample demonstration of four input values of MAP (110), HUO (120), CVP (5.80) and HBR (90). The IFR output result of 831 ml/hr was displayed after pressing compute button and the membership function indicated a high result. The graph review of possible result of 81 rules was shown in figure 3 while IFR membership function graph in figure 4.

6 TESTING AND EVALUATION

Table 2 and 3 illustrate part of sample results generated by keying in two and four variables collected from the State General Hospital, Abeokuta, Ogun State of Nigeria, for demonstration purpose. Looking at both IFR output values from the two tables i.e. two-input and four-input variables, the values are either increasing or decreasing.

What this really indicates is that with two inputs only a patient might not be well transfused. In a case, when there is increase, it means that what goes out of the body system is much and the body could not balance up so there is the need to externally boost the body fluid.

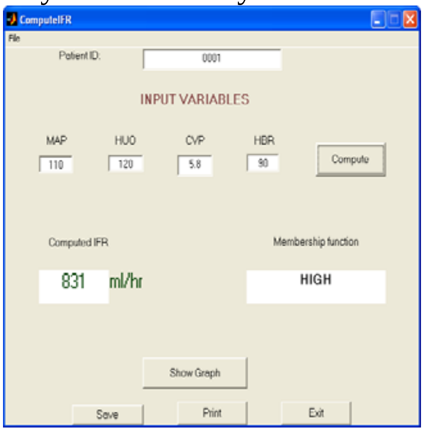


Fig. 2: IFR Interface for Four Input Variables

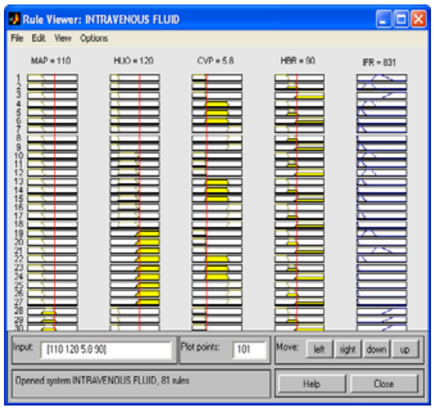


Fig. 3: The Rule Viewer of the Input and Output

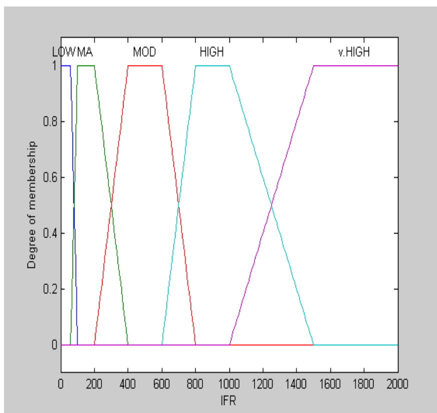


Fig. 4: IFR membership function graph

And in some cases, it might be due to some disease conditions of the body organ that actually regulate the body fluid (e.g. heart), therefore the fluid given has to be minimal so that it can cope with the regulation. This design has been based on 3 to 4 different experts' idea and the results being generated in the two tables in the membership functions were viewed positive by the medical experts. The addition of CVP and HBR has actually improved the value of IFR as the body fluid volume has to be seriously taken care of as being positioned by medical experts. They emphasised that care must be taken not to give too much or less needed fluid to the patients. The value of CVP needed to be considered as a sign of circulatory overload and heart failure while a decrease indicates there is hypovolemia (under transfusion) and peripheral venodilation. HBR as a factor must also be considered alongside as it has a great effect on the cardiac output i.e. the volume of fluid pumped out by the heart as described below

Cardiac Output = HBR x Stroke volume

A decrease in HBR results in a fall in time for ventricular filling, fall in stroke volume also increase in myocardial oxygen consumption while a decrease will result into a decrease in cardiac output.

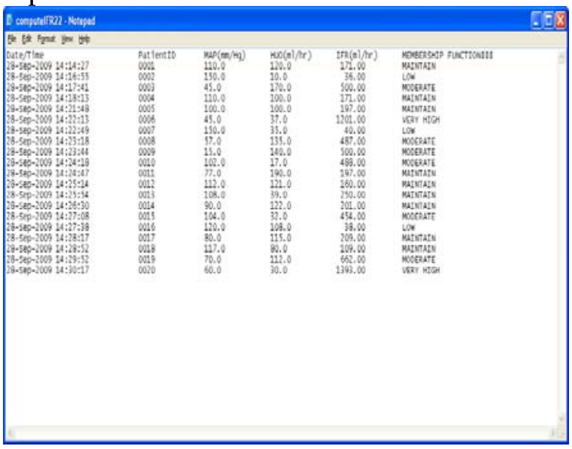
6.1 USABILITY TESTING

A series of data on MAP, HUO, CVP and HBR were collected from different expert hospitals apart from the information in table 2 and 3. The collected data were entered into the developed statistical interface. In comparing the two-parameter based technique with the new technique (four-parameter based), the two systems were tested using patients' records. The usability testing from the use of our tool revealed that 98% of medical doctors consulted confirmed the recommendations of the new system. Also, using the generated output shown in the report file of IFR values based on two and four parameters respectively, a paired-sample t-test conducted to evaluate difference on the generated IFR in both systems, there was a statistically significant increase in IFR based on two inputs (μ = 217.6, σ = 210.825) to IFR based on four inputs (μ = 718.7, σ = 544.774), $p(0.034) < 0.05$. This indicates that IFR values based on four parameters tested significantly better than IFR values based on two parameters.

CONCLUSION

This design can be implemented in practice by having a human computer operator who at intervals enters the various considered inputs and does the computation. The output result can then be applied immediately without having to wait as delay might cause a great havoc especially in health section where survival is the most concern.

Table 2: The IFR and MF results for two input variables


computeIFR22 - Notepad

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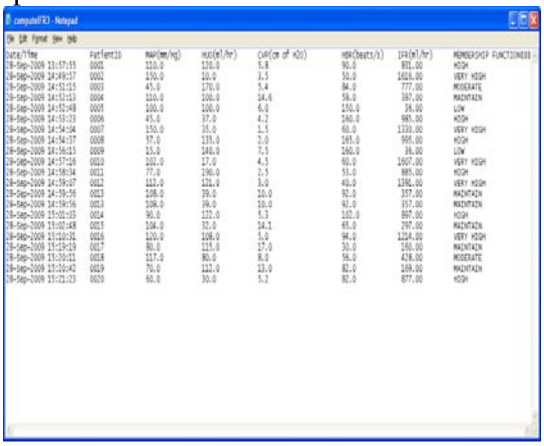
Date/Time	PatientID	MAP(mm/Hg)	HUO(ml/hr)	IFR(ml/hr)	MEMBERSHIP FUNCTIONS
28-Sep-2009 14:14:27	0001	110.0	120.0	171.00	MAINTAIN
28-Sep-2009 14:16:55	0002	150.0	10.0	36.00	LOW
28-Sep-2009 14:17:41	0003	45.0	170.0	500.00	MODERATE
28-Sep-2009 14:18:13	0004	110.0	100.0	171.00	MAINTAIN
28-Sep-2009 14:21:48	0005	100.0	100.0	197.00	MAINTAIN
28-Sep-2009 14:22:13	0006	45.0	37.0	1201.00	VERY HIGH
28-Sep-2009 14:22:49	0007	150.0	35.0	40.00	LOW
28-Sep-2009 14:23:18	0008	57.0	135.0	487.00	MODERATE
28-Sep-2009 14:23:44	0009	15.0	140.0	500.00	MODERATE
28-Sep-2009 14:24:18	0010	102.0	17.0	488.00	MODERATE
28-Sep-2009 14:24:47	0011	77.0	190.0	197.00	MAINTAIN
28-Sep-2009 14:25:14	0012	112.0	121.0	160.00	MAINTAIN
28-Sep-2009 14:25:54	0013	108.0	39.0	250.00	MAINTAIN
28-Sep-2009 14:26:30	0014	90.0	122.0	201.00	MAINTAIN
28-Sep-2009 14:27:08	0015	104.0	32.0	454.00	MODERATE
28-Sep-2009 14:27:38	0016	120.0	108.0	38.00	LOW
28-Sep-2009 14:28:17	0017	80.0	115.0	209.00	MAINTAIN
28-Sep-2009 14:28:52	0018	117.0	80.0	109.00	MAINTAIN
28-Sep-2009 14:29:52	0019	70.0	112.0	662.00	MODERATE
28-Sep-2009 14:30:17	0020	60.0	30.0	1393.00	VERY HIGH

Table 3: The IFR and MF results for four input variables



computeIFR3 - Notepad

Date/Time	PatientID	MAP(mm/Hg)	HUO(ml/hr)	CVP(cm of H2O)	HBR(beats/s)	IFR(ml/hr)	MEMBERSHIP FUNCTION
28-Sep-2009 13:57:55	0001	110.0	120.0	5.8	90.0	831.00	HIGH
28-Sep-2009 14:49:57	0002	150.0	10.0	3.5	50.0	1616.00	VERY HIGH
28-Sep-2009 14:51:15	0003	45.0	170.0	5.4	84.0	777.00	MODERATE
28-Sep-2009 14:52:13	0004	110.0	100.0	14.6	58.0	387.00	MAINTAIN
28-Sep-2009 14:52:48	0005	100.0	100.0	6.0	150.0	36.00	LOW
28-Sep-2009 14:53:23	0006	45.0	37.0	4.2	160.0	985.00	HIGH
28-Sep-2009 14:54:04	0007	150.0	35.0	1.5	60.0	1330.00	VERY HIGH
28-Sep-2009 14:54:37	0008	57.0	135.0	2.0	165.0	995.00	HIGH
28-Sep-2009 14:56:15	0009	15.0	140.0	7.5	160.0	36.00	LOW
28-Sep-2009 14:57:16	0010	102.0	17.0	4.5	60.0	1607.00	VERY HIGH
28-Sep-2009 14:58:34	0011	77.0	190.0	2.5	55.0	885.00	HIGH
28-Sep-2009 14:59:07	0012	112.0	121.0	3.0	40.0	1391.00	VERY HIGH
28-Sep-2009 14:59:56	0013	108.0	39.0	10.0	92.0	357.00	MAINTAIN
28-Sep-2009 14:59:56	0013	108.0	39.0	10.0	92.0	357.00	MAINTAIN
28-Sep-2009 15:01:03	0014	90.0	122.0	5.3	102.0	897.00	HIGH
28-Sep-2009 15:02:48	0015	104.0	32.0	14.1	65.0	297.00	MAINTAIN
28-Sep-2009 15:10:31	0016	120.0	108.0	5.0	94.0	1214.00	VERY HIGH
28-Sep-2009 15:19:19	0017	80.0	115.0	17.0	30.0	160.00	MAINTAIN
28-Sep-2009 15:20:11	0018	117.0	80.0	8.0	56.0	428.00	MODERATE
28-Sep-2009 15:20:42	0019	70.0	112.0	13.0	82.0	169.00	MAINTAIN
28-Sep-2009 15:21:23	0020	60.0	30.0	5.2	82.0	877.00	HIGH

The work requires incorporating weight, age and height of the patients and type of fluid given (colloids/crystalloids) as part of parameter requirement for future work. A fully automation can be done where all these inputs are taken/or read with appropriate gadgets/machine, sent to the computer system for automatic generation of output results for expert analysis. This would greatly increase both reliability and save labour.

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