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COMPUTER-ASSISTED ENVIRONMENTAL CONTROL FOR NEWBORNS

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INTRODUCTION

A computer was first introduced into the intensive care unit nursery (ICU nursery) at Cincinnati General hospital in 1971. Initial use centered around implementation of an algorithm for controlling temperatures in standard convectively heated incubators.[1] The goal was to maintain a thermally neutral microclimate in incubators so as to keep the body temperatures of infants within the normal range and reduce thermally induced metabolic work to a minimum. In addition, the algorithm was designed to prevent sudden temperature changes within the incubators and thus reduce apneic spells and bradycardia in susceptible infants.[2, 3] Furthermore, because infants tend to become adapted to thermoneutral conditions, the algorithm was modified to wean babies transitionally from a consistently warm incubator to the less-controlled temperature environment of the air-conditioned nursery.[4] This computer-assisted environmental control system was named Alcyon for its purpose, after the mythical bird that calms the ocean storms during incubation of its young.

The use of the Alcyon system was documented to correlate with an increase in infant survival for babies requiring neonatal intensive care for respiratory distress syndrome (RDS) and weighing greater than 799 grams at birth.[1] Furthermore, it was shown that the group of infants in incubators with computer-assisted temperature control required significantly fewer calories per kilogram body weight per day during the first 6 days of life than did a matched control group of infants receiving care in standard incubators, and yet the 7-day weight loss (expressed in percent of birth weight) was slightly less in the study as compared with the control group.[1]

The computer has also been programmed to detect errors that can make an incubator environment "uncontrollable." When an incubator is determined to be uncontrollable, a "control alarm" message is made to flash on computer-driven television sets in the nursery, alerting personnel to check out the system and take appropriate action. Evaluation of the effects of the alarm system demonstrated that the time individual babies are housed in uncontrollable incubators can be significantly reduced through its application.[5]

The development of the Cincinnati ICU nursery computer system is ongoing and, in addition to the control and alarm functions, now provides video display of patient monitoring and laboratory data. It also generates outputs relevant to medical records, patient billing, quality control, and so forth. These new systems are being evaluated using controlled trials to assess both the beneficial and adverse influences upon the care of sick neonates.

HARDWARE

The original Alcyon algorithm was programmed into a Digital Equipment Corporation PDP-11/20 minicomputer. The computer was located in the Newborn Division office area, approximately one-eighth mile from the nursery. Data transmission to and from the nursery was accomplished by way of private transmission lines rented from the telephone company.

All algorithms are currently programmed into a DEC PDP-11/40 minicomputer using an RSX 11M real-time operating system in which 128,000 words of core memory and 150 megabytes (MB) of disk storage are available. Further mass storage is provided by two attached magnetic tape units. Two nurseries in two separate hospitals (Cincinnati General Hospital and Cincinnati Children's Hospital Medical Center) are now connected to the service. Voice-grade telephone lines are used to transmit all data. Transmission lines have been terminated in interfacing hardware designed and fabricated by the electrical engineering staff in the Newborn Division of the Department of Pediatrics at the University of Cincinnati. In these interfacing designs, patient safety has been maximized by redundancy and distributed logic that assures through continual system checking that the computer hardware (and software) are functioning as expected.

The incubators controlled by the computer are standard Air-

Shields Isolettes with either on-off or proportional servocontrol electronic units. The incubators are prepared by attaching Yellow Springs Instrument Company thermistor probes to the inside, top, back and front walls of the Plexiglas chamber (Fig. 21.1). A fourth thermistor is suspended in the midincubator air stream and a fifth measures the infant's skin temperature.

These temperature probes are plugged into an input box attached to the incubator pedestal. The input box is connected to a bedside multiplexer which, in turn, transmits data to the computer. The decision to turn the incubator on or off is transmitted back to the incubator by way of electronics in the bedside box. These electronics cause simulation of a 30°C skin temperature for a heater ON command, or 40°C temperature for a heater OFF command. This simulated temperature is passed from the input box to the skin thermistor input jack on the incubator's electronics module. By setting the incubator for servo-

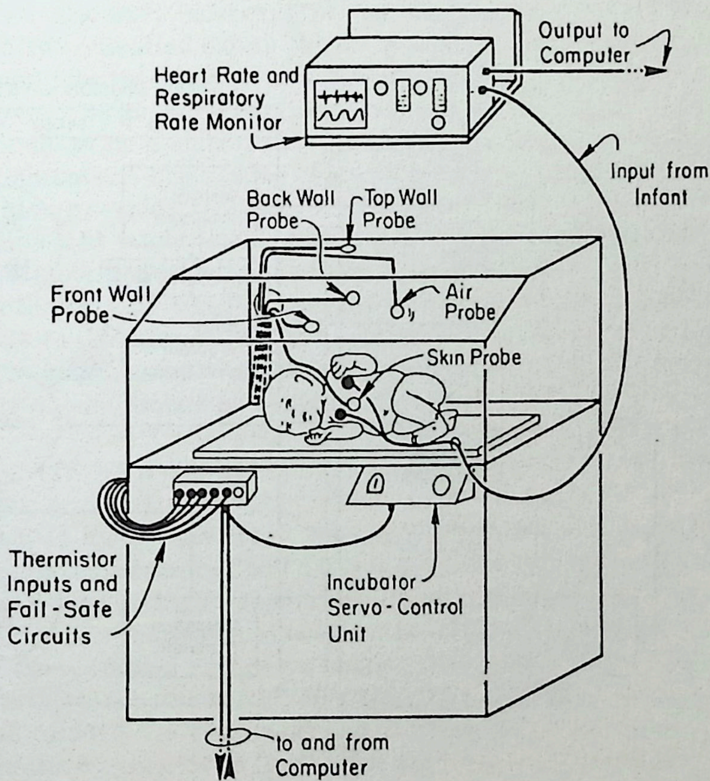

FIGURE 21.1. Schematic of computer-monitored, computer-controlled Alcyon incubator. Source: Perlstein PH, et al: Pediatrics 57: 496, 1976.[1]

control operation, the Isolette electronics can be used without modification to turn the incubator on or off as a slave to the external computer logic. In the event of a computer failure, additional circuitry automatically transfers heater control away from the computer-connected pathways to the local, single, skin-temperature servocontrol logic. The incubators are all set to deliver maximum humidity to the infant chambers.

At present, the computer is programmed to control up to 30 incubators at a time. The outputs of heart rate and respiratory rate monitors on these patients also feed into the computer. Blood gas data are automatically entered into the computer, and patient ventilator data are manually entered by respiratory therapists. All monitored and computed data appear on numerous strategically located video-display terminals (Tektronix 4010 in the newborn nurseries). These data are provided at the patient stations either in the form of selectable graphic summaries, ranging from a 3-hour to 4-day span, or tabular display. An overall blood gas systems diagram is illustrated in Figure 21.2.

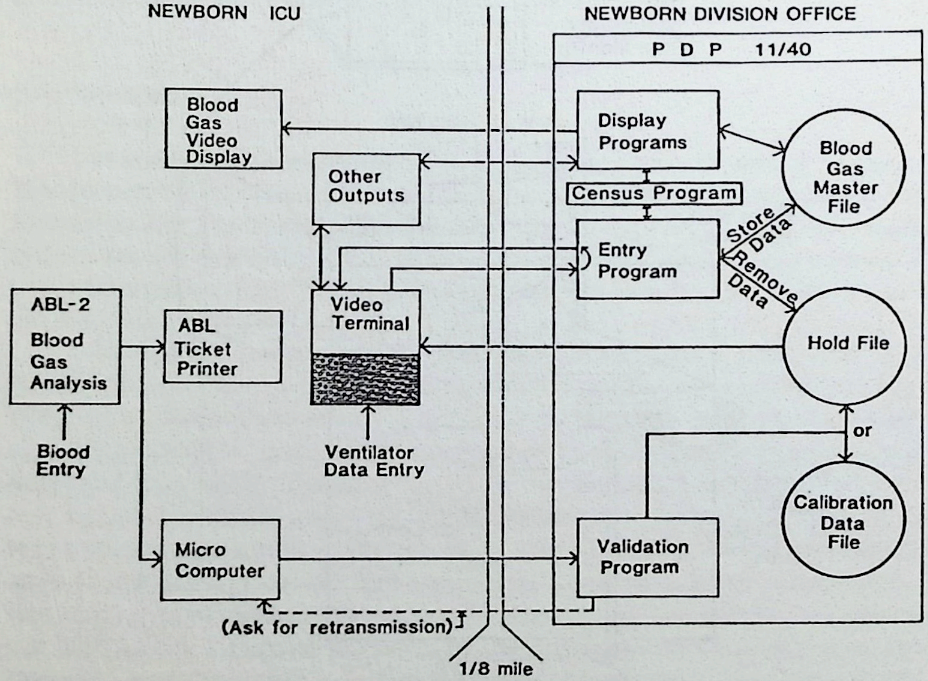

FIGURE 21.2. Systems diagram of present computerized blood gas monitoring and display system at Cincinnati Children's Hospital Medical Center.

System reliability is reflected in the fact that during 40,000 hours of use, the computer operated continuously except for an accumulated total down time of 37 hours. Thus, the computer is up and running 99.91 percent of the time. Much of the credit for this high degree of reliability goes to careful engineering design and maintenance.

SPECIFIC APPLICATIONS

The Alcyon Incubator Temperature Control Algorithm

The computer is programmed to maintain the infant's skin temperature within a normal range of 35.5-36.5°C. If the infant's skin temperature falls below 35.5°C, the incubator environmental temperature is raised to a level above 35.5°C. The heat-gaining environment is limited by setting a maximum allowable incubator air temperature at 38°C. The 38°C temperature was chosen to back up the thermostatically controlled safety alarms and heater disconnect features designed into the incubators to prevent heating in excess of this level. Moreover, 38°C is the environmental temperature found by Adamson and Gandy to be metabolically stimulating to infants in heat-gaining environments.[6] The setting of a maximum upper incubator temperature limit also provides an absolute limit to any rapid and sudden temperature rise that might induce apneic spells in susceptible infants.[2]

Metabolically neutral conditions were established by again relying on the data of Adamson and Gandy.[6] When an infant's skin temperature is in the normal 35.5-36.5°C range, the environmental temperature is constrained to within 2°C of the infant's skin temperature. This is accomplished by using the formula

$$K\ (TS + TE) = SETPOINT \qquad (1)$$

where K is a constant set to the value of 0.5, TS is the actual measured skin temperature, and TE is a computed environmental temperature. As long as high temperature limits are not exceeded and the temperature remains within other well-defined ranges, the setpoint is the servocontrol reference temperature used to trigger the decision to turn the incubator heater on or off. The setpoint is initially assigned a value of 35.5°C. This value ensures that within the normal skin-temperature range of 35.5-36.5°C, the environmental temperature will never fall below 34.5°C and therefore will not be more than 2°C below skin temperature.

When the infant's skin temperature exceeds 36.5°C for more than 5 minutes, the assumption that maintenance of a thermoneutral environment will benefit the infant is abandoned and the setpoint value is shifted slowly downward to produce increasing gradients between the skin and environmental temperatures to a maximum gradient of 4°C. The resetting of setpoint values is called the adaptive mode and is designed to encourage reacquisition of homeothermic capabilities before the infant is transferred to an open bassinet.

Since air temperature is the only variable that is actually controllable in a convectively heated single thickness Plexiglas wall incubator, it is necessary to compute the true incubator environmental temperature using the following equation:

$$TE = K_1\ TA + K_2\ (TTW + TFW + TBW) \qquad (2)$$

where TE is the computed environmental temperature, K_1 is a constant equal to 0.5, TA is the measured midincubator chamber air temperature, K_2 is a constant equal to 0.167, TTW is the temperature of the top wall, TFW is the temperature of the front wall, and TBW is the temperature of the back wall of the incubator. All temperatures are measured and expressed in degrees centigrade. This equation only takes into consideration the convective and radiant components of heat loss. Hence its validity presumes that evaporative and conductive heat losses are negligible. Since conductive heat loss is not a significant factor in a conventional incubator, this validity is established by maintaining a better than 70 percent humidity level in the controlled incubators. This equation helped establish that incubators in the study nursery have environmental temperatures approximately 2°C less than the measured air temperatures. This is near the same value determined for the relationship between incubator air and environmental temperatures independently reported by Hey and Mount.[7]

As a corollary, the logic used in programming the computer to generate neutral thermal conditions is, within defined limits, reducible to the following relatively simple equation, which can be used to control incubators in nurseries without computer resources:

$$TS + TE = 71^{\circ}C \qquad (3)$$

where TS is again the actual measured skin temperature of the infant, and TE is the incubator environmental temperature measured in degrees Celsius. Solving this equation for TE results in the following equation:

$$TE = 71^{\circ}C - TS \qquad (4)$$

Thus, from the measured value of the skin temperature, it is possible to calculate an appropriate temperature for the incubator environment.

However, there are a number of precautions that must be taken in applying this formula. First, it is not easy either to measure or to calculate the "true" environmental temperature in an incubator. It is best derived using complex equations that at least take into account the incubator humidity and various incubator wall temperatures, as was done above in equation (2). For practical purposes, however, equation (4) is valid if TE is replaced in the formula by a temperature value 2°C less than the measured midincubator air temperature, if relative humidity is kept at 70 percent or more (to minimize heat losses by evaporation), and if the incubator walls are kept warm (to minimize heat losses by radiation).

The Control Alarm Algorithm

Electronic control by any process is still subject to the disruptions caused by misuse or malfunction of equipment.[5] For example, an incubator can develop a problem with uncontrollable sources of heat loss, such as cold gas flowing into a headhood or from a resuscitation bag within the incubator, or the skin probe or power plug can become dislodged. To minimize such difficulties, a computerized incubator-monitoring program was written that generated visual alarms on video-display screens in the nursery, alerting personnel quickly of any detectable malfunctions or electronically uncontrollable situations.

As long as the infant's incubator is under predictable control, according to the Alcyon algorithm described above, the words ALCYON CONTROL are displayed next to the incubator station (STA) number and other parameters displays on the video-display terminal (Fig. 21.3a). If, on the other hand, the computer determines that the incubator temperatures are not responding to the heater ON or OFF commands, the problem is immediately flashed in the nursery as a CONTROL ALARM next to the station number of the incubator involved (see number 7 station in Fig. 21.3b). Alarm displays persist until the computer is logically satisfied that the dysfunctional incubator is again responding as expected to the transmitted heater status commands.

Abnormal Blood Gas Display

A pilot study of 301 consecutive blood gas studies in the ICU nursery at Cincinnati Children's Hospital Medical Center demonstrated that 18 infants (6 percent) were severely acidotic (i.e., had a pH value of less than 7.25) and that the mean time lag to pH correction was 5 hours and 53 minutes. Of the severely acidotic samples, 10 had been a

ALCYØN MAR 11, 1977 08:11:46

STA	HR	RR	IMP	TS	
1	135	59	558	35.5	ALCYØN CØNTRØL
2	139	36	640	35.5	ALCYØN CØNTRØL
3	168	23	430	35.9	ALCYØN CØNTRØL
5	142	32	0	36.1	ALCYØN CØNTRØL
6	133	48	142	34.9	ALCYØN CØNTRØL
7	159	64	47	36.6	ALCYØN CØNTRØL

b

ALCYØN MAR 11, 1977 09:38:16

STA	HR	RR	IMP	TS	
1	131	39	557	35.7	ALCYØN CØNTRØL
2	151	29	603	36.0	ALCYØN CØNTRØL
3	159	23	415	36.1	ALCYØN CØNTRØL
5	115	50	50	36.6	ALCYØN CØNTRØL
6	63	23	15	35.7	ALCYØN CØNTRØL
7	158	61	39	35.9	CØNTRØL ALARM

FIGURE 21.3. Computer-generated information displayed on video screens when patients are on the Alcyon system. (a) Typical situation when all incubators are well controlled. (b) Situation when "control alarm" message is transmitted from one of the patient stations (i.e., number 7). STA = incubator station number; HR = heart rate/min; RR = respiratory rate/min; IMP = skin impedance in ohms; TS = baby's skin temperature. Source: Perlstein PH, et al: Perinatology-Neonatology 1: 18, 1977.[5]

mildly acidotic on the previous sample. In an attempt to lessen the frequency and duration of severely abnormal blood gas values and ultimately improve the outcome of these neonates, a program was written for the computer to display this crucial information on the video screens in the nursery.

Blood gas values are displayed on the video-display screens (as in Fig. 21.4) when a pH value is less than 7.25 or greater than 7.50. They are also displayed when a pH is mildly abnormal but further from normal than the previous determination (i.e., it appears that an unfavorable trend is being established). The blood gas values are removed from the video-display screens only if they improve and

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                    BLOOD GAS DATA

BED  NAME               TIME   PH   PCO2   BE   PO2 FIO2

Y 11 KING               2254  7.25*  69    0.8  46C  54
G 17 FRANKLIN           0904  7.23@  67  -2.3  49A  40
B  1 DUNLAP             1017  7.53@  30    2.9  49C  36



REASON FOR DISPLAY:
 @ = ABSOLUTE VALUE          * = TREND DETECTED

LAST UPDATE: 11:45 02-SEP-81
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FIGURE 21.4. Typical video screen display of abnormal blood gas results flashed in the ICU nursery to remind staff of the condition.

are no longer severely abnormal, if they have been displayed for a total of 24 hours, or if the patient is discharged.

As part of the evaluation of the effect of this display of abnormal blood gas values on video terminals within the ICU nursery, the clinicians' response is being measured without their knowledge. Measurements are being made of the time lag from display of a markedly abnormal pH value to sampling of the next blood gas value, the time lag to the next normal blood pH level, the incidence of trends progressing from mildly abnormal to severely abnormal, and the incidence of overcorrection of blood gas values.

CONCLUSIONS

The credibility of this computer system has grown out of a critical appraisal of the system's worth. The use of the Alcyon system has been documented to correlate with an increase in infant survival.[1] It has also been shown to decrease management errors during the care of high-risk infants.[5, 8]

The positive study results have provided justification for setting reasonable fees for the service. These fees establish a financial base that sustains the system and enables it to be upgraded.

Future expansion of the Cincinnati ICU nursery computer system will adhere to past philosophies. Both data base collection and additional device control programs are planned. However, none of these programs will be implemented until it can be documented that they truly resolve specific problems without introducing new impediments to patient care.

ACKNOWLEDGMENTS

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