Original Article

CDI Blood Parameter Monitoring System 500—A New Tool for the Clinical Perfusionist

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ABSTRACT

Sarns/3M Health Care has recently introduced the CDI 500 Blood Parameter Monitoring System. In addition to parameters previously available, this system now offers continuous monitoring of the patient's oxygen consumption (VO_2/min) and potassium concentration ($[K^+]$). The purpose of this study was: (1) to compare the $[K^+]$ from the CDI 500 with the $[K^+]$ derived from our hospital's laboratory; and (2) to compare the VO_2/min from the CDI 500 with the results obtained utilizing the "gold-standard" Fick equation.

The mean absolute difference in $[K^+]$ was 0.10 mEq/L with a mean percentage error of only 3.93%. The mean absolute difference in VO_2/min was 18.78 ml O_2/min, with a mean percentage error of 11.63%.

We concluded that the $[K^+]$ correlated well and that 9.13% of the oxygen consumption percentage error was attributable to the exclusion of dissolved oxygen in the calculation used by the CDI 500, with the remaining 2.5% attributable to differences in technology.

We recommended that future upgrades to the CDI 500 should include dissolved O_2 when measuring oxygen consumption and consideration should be given to increasing the operating range for $[K^+]$.

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INTRODUCTION

Sarns/3M Health Care has recently introduced the CDI 500 Blood Parameter Monitoring System. In addition to the parameters monitored in previous units (Table 1), the CDI 500 can also monitor the patient's potassium concentration [K^+] as well as the patient's oxygen consumption (VO_2/min). It is the purpose of this study: (1) to clinically compare the [K^+] from the CDI 500 with the [K^+] derived from our hospital's laboratory; and (2) to clinically compare the VO_2/min from the CDI 500 with the results obtained utilizing the Fick equation (1).

MATERIALS AND METHODS

CDI 500

The CDI 500[a] is an AC-powered, microprocessor-based monitor. It uses an optical fluorescence technology to measure blood gases, pH, and potassium. In addition, it uses an optical reflectance technology to measure oxygen saturation, hematocrit, and hemoglobin (2).

From the three basic modules; arterial blood gases, venous blood gases, and hematocrit/saturation, the CDI 500 offers the clinician a choice of seven monitor configurations (Table 2). For our study, we chose to use the arterial blood gas module coupled with the hematocrit/saturation module.

Before placement of the arterial blood gas sensor into the arterial filter purge line of the cardiopulmonary bypass (CPB) circuit, it undergoes a 10-minute, two-point tonometered calibration to expose the sensor(s) to well-defined pH, PCO2, and PO2 values (3). The ½ inch CDI Hematocrit/Saturation (H/S) curvette is placed directly into the venous return line. The CDI H/S probe will perform a self-check automatically when it is connected to the monitor's optical reference color chip during start up.

During this study, we used the Avecor Affinity Membrane Oxygenator.[b] Venous blood enters at the bottom of the oxygenator into a stainless steel, bellows-type heat exchanger. From the heat exchanger, the blood is then directed to the 2.5 m^2 fiber bundle. Oxygenated blood then exits the unit through the arterial blood outlet port located at the bottom of the fiber bundle.

DATA COLLECTION

After the initiation of CPB and an adequate equilibration period (at least 5 min), an in vivo recalibration was performed. Arterial and venous blood samples were drawn from the CPB circuit while simultaneously pressing the "store" key on the monitor, which saves the currently displayed values into the monitor's memory. After receiving the samples back from the hospital's laboratory, the "recall" key was pressed. The stored values were compared with the laboratory values and adjusted, if necessary.

After the *in vivo* recalibration was performed, we collected two sets of blood samples (one arterial and one venous) during the cooling phase and two sets of samples during the rewarming phase for each patient. In all, we collected four sets of samples from 10 different patients for a total of 40 sets of blood samples. It should be pointed out that after making any required changes to the CPB circuit; that is, FiO_2, blood flow, etc., a mandatory 2-min "hands-off" period was required before sampling. The values at the time of sampling, for the CDI 500 as well as the laboratory, were entered into a data collection worksheet.

Table 1: Measured and calculated parameters of the CDI monitors

Parameter	CDI 100	CDI 200	CDI 300	CDI 400	CDI 500
pH a (m)		X	X	X	X
Ph v (m)		X	X	X	X
$PaCO_2$ (m)		X	X	X	X
$PvCO_2$ (m)		X	X	X	X
PaO_2 (m)		X	X	X	X
PvO_2 (m)		X	X	X	X
Temp (m)			X	X	X
SaO_2 (m)	X				X
SvO_2 (m)	X		X	X	X
Hct (m)	X				X
Hb (m)	X				X
BE (c)			X	X	X
HCO_3^- (c)			X	X	X
VO_2/min (c)					X
[K^+] (m)					X
Blood Q (m)*					X

m = measured.
c = calculated.
* = using serial interface port CDI 500 can receive flow data from selected pumps.

Table 2: Monitor configurations for the CDI 500

Configuration	Modules
1	Arterial/venous blood gases & hematocrit/saturation
2	Arterial/venous blood gases
3	Arterial blood gases & hematocrit/saturation
4	Venous blood gases & hematocrit/saturation
5	Arterial blood gases
6	Venous blood gases
7	Hematocrit/saturation

a Sarns/3M Health Care, Ann Arbor, MI
b Medtronic Cardiopulmonary, Minneapolis, MN

[K^+] COMPARISON

Forty [K^+] values from the CDI 500 were compared with the results obtained from the hospital's OR Stat Laboratory, which uses the CIBA Corning 288.[c] This device is self-calibrating, and controls are performed every 8 h as required by CLIA standards. The absolute difference between the two values was found according to:

$$\text{Absolute Difference} = \left|\text{Lab } [K^+] - \text{CDI 500 } [K^+]\right|$$

The [K^+] percentage error was then calculated according to:

$$\text{Percent Error} = \frac{\text{Absolute Difference}}{\text{Lab } [K^+]}$$

The [K^+] mean percentage error was found according to:

$$\text{Mean Percentage Error} = \frac{\Sigma \text{ Percentage Error}}{\#\text{ Samples}}$$

OXYGEN CONSUMPTION COMPARISON

The patient's oxygen consumption per minute (VO_2/min) was calculated for the 40 sets of arterial and venous blood samples utilizing the Fick equation. The Fick equation requires six measured parameters in addition to the two constants.

$$VO_2/\text{min} = [(SaO_2 - SvO_2) \times 1.39 \times \text{Hgb} \times Q \times 10] + [(PaO_2 - PvO_2) \times 0.003 \times 10 \times Q]$$

where:

SaO_2 = arterial oxygen saturation
SvO_2 = venous oxygen saturation
Hgb = Hemoglobin concentration/100 mL
Q = blood flow/min
PaO_2 = oxygen partial pressure of arterial blood
PvO_2 = oxygen partial pressure of venous blood
1.39 = constant for ml O_2 per gram of Hgb
0.003 = constant for ml O_2 per mmHg

These values were compared with the oxygen consumption values obtained from the CDI 500. The calculation used by the CDI 500 to measure oxygen consumption is:

$$VO_2/\text{min} = (SaO_2 - SvO_2) \times 1.39 \times \text{Hgb} \times Q \times 10$$

The absolute difference between the two values was found according to:

$$\text{Absolute Difference} = |\text{Fick } VO_2/\text{min} - \text{CDI 500 } VO_2/\text{min}|$$

The oxygen consumption percentage error was then calculated according to:

$$\text{Percentage Error} = \frac{\text{Absolute Difference}}{\text{Fick } VO_2/\text{min}}$$

c Corning, Medfield, MA

The oxygen consumption, mean percentage error was found according to:

$$\text{Mean Percentage Error} = \frac{\Sigma \text{ Percentage Error}}{\#\text{ Samples}}$$

RESULTS

The raw data from the CDI 500 and the hospital's blood gas laboratory are presented in Tables 3 and 4, respectively. The mean [K^+] for the 40 samples from the CDI 500 was 5.32 mEq/L and the mean [K^+] for the lab was 5.42 mEq/L. The absolute difference in [K^+] between the two was 0.10 mEq/L with a mean percentage error of 3.93% (Table 5).

The mean VO_2/min for the 40 samples from the CDI 500 was 142.68 mL O_2/min, and the mean VO_2/min utilizing the Fick equation was 161.46 mL O_2/min. The absolute difference in VO_2/min between the two, was 18.78 mL O_2/min, with a mean percentage error of 11.63% (Table 6).

DISCUSSION

Our finding of a mean [K^+] percentage error of only 3.93% is an entirely acceptable degree of accuracy for this measured parameter. Based upon this percentage error, if the actual [K^+] were 5.0 mEq/L, the CDI 500 would range from 4.8 mEq/L–5.2 mEq/L. The highest percentage error during our study, 11.63% (sample #2), was found during an open-heart procedure in which continuous warm retrograde cardioplegia was used. During this procedure, the actual [K^+] exceeded 8 mEq/L. Although the CDI 500 will display [K^+] values above 8 mEq/L, its operating range is defined as 1.0 to 8.0 mEq/L (3). For those centers, such as ours, that deliver continuous potassium cardioplegia with a syringe pump or peristaltic infusion pump, the ability to measure not only the patient [K^+] but the [K^+] of the delivered cardioplegia, would be very helpful. Because we are not using defined blood:crystalloid ratios, the actual cardioplegia [K^+] is not known with any precision. It would be more accurate to say, in these cases, that the potassium is titrated to effect; that is, maintenance of cardiac arrest. This would require future generations of CDI Monitors to increase their [K^+] operating range considerably.

The oxygen consumption difference of 18.78 ml O_2/min was due primarily to the fact that the CDI 500 does not include PaO_2 and PvO_2 in its determination of VO_2/min. In this study, we found the mean PaO_2, PvO_2 and blood flow to be 145.93 mL, 30.28 mL and 4.25 l/min, respectively. From these data, we could estimate that the CDI 500 under estimated oxygen consumption by an average of 14.75 mL O_2/min.

$$(145.93 \text{ mmHg} - 30.28 \text{ mmHg}) \times 0.003 \text{ mL } O_2/\text{mmHg} \times 4.25 \text{ L/min} \times 10 = 14.75 \text{ mL } O_2/\text{min}$$

If the value is then added to the mean CDI 500 oxygen transfer (142.68 mL/min), the result would be 157.43 mL/min. This is

Table 3: Raw data for CDI 500

Sample #	Hb	SaO_2	SvO_2	PaO_2(Corr)	PvO_2	Blood Flow
1	7.8	99	72	130	——	2.6
2	7.5	99	68	145	——	2.3
3	7.9	99	68	141	——	3.3
4	8.0	99	67	144	——	4.9
5	6.6	100	70	150	——	4.1
6	6.5	100	69	137	——	4.1
7	7.1	99	70	147	——	4.5
8	7.3	99	66	144	——	5.8
9	8.9	99	69	149	——	3.2
10	8.8	99	71	128	——	3.2
11	8.9	98	69	148	——	3.7
12	8.8	99	70	149	——	5.0
13	8.8	99	72	124	——	3.6
14	8.9	99	72	133	——	3.3
15	8.6	99	68	144	——	4.1
16	8.5	99	71	134	——	3.9
17	11.5	99	76	132	——	4.0
18	11.4	99	75	134	——	3.8
19	10.9	99	69	136	——	5.1
20	11.0	99	69	150	——	5.6
21	7.7	99	67	136	——	2.3
22	7.4	100	73	147	——	2.7
23	6.8	99	63	141	——	5.1
24	7.5	98	68	127	——	5.5
25	8.7	99	73	146	——	3.3
26	8.9	99	72	136	——	3.2
27	9.0	98	73	144	——	5.5
28	8.9	97	71	139	——	5.8
29	8.3	99	69	131	——	4.7
30	8.4	100	71	154	——	4.8
31	8.9	99	68	136	——	5.9
32	8.7	99	71	142	——	6.2
33	8.0	98	67	132	——	3.2
34	7.9	98	70	134	——	3.5
35	7.2	96	69	145	——	5.5
36	7.7	95	69	139	——	5.7
37	7.8	100	70	134	——	3.0
38	7.5	100	69	142	——	3.3
39	8.2	99	71	146	——	4.8
40	7.6	99	69	149	——	5.7
Mean	**8.37**	**98.80**	**69.85**	**139.98**	**——**	**4.25**

Table 4: Raw data for Fick equation

Sample #	Hb	SaO_2	SvO_2	PaO_2 (Corr)	PvO_2 (Corr)	Blood Flow
1	7.2	99.2	73.5	131	22	2.6
2	7.4	99.2	70.9	155	27	2.3
3	7.3	99.0	67.4	153	36	3.3
4	7.7	99.0	66.3	159	35	4.9
5	6.6	99.4	71.3	159	21	4.1
6	6.4	99.3	71.6	150	22	4.1
7	7.2	99.3	69.2	161	22	4.5
8	7.4	99.0	68.8	152	36	5.8
9	9.2	99.3	68.6	163	27	3.2
10	8.2	99.1	72.2	151	29	3.2
11	8.8	99.1	68.0	160	37	3.7
12	8.5	99.1	71.7	158	38	5.0
13	8.8	99.0	73.1	124	23	3.6
14	9.0	99.2	70.4	154	26	3.3
15	9.0	98.9	66.1	153	36	4.1
16	8.5	98.8	69.3	144	37	3.9
17	10.9	98.9	73.3	123	27	4.0
18	11.2	98.9	71.0	129	27	3.8
19	10.5	98.5	65.5	132	36	5.1
20	10.9	98.7	65.2	138	36	5.6
21	7.7	98.9	68.6	129	22	2.3
22	7.6	99.0	70.5	137	23	2.7
23	6.6	98.7	60.2	138	33	5.1
24	7.6	98.2	66.9	123	36	5.5
25	9.2	99.2	71.2	159	31	3.3
26	9.0	99.1	69.7	144	25	3.2
27	8.5	98.8	63.4	148	35	5.5
28	8.5	98.7	69.9	143	40	5.8
29	8.8	99.0	70.4	137	27	4.7
30	8.8	99.3	73.7	159	27	4.8
31	8.6	98.9	69.7	145	37	5.9
32	8.5	98.9	71.4	151	40	6.2
33	7.9	99.2	66.5	145	23	3.2
34	8.2	99.1	69.6	141	23	3.5
35	7.8	99.0	68.7	151	37	5.5
36	7.8	98.9	68.0	154	37	5.7
37	7.8	99.2	71.9	137	22	3.0
38	7.2	99.3	73.9	147	22	3.3
39	7.8	99.0	68.3	146	35	4.8
40	7.4	99.0	67.1	154	36	5.7
Mean	**8.30**	**99.01**	**69.33**	**145.93**	**30.28**	**4.25**

now only 4.03 mL/min different than that which we calculated using the "gold-standard" Fick equation and represents a mean percentage error of only 2.50%. It can then be concluded that 9.13% of the oxygen consumption percentage error can be attributed to the exclusion of dissolved oxygen by the CDI 500, while the remaining 2.5% was attributable to differences in technology.

We recommend that when measuring oxygen consumption, the CDI 500 software should not ignore dissolved O_2. Of the seven possible monitor configurations for the CDI 500, four are compatible with the measurement of oxygen consumption. When both the arterial and venous blood gas modules are used in conjunction with the CDI H/S Probe, all six necessary parameters are available to the CDI 500 to calculate O_2/min. When only the arterial and venous blood gas modules are used, a hematocrit value must be manually input. When the venous

Table 5: Potassium concentration comparison

	$[K^+]$ mEq/L			
Sample #	**CDI 500**	**Laboratory**	**Abs. Diff**	**% Error**
1	6.6	7.3	0.7	9.59
2	7.6	8.6	1.0	11.63
3	8.4	8.9	0.5	5.62
4	8.0	8.3	0.3	3.61
5	3.7	3.7	0.0	0.00
6	4.0	3.9	0.1	2.56
7	4.6	4.5	0.1	2.22
8	5.3	5.1	0.2	3.92
9	5.8	5.8	0.0	0.00
10	6.0	6.4	0.4	6.25
11	7.1	7.3	0.2	2.74
12	6.3	6.5	0.2	3.08
13	5.7	5.9	0.2	3.39
14	5.8	6.5	0.7	10.77
15	6.8	7.0	0.2	2.86
16	6.4	6.5	0.1	1.54
17	6.4	6.7	0.3	4.48
18	6.9	7.5	0.6	8.00
19	7.8	7.7	0.1	1.30
20	7.0	6.9	0.1	1.45
21	4.2	4.6	0.4	8.70
22	4.1	4.5	0.4	8.89
23	3.9	3.9	0.0	0.00
24	3.8	3.8	0.0	0.00
25	5.3	5.1	0.2	3.92
26	4.6	4.5	0.1	2.22
27	4.6	4.2	0.4	9.52
28	4.3	4.0	0.3	7.50
29	3.7	3.7	0.0	0.00
30	4.1	4.1	0.0	0.00
31	4.6	4.4	0.2	4.55
32	5.2	4.8	0.4	8.33
33	3.9	3.9	0.0	0.00
34	3.8	3.9	0.1	2.56
35	4.6	4.3	0.3	6.98
36	4.3	4.2	0.1	2.38
37	4.6	4.7	0.1	2.13
38	4.2	4.3	0.1	2.33
39	4.4	4.4	0.0	0.00
40	4.3	4.4	0.1	2.27
Mean	**5.32**	**5.42**	**0.10**	**3.93**

Table 6: Oxygen consumption comparison

	Oxygen Transfer (mL/min)			
Sample #	**CDI 500**	**Fick Equation**	**Abs. Diff.**	**% Error**
1	78	75.38	2.62	3.48
2	78	75.78	2.22	2.93
3	109	117.40	8.40	7.16
4	176	189.72	13.72	7.23
5	112	122.67	10.67	8.70
6	113	116.78	3.78	3.24
7	135	154.32	19.32	12.52
8	184	200.35	16.35	8.16
9	121	138.69	17.69	12.76
10	107	109.83	2.83	2.58
11	123	154.41	31.41	20.34
12	173	179.87	6.87	3.82
13	116	124.96	8.96	7.17
14	118	131.57	13.57	10.31
15	154	182.63	28.63	15.68
16	130	148.45	18.45	12.43
17	150	166.67	16.67	10.00
18	157	176.68	19.68	11.14
19	235	260.32	25.32	9.73
20	260	301.37	41.37	13.73
21	80	81.97	1.97	2.40
22	72	90.52	18.52	20.46
23	170	196.20	26.20	13.35
24	171	196.21	25.21	12.85
25	101	130.82	29.83	22.80
26	108	129.12	21.12	16.36
27	179	248.68	69.68	28.02
28	190	215.28	25.28	11.74
29	165	179.93	14.93	8.30
30	159	169.31	10.31	6.09
31	224	225.06	1.06	0.47
32	212	222.09	10.09	4.54
33	103	126.62	23.62	18.65
34	108	130.07	22.07	16.97
35	150	199.49	49.49	24.81
36	155	210.97	55.97	26.53
37	96	99.15	3.15	3.18
38	103	96.26	6.74	7.00
39	152	175.75	23.75	13.51
40	180	207.21	27.21	13.13
Mean	**142.69**	**161.46**	**18.78**	**11.63**

blood gas module is used with the CDI H/S Probe, the SaO_2 and PaO_2 needs to be manually input. If the clinician chooses the arterial blood gas module in conjunction with the CDI H/S Probe (as we did), the PvO2 could be manually input or internally approximated (i.e., 40 mmHg). With these few suggestions implemented, the oxygen consumption accuracy of the CDI 500 should be within a few percentage points of that obtained using the Fick equation.

In a previous article, this author has stated, "The need for continuous monitoring of the patient's VO_2/min, and the subsequent oxygen transfer requirement of the oxygenator, is clear. Many in-line and on-line devices currently available only offer selected pieces of the physiological puzzle. The perfusionist must integrate the data from these devices with the data available from other sources to form a complete picture" (5). In a published case report, the authors used oxygen consumption

measurements to ". . . differentiate between (1) a normal oxygenator with reserve transfer: (2) a normal oxygenator without reserve; and (3) a failing or suboptimally performing oxygenator" (6).

Devices that can provide automated, continuous oxygen consumption monitoring during cardiopulmonary bypass are long overdue. The CDI Blood Parameter Monitoring System 500 offers the clinician an additional tool in the effort to make cardiopulmonary bypass safer for the open-heart patient.

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