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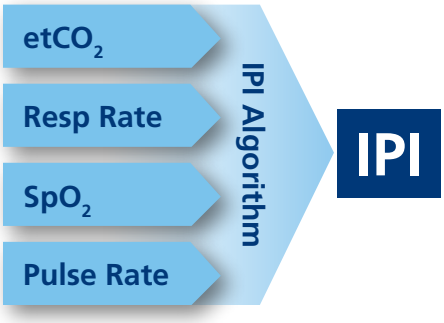
Integrated Pulmonary Index™ (IPI) Technology Brief

IPI simplifies assessment of respiratory status

Monitoring and managing your patient's respiratory status is now easier with the Integrated Pulmonary Index™ (IPI).



IPI graphical trend screen

The IPI algorithm incorporates four real-time respiratory measurements into a single number that represents an inclusive respiratory profile: end-tidal CO_2 ($etCO_2$), respiratory rate, pulse rate and SpO_2. IPI is displayed on a scale from 1 to 10, with 10 indicating a normal respiratory status. IPI provides a real-time indication of changes in the patient's respiratory status that may not be reflected by the current values of any of the four individual parameters.[1-3] To aid in monitoring patients over time, IPI is captured and analyzed to show upward and downward trends.

Table 1: IPI patient status

IPI	Patient Status
10	Normal
8-9	Within normal range
7	Close to normal range; requires attention
5-6	Requires attention and may require intervention
3-4	Requires intervention
1-2	Requires immediate intervention

How IPI works: A closer look at "fuzzy logic"

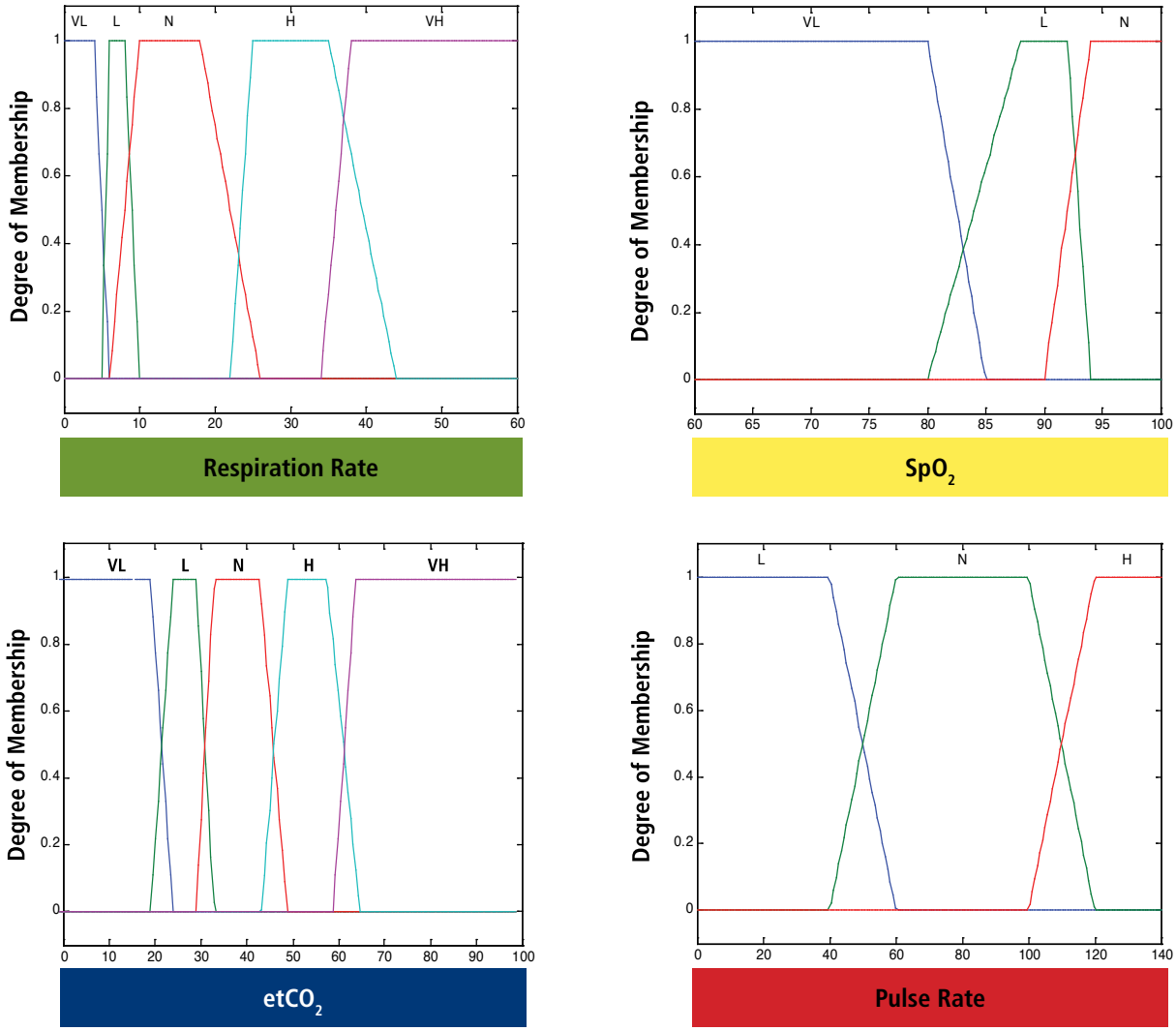
IPI is an algorithm that uses a "fuzzy logic" mathematical model. Fuzzy logic mimics a human's logical thinking pattern by approximating rather than precise deduction. Fuzzy logic uses verbal descriptors to define variables such as "normal", "high", "low", and logical functions such as "and", "or" and "if/then".

The fuzzy logic algorithm was built using the opinions of 30 medical experts. They evaluated the measured parameters from 235 patient cases to assign an IPI value according to the predefined scale shown in Table 1. The expert panel consisted of licensed clinicians including anesthesiologists, registered nurses, respiratory therapists, and physiologists.

Fuzzy Membership Functions

IPI uses Fuzzy Membership Functions that describe each physiological parameter by defined ranges: Very Low (VL), Low (L), Normal (N), High (H), and Very High (VH). Not all parameters have the same number of ranges.

Fuzzy Membership Function for Each IPI Parameter



The Fuzzy Membership Function takes into account the overlap between the ranges, providing degrees of membership for each range. This helped make the logic used to define the IPI precise and sensitive to changes in parameter values.

To meet the physiological parameter ranges of different patient age groups, IPI has defined Fuzzy Membership Functions for:

- Pediatric 1-3 years
- Pediatric 3-6 years
- Pediatric 6-12 years
- Adult

As an example, the Fuzzy Membership Function for pulse rate has 80 as normal, so it has 100% membership of 100% in the normal group. A pulse rate of 55 is still normal, but slightly low so it has 80% membership in the normal group and 20% membership in the low group.

With a Fuzzy Membership Function defined for each parameter, "if/then" rules were created to mimic the experts ' IPI scores for specific parameter set values. For example:

> **If** $etCO_2$ is VH, and RR is VH, and SpO_2 is N, and PR is H,
> **then** (IPI is 2) = patient requires immediate intervention

Rules Matrix

A Rules Matrix (Table 2) illustrates how fuzzy logic works to determine a single IPI score by simultaneously evaluating the values of $etCO_2$ and RR, with SpO_2 and PR both set to normal. The IPI score is the intersecting point of RR and $etCO_2$ values.

The Effect of SpO_2, Pulse Rate, and "No Breath" Alarm on IPI

SpO_2 values that fall outside of the normal range impact the IPI score as follows:

- If SpO_2 is in the LOW range, then one is subtracted from the Rules Matrix. For example, if $etCO_2$ is VH, and RR is N and SpO_2 is L, the IPI is reduced from 4 to 3.
- If SpO_2 is VERY LOW (<85%), then the IPI score automatically decreases to 1.

Pulse rates (PR) outside of the normal range will effect the IPI score as follows:

- If PR is L, and $etCO_2$ is H/VH, and RR is H/VH, then 1 is subtracted from the Rules Matrix
- If PR is H, and $etCO_2$ is L/VL, and RR is L/VL, then 1 is subtracted from the Rules Matrix
- When PR is L or H, and SpO_2 is <95, then the lowest value they individually effect on the Rules Matrix is applied.

Table 2: Rules Matrix (Adult)

If $etCO_2$ = 70 mmHg (VH 100%) and RR = 4 bpm (VL 100%) and SpO_2 = 100% (N 100%) and PR = 80 bpm (N 100%) **then** IPI = 2

SpO_2 is Normal Pulse Rate is Normal		Respiration Rate (RR) Value Ranges, bpm								
		Very High (VH 100%) 34-36	VH-H 34-36	High (H 100%) 25-35	H-N 21-24	Normal (N 100%) 10-20	N-L 9-11	Low (L 100%) 7-8	L-VL 6	Very Low (VL 100%) ≤5
$etCO_2$ Value Ranges, mmHg	Very High (VH 100%) ≥ 70	2		5		4		3		2
	VH-H 61-69									
	High (H 100%) 50-60	3		8		7		5		3
	N-H 46-49									
	Normal (N 100%) 35-45	4		8		10		7		6
	L-N 31-34									
	Low (N 100%) 25-30	5		6		8		4		2
	VL-L 21-24									
	Very Low (VL 100%) ≤ 20	3		3		4		2		2

When a parameter has partial membership in adjacent ranges, the fuzzy logic becomes more complex. For example: **If** $etCO_2$ = 48 mmHg (N 40%; H 60%), RR = 17 (N 100%), SpO_2 = 97% (N 100%) and PR = 70 bpm (N 100%), **then** IPI = 8

Table 3: Impact of No Breath

	10	9	8	7	6	5	4	3	2	1
SpO_2 Value, %	IPI Value Based SpO_2 Effect (PR Normal)									
95 – 100	10	9	8	7	6	5	4	3	2	1
94	9	9	8	7	6	5	3	3	2	1
92 – 93	9	9	7	7	5	4	3	2	1	1
91	7	7	6	6	4	3	3	2	1	1
90	6	6	5	5	3	3	3	2	1	1
89	5	5	4	4	3	2	2	1	1	1
88	4	4	3	3	3	2	2	1	1	1
87	3	3	3	3	2	2	2	1	1	1
86	2	2	2	2	1	1	1	1	1	1
≤85	1	1	1	1	1	1	1	1	1	1

When a "no breath" alarm occurs, the IPI score equals 1, independent of any other parameter value.

IPI Sensitivity to Changes in $etCO_2$ and SpO_2 Parameters

IPI provides an indication of changes in the patient's respiratory status that may not be reflected by the current value of any of the four individual parameters, as illustrated in Table 4. These examples illustrate the utility of IPI as a respiratory trend index.

Table 4: IPI sensitivity to subtle parameter changes

Example 1

Time (secs)	0	30	60	90
$etCO_2$	41	41	46	49
RR	16	20	17	16
SpO_2	97	98	98	98
PR	69	72	71	71
IPI	10	9	8	7

Example 2

Time (secs)	0	30	60	90
$etCO_2$	29	29	27	26
RR	16	21	17	14
SpO_2	97	99	92	88
PR	68	72	68	64
IPI	8	7	5	4

Clinical Validation

The results of the IPI model strongly correlated with the average score of the medical experts with mean absolute differences = 0.64±0.5 on the IPI scale. When comparing the data across all medical experts and cases, the average absolute difference between medical experts and the model was 1±0.35 on the IPI scale.[1]

Many clinical studies have been conducted to validate the Index. In one study, the IPI correlated with the respiratory status in 100% of 57 pediatric patients who received deep sedation.[2]

The investigators from both studies concluded[1,2]:

- IPI correlates with respiratory status.
- The single numeric value of IPI may be particularly valuable for promoting early awareness of respiratory distress.
- IPI simplifies the monitoring of patients in busy clinical environments.

In another study, all 30 postoperative patients enrolled had IPI scores that correlated with the respiratory status of adult patients postsurgery with general anesthesia.[3]

1. A Novel Integrated Pulmonary Index (IPI) Quantifies, Heart Rate, $EtCO_2$, Respiratory Rate, and SpO_2%. A. Taft, M. Ronen, et al. American Society of Anesthesiologists (ASA), October 2008. Abstract.
2. The Integrated Pulmonary Index: Validity and Application in the Pediatric Population. D. Gozal, Y. Gozal. Society for Technology in Anesthesia (STA), January 2009. Page 2; American Society of Anesthesiologists, October, 2009.
3. Reliability of the Integrated Pulmonary Index Postoperatively. Y. Gozal, D. Gozal. Society for Technology in Anesthesia (STA), January 2009. Page 8; European Journal of Anaesthesiology. Volume 26, Supplement 45, 2009.

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