

APPENDIX **D** ASV (adaptive support ventilation)

D.1 Introduction..... D-2

D.2 ASV use in clinical practice..... D-3

 Step 1: Before connecting the patient to the HAMILTON-G5..... D-5

 Step 2: Preparing the HAMILTON-G5 for ASV before ventilation..... D-5

 Step 3: Compensation for changes in apparatus dead space..... D-7

 Step 4: Adjusting ventilation: maintaining adequate ventilation..... D-8

 Step 5: Alarm settings review and special ASV alarms..... D-9

 Step 6: Monitoring ASV..... D-11

 Step 7: Weaning..... D-15

D.3 Detailed functional description of ASV..... D-16

 D.3.1 Normal minute ventilation..... D-16

 D.3.2 Targeted minute ventilation..... D-16

 D.3.3 Lung-protective rules strategy..... D-18

 D.3.4 Optimal breath pattern..... D-21

 D.3.5 Dynamic adjustment of lung protection..... D-24

 D.3.6 Dynamic adjustment of optimal breath pattern..... D-25

D.4 Minimum work of breathing (Otis' equation)..... D-27

D.5 ASV technical data..... D-29

D.6 Initialization of ventilation..... D-31

D.7 References..... D-32

D.1 Introduction

In 1977, Hewlett et al. introduced mandatory minute volume (MMV). "The basic concept is that the system is supplied with a metered, preselected minute volume of fresh gas, from which the patient breathes as much as he is able, the remainder being delivered to him via a ventilator. Thus the patient is obliged to breathe, one way or the other, a Mandatory Minute Volume MMV" (Hewlett 1977).

Since then, many ventilators have included versions of MMV under different names. However, all commercially available MMV algorithms have clear limitations, which lead to certain risks for the patient (Quan 1990). These include rapid shallow breathing, inadvertent PEEP creation, excessive dead space ventilation, and inadvertent wrong user settings due to very complicated use.

Adaptive Support Ventilation (ASV) was designed to minimize those risks and limitations. ASV maintains an operator-preset, minimum minute ventilation independent of the patient's activity. The target breathing pattern (tidal volume and rate) is calculated using Otis' equation, based on the assumption that if the optimal breath pattern results in the least work of breathing, it also results in the least amount of ventilator-applied inspiratory pressure when the patient is passive. Inspiratory pressure and machine rate are then adjusted to meet the targets. A lung protection strategy ensures ASV's safety. In contrast to MMV, ASV attempts to guide the patient using a favorable breathing pattern and avoids potentially detrimental patterns like rapid shallow breathing, excessive dead space ventilation, breath stacking (inadvertent PEEP), and excessively large breaths.

Contrary to what may be believed, ASV does not eliminate the need for a physician or clinician. However, ASV alleviates the need for tedious tasks and laborious readjustments of the ventilator; thus, it is a modern tool for the clinician. As such, ASV does not make clinical decisions. ASV executes a general command from the clinician and the clinician can modify it.

This command can be summarized as follows, where the modifiable parts are in bold:

Maintain a **preset minimum minute ventilation**,
take spontaneous breathing into account,
prevent tachypnea,
prevent AutoPEEP,
prevent excessive dead space ventilation,
fully ventilate in apnea or low respiratory drive,
give control to the patient if breathing activity is okay,
and do all this without exceeding a plateau pressure of 10 cmH₂O
below the **upper pressure limit**.

This appendix explains in practical terms how to use ASV at the patient's bedside and provides a detailed functional description. Since Otis' equation (Otis 1950) is the cornerstone of the optimal-breath pattern calculation, this equation is included and described. A table of detailed technical specifications and pertinent references is also given.

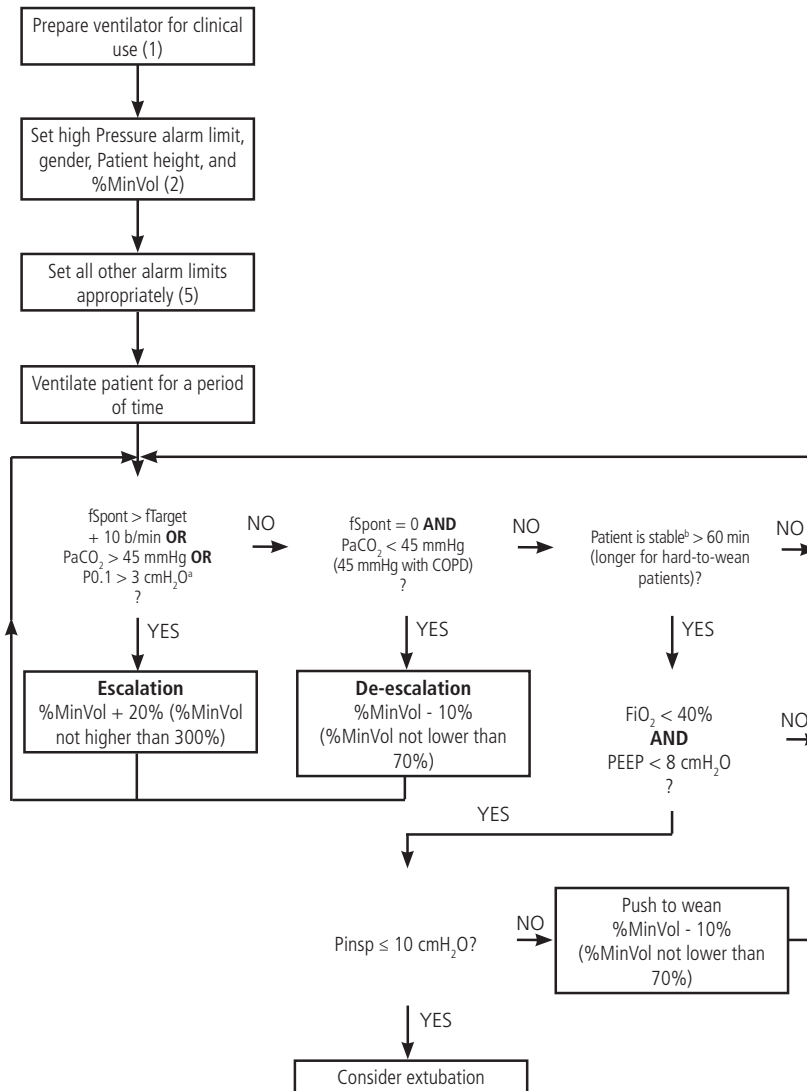
WARNING

This appendix describes ASV as it is implemented in the HAMILTON MEDICAL HAMILTON-G5 ventilator. It does not replace the clinical judgment of a physician and should not be used for clinical decision making.

D.2 ASV use in clinical practice

ASV does not require a special sequence of actions. It is used in much the same way as are older modes of ventilation. Figure D-1 summarizes how to use ASV, while the subsequent subsections explain it in detail. Figure D-2 shows the control settings active in the ASV mode.

D ASV (adaptive support ventilation)



a. Only with P-trigger
 b. Stable means $f_{\text{Control}} = 0$ b/min AND $\text{PaCO}_2 \leq 45$ mmHg (50 mmHg with COPD) AND $\text{P}0.1 \leq 3$ cmH₂O

Figure D-1. Clinical use of ASV. The numbers in parentheses are step numbers, which are explained in the next subsections.



Figure D-2. ASV control window

Step 1: Before connecting the patient to the HAMILTON-G5

It is important to prepare the HAMILTON-G5 for clinical use according to Section 2. This includes, but is not limited to, performing the preoperational procedures and testing indicated.

Step 2: Preparing the HAMILTON-G5 for ASV before ventilation

ASV requires that you set the following basic parameters:

Pressure	High Pressure alarm limit, in cmH ₂ O
Patient height	Patient height, in cm or in.
Gender	Sex of patient
%MinVol	Desired minute ventilation, in % of normal values

It is suggested you do the following before connecting the patient to the ventilator:

1. Remove the demonstration lung, when a demonstration lung is used, and silence the alarm.
2. Set the high Pressure alarm limit to an appropriate value (e.g., 45 cmH₂O or 50 cmH₂O for COPD patients). The maximum inspiratory pressure delivered in ASV (Pasv) will be **10 cmH₂O below the preset high Pressure limit**, indicated by a blue band on the pressure curve display. The maximal inspiratory pressure for ASV can be also set using the Pasv control in the **Controls** window. Changing the Pasv value will also change high Pressure limit.

NOTE:

The high limit must be at least 25 cmH₂O above PEEP/CPAP.

3. Activate ASV in the **Modes** window and then **Confirm** the mode change. The **Controls** window automatically opens.
4. Make the following control settings:
 - **Patient height**
 - **Gender**
 - **%MinVol.** A logical starting point is a %MinVol that will result in the same minute volume as a previous mode, if applicable. The %MinVol for a normal patient might be 100%; for a COPD patient, 90%; for an ARDS patient, 120%; and for other patients, 110%. Add 20% if body temperature > 38.5 °C (101.3 °F) and 5% per 500 m (1640 ft) above sea level.
 - **Trigger.** Suggested settings are a Flowtrigger of 2 l/min; or you can leave the previous patient trigger method and sensitivity, if applicable.
 - **ETS.** A suggested setting is 25% (40% for a COPD patient); or you can leave this unchanged, if applicable.

-
- **TRC.** It is suggested that TRC be enabled, with Compensate set to 100%.
 - **Other settings.** Set PEEP/CPAP and Oxygen values according to clinical requirements. You can leave the P-ramp setting at its standard value unless clinical judgment calls for adjustment. To set it, see Section 4.
5. **Confirm** the settings.
 6. Connect the patient to the ventilator if applicable. This will initiate three test breaths.

Step 3: Compensation for changes in apparatus dead space

The HAMILTON-G5 calculates the (anatomical or "series") dead space based on the IBW calculated from the patient height input. Dead space is calculated as 2.2 ml per kg (1 ml per lb). This dead space is a nominal value that is valid, on average, for intubated patients whose endotracheal tube is connected to the Y-piece of the ventilator by a standard catheter mount. If this dead space is altered by an artificial airway configuration such as the use of a heat and moisture exchange filter (HME) or nonstandard tubing, modify the Patient height setting accordingly to take into account the added or removed dead space.

Consider the following when compensating dead space:

- A shorter-than-standard endotracheal or tracheostomy tube probably does not require compensation.
- Different sizes of endotracheal tube probably do not require compensation.
- A much longer-than-normal catheter mount may require compensation.
- A bacterial filter or an HME may require compensation. The volume of these devices, for an adult, is on average 50 to 60 ml, but may be as high as 95 ml (Mallinckrodt Hygroster). For an HME, a simple rule of thumb is to add 10% to the IBW (by adjusting the Patient height control).

NOTE:

Changes in alveolar dead space due to ventilation/perfusion mismatch must be compensated via the %MinVol control.

Step 4: Adjusting ventilation: maintaining adequate ventilation

Once ASV is started, the HAMILTON-G5 calculates an optimal breath pattern and associated target values for tidal volume and rate according to the rules in Section D.4. ASV then adjusts the inspiratory pressure (P_{insp}) and machine rate (f_{Control}) to achieve the targets.

Once the calculated targets are reached, the result of the ventilation needs to be assessed. All HAMILTON-G5 monitored parameters can be used for this purpose. However, to assess respiratory acid-base status, it is recommended that arterial blood gases be measured and minute ventilation be adjusted accordingly. Table D-1 provides examples of how to adjust the %MinVol setting.

WARNING

It is inappropriate to adjust the IBW (through the Patient height control) to change minute volume. Always use the %MinVol control to adjust minute volume.

Table D-1. Blood gas and patient conditions and possible adjustments for ASV

Condition	%MinVol change	Remarks
Normal arterial blood gases	None	--
High PaCO ₂	Increase %MinVol	Pay attention to inspiratory pressures
Low PaCO ₂	Decrease %MinVol	Pay attention to mean pressures and oxygenation status
High respiratory drive	Consider increase in %MinVol	Consider sedation, analgesia, or other treatments
Low O ₂ saturation	None	Consider increase in PEEP/CPAP and/or Oxygen

Step 5: Alarm settings review and special ASV alarms

To monitor the breathing pattern, you must review the alarm settings periodically and set them according to clinically acceptable values. As described below, ASV changes the breathing pattern according to the respiratory system mechanics and within the boundaries resulting from the operator's settings for ASV. However, you can closely monitor ASV's actions through the alarm system, since the alarm settings work totally independently of ASV.

It is possible to select a %MinVol that is incompatible with the lung-protective rules that govern ASV (for a detailed description, see Section D.3.3). For example, the operator might want a high ventilation for a COPD patient in spite of severe pulmonary obstruction. In such a case, ASV tries to achieve the maximum possible ventilation and alarms that **ASV: Cannot meet target**. Such a case is shown in Figure D-3, where a high ventilation (300% at 70 kg) was set by the operator for a patient with severely obstructed lungs ($R_{aw} = 40 \text{ cmH}_2\text{O}/(\text{l/s})$). The high ventilation moves the minimum minute volume curve to the right while the obstructive disease causes the safety limit of rate to shift to the left. These two effects cause the minute volume curve to lie outside the safety limits as determined by the lung-protective rules strategy (see functional description below). ASV thus chooses the safest point closest to the user-set minute volume.

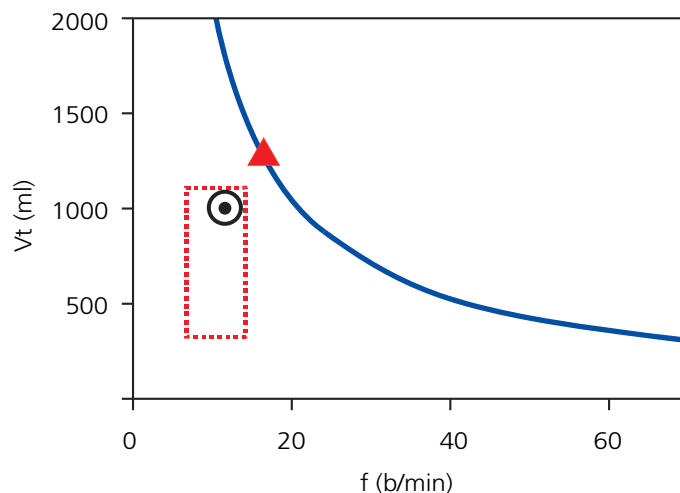
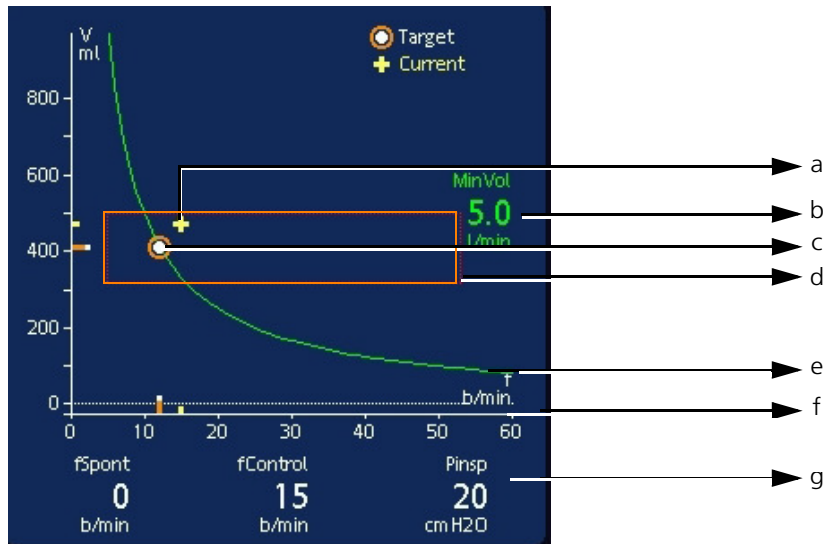


Figure D-3. Hypothetical example of high %MinVol setting incompatible with the lung-protective rules strategy. The open circle denotes the actual target, the closed triangle (never shown on the ventilator) denotes the (energetically) optimal target according to Otis' equation. The HAMILTON-G5 will alarm and inform the user that the ASV target cannot be achieved.

Step 6: Monitoring ASV

ASV interacts with the patient continuously. Whenever the patient's respiratory mechanics change, ASV adapts to this change. Whenever the patient's breathing activity changes, ASV adapts. To let you view the current status, the HAMILTON-G5 provides the ASV target graphics window (Figure D-4) and the ASV monitored data window (Figure D-5).

To monitor progress over time, it is recommended that you plot trends for P_{insp} , f_{Total} , and f_{Spont} . Interpret these trends, together with the %MinVol setting. Table D-2 through Table D-4 provide interpretation of typical ventilatory patterns. Figure D-1 is a flow chart to guide you through the ASV adjustment/weaning process.



- a. Current measured point, formed by intersection of measured tidal volume and rate.
- b. Numerical value of target minute volume.
- c. Target point, formed by intersection of target tidal volume and target rate.
- d. Safety frame in which target point may move.
- e. Minute volume curve.
- f. Horizontal axis for rate (f). Vertical axis for tidal volume (Vt).

Figure D-4. ASV target graphics window

	Target	Current
MinVol l/min	5.0	7.1
Vt ml	413	470
fTotal b/min	12	15
Insp time s	2.00	1.99
fSpont b/min	0	
fControl b/min	15	
Pinsp cmH2O		20

Figure D-5. ASV monitored data window

Table D-2. Interpretation of breathing pattern at 100% MinVol setting

Pinsp	fControl	fSpont	Interpretation
> 10	> 10	0	Fully controlled, mechanical ventilation. To start weaning, consider reducing %MinVol.
> 10	0	Acceptable	Supported spontaneous breathing. Consider reducing %MinVol.
< 8	0	Acceptable	Unsupported breathing. Consider extubation.
> 10	0	High	Dyspnea. Consider increasing %MinVol and other clinical treatments. Check for autotriggering.

Table D-3. Interpretation of breathing pattern at much higher than 100% MinVol setting

Pinsp	fControl	fSpont	Interpretation
> 10	> 10	0	Fully controlled mechanical ventilation. Check arterial blood gases. To start weaning, consider reducing %MinVol.
> 10	0	Acceptable	Supported spontaneous breathing. Check reason for increased ventilation requirement. Consider reducing %MinVol.
< 8	0	Acceptable	Unsupported breathing. Check reason for increased ventilation requirement. Consider reducing %MinVol and extubation.
> 10	0	High	Dyspnea. Check reason for increased ventilation requirement. Consider other mode of ventilation and clinical treatment. Check for autotriggering.

Table D-4. Interpretation of breathing pattern at much lower than 100% MinVol setting

Pinsp	fControl	fSpont	Interpretation
>10	> 10	0	Danger of hypoventilation. Check arterial blood gases and consider increasing %MinVol.
>10	0	Acceptable	Enforced weaning pattern. Monitor arterial blood gases and patient respiratory effort. Consider decreasing or increasing %MinVol accordingly.
<8	0	Acceptable	Unsupported breathing. Consider extubation.
>10	0	High	Dyspnea. Consider increasing %MinVol and other clinical treatments. Check for autotriggering.

Step 7: Weaning

Weaning patients from the ventilator is a clinical task that requires tremendous experience and involves more than just ventilation issues. This appendix does not intend to provide clinical information other than that needed to operate the ventilator with ASV.

ASV always allows patients to take spontaneous breaths. Episodes of spontaneous breathing can occur and are supported by ASV even within a period of fully controlled ventilation. In other words, weaning can start with ASV so early that it may go unrecognized clinically. It is therefore important to monitor the spontaneous efforts of the patient over time.

The weaning progress can be monitored in the trends display when inspiratory pressure (P_{insp}), total rate (f_{Total}), and spontaneous rate (f_{Spont}) are plotted. If the patient tolerates minimum respiratory support after a period of time with

$$P_{insp} < 8 \text{ cmH}_2\text{O}$$

$$f_{Control} = 0$$

weaning can be considered achieved, if minimum

f_{Spont} is acceptable

ExpMinVol is acceptable

What is "acceptable" must be defined by the clinician.

It may be necessary to reduce the %MinVol setting to 70% or even lower to "motivate" the patient to resume spontaneous breathing. If a patient can sustain minutes or even hours with a low %MinVol setting, it does not mean that weaning is complete. In fact, the %MinVol setting must always be interpreted in conjunction with the level of P_{insp} needed to achieve the set minute ventilation. Only if P_{insp} and f_{Control} are at their minimal values can weaning be assumed to be complete.

D.3 Detailed functional description of ASV

D.3.1 Normal minute ventilation

ASV defines normal minute ventilation according to the graph in Figure D-6.

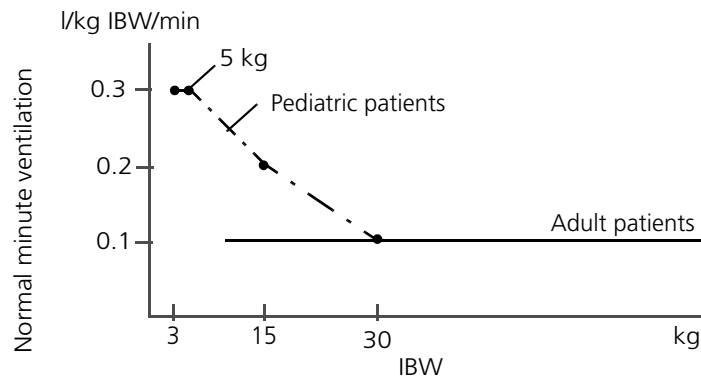


Figure D-6. Normal minute ventilation as a function of ideal body weight (IBW). For adult patients, minute ventilation is calculated as $0.1 \text{ l/kg} \cdot \text{IBW}$ (solid line). For pediatric patients, the value indicated by the dotted line is used. Minute ventilation for a 15 kg patient thus is calculated as $0.2 \text{ l/kg} \cdot 15 \text{ kg} = 3 \text{ l/min}$.

For example, for an IBW of 70 kg, normal minute ventilation corresponds to 7 l/min.

D.3.2 Targeted minute ventilation

When selecting ASV, it is necessary to select an appropriate minute ventilation for the patient. Minute ventilation is set with the %MinVol control, which, together with the Patient height control, determines the total minute ventilation in liters per minute.

A %MinVol setting of 100% corresponds to a normal minute ventilation, as defined above. A setting less than 100% or higher than 100% corresponds to a minute ventilation lower or higher than normal.

From the %MinVol, the target minute ventilation (in l/min) is calculated as:

$$\text{Bodyweight (in kg)} \times \text{NormMinVent (in l/kg/min)} \times (\% \text{MinVol}/100)$$

where NormMinVent is the normal minute ventilation from Figure D-6.

For example, with a %MinVol = 100 and an IBW = 70 kg, a target MinVol of 7 l/min is calculated. This target can be achieved with a number of combinations of tidal volume (Vt) and respiratory rate (f). This is shown in Figure D-7, where all possible combinations of Vt and f lie on the bold line, the target minute volume curve.

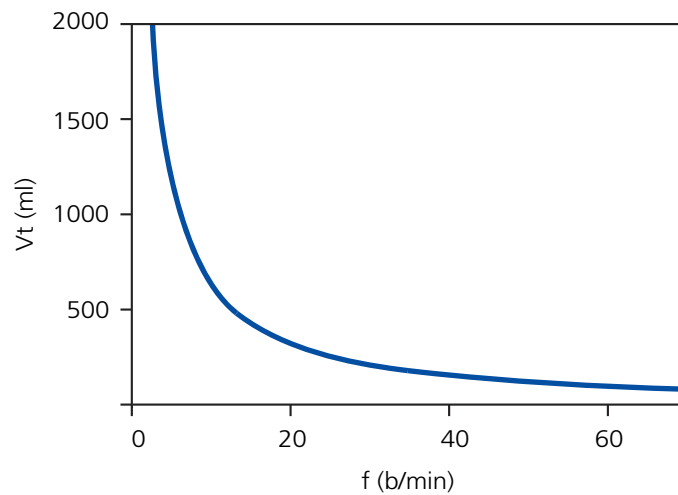


Figure D-7. MinVol = 7 l/min. All possible combinations of Vt and f which result in a minute ventilation of 7 l/min lie on the bold line.

D.3.3 Lung-protective rules strategy

Not all combinations of V_t and f shown in Figure D-7 are safe for the patient. The high tidal volumes would overdistend the lungs and the small tidal volumes may not produce alveolar ventilation at all. Another risk lies in inadequate respiratory rates. High rates could lead to dynamic hyperinflation or breath stacking and thus inadvertent PEEP. Low rates may lead to hypoventilation and apnea. It is therefore necessary to limit the number of possible combinations of V_t and f . In limiting the possible combinations of V_t and f , ASV uses a double strategy:

- The operator input for ASV determines the absolute boundaries.
- Internal calculations based on patient measurements further narrow the limits to counteract possible operator errors and to follow changes of respiratory system mechanics.

The effect of the strategy is shown in Figure D-8 and explained in the subsequent subsections.

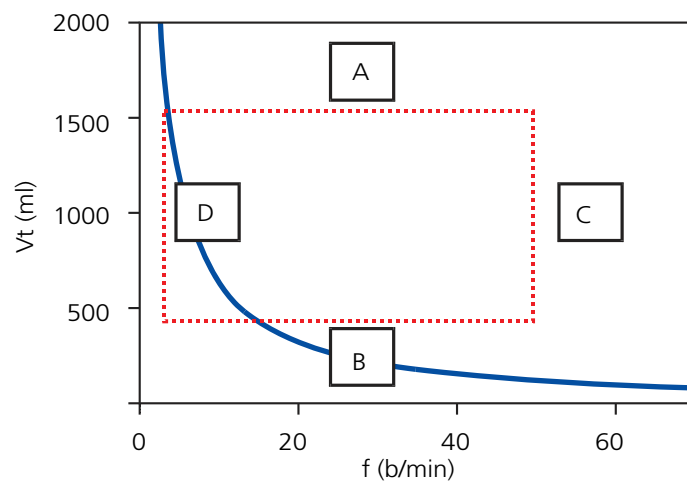


Figure D-8. Lung-protective rules strategy to avoid high tidal volumes and pressures (A), low alveolar ventilation (B), dynamic hyperinflation or breath stacking (C), and apnea (D)

A: High tidal volume limit

The tidal volume applied by ASV is limited (see A in Figure D-8) by two operator settings: high Pressure alarm limit and Patient height.

The operator is required to set the high Pressure limit before connecting a patient to the HAMILTON-G5. It was recommended by a group of physicians (Slutsky 1994) that the plateau pressure not exceed 35 cmH₂O. To achieve this with ASV, the high Pressure limit must be set to 45 cmH₂O. The maximum pressure to be applied in the ASV mode is 10 cmH₂O below the high Pressure limit.

For example, a normal 70 kg normal (post-operative) patient would have a compliance of about 50 ml/cmH₂O. A high Pressure limit of 45 cmH₂O would result in a maximum applied pressure of 35 cmH₂O. With a PEEP level of 5 cmH₂O, the effective pressure swing would be 30 cmH₂O. This in turn would lead to an effective V_t of equal to or less than 1500 ml. If the patient's lungs stiffen, say to a compliance of 30 ml/cmH₂O, the maximum tidal volume becomes 900 ml.

If the operator sets the Pressure limit to a very high pressure, say 60 cmH₂O, the target volume is limited by the second criterion: 22 x IBW. For the 70 kg sample patient, a maximum target volume of 1540 ml results.

B: Low tidal volume limit

The minimum target V_t in ASV (see B in Figure D-8) is determined by the IBW calculated from the Patient height, which corresponds to 4.4 ml/kg. Thus, in a 70 kg patient, the minimum target V_t is 308 ml.

The danger with low tidal volumes is insufficient alveolar ventilation. The determining parameter for alveolar ventilation is dead space (V_{Daw}). Tidal volume must always be larger than V_{Daw}. It is widely accepted that a first approximation of dead space can be obtained by the following simple equation (Radford 1954):

$$V_{Daw} = 2.2 * IBW \quad (1)$$

The lower limit for tidal volume is based on this equation and calculated to be at least twice the dead space. In other words, the minimum V_t is $4.4 \times IBW$.

C: High rate limit

The maximum rate (see C in Figure D-8) is derived from the operator-set %MinVol and the calculated IBW, which is calculated from the operator-set Patient height. The equation used to calculate the maximum rate is as follows:

$$f_{\max} = \text{target MinVol} / \text{minimum } V_t \quad (2)$$

For example, the 70 kg patient described above would have a maximum rate of 22 b/min, when %MinVol is set to 100%.

However, if the operator chooses an excessively high %MinVol of, say, 350%, the maximum rate becomes 77 b/min. To protect the patient against such high rates, ASV employs a further safety mechanism, which takes into account the patient's ability to exhale.

A measure of the ability to exhale is the expiratory time constant (RC_{exp}) (Marini 1989, Brunner 1995). In order to achieve a nearly complete exhalation to the equilibrium point of the respiratory system (90% of the maximum potential volume change), an expiratory time of at least $2 \times RC_{\text{exp}}$ is theoretically required. For this reason, ASV calculates the maximum rate based on the principle of giving a minimum inspiratory time equal to $1 \times RC_{\text{exp}}$ and a minimum expiratory time equal to $2 \times RC_{\text{exp}}$, which results in the following equations:

$$\begin{aligned} f_{\max} &= 60 / (3 \times RC_{\text{exp}}) = 20 / RC_{\text{exp}} \\ f_{\max} &\leq 60 \text{ b/min} \end{aligned} \quad (3)$$

For example, the 70 kg patient with a respiratory system compliance of $50 \text{ ml/cmH}_2\text{O}$ (equal to $0.05 \text{ l/cmH}_2\text{O}$), an airway resistance including endotracheal tube of $5 \text{ cmH}_2\text{O/l/s}$, and a resistance of the expiratory hose and valve of another $5 \text{ cmH}_2\text{O/l/s}$, would have an RC_{exp} of

$$0.05 \text{ l/cmH}_2\text{O} \times (5+5) \text{ cmH}_2\text{O/l/s} = 0.5 \text{ s}$$

and thus a maximum rate of 40 b/min. Since this value is higher than the one calculated above, the lower of the two values is in effect, i.e., 22 b/min.

This limit applies to the respiratory rate of the ventilator only, *not* to the respiratory rate of the patient.

D. Low rate limit

The lowest target rate (see D in Figure D-8) is fixed at 5 b/min. This low rate in turn limits the maximum tidal volume to 1400 ml in the example of the 70 kg patient above, when %MinVol is set to 100%.

D.3.4 Optimal breath pattern

Although the lung-protective rules strategy limits possible combinations of V_t and f , ASV prescribes an explicit target combination. In fact, Figure D-8 shows considerable room for selection within the dotted rectangle. The selection process is an exclusive feature of ASV. The basic assumption is that the optimal breath pattern is identical to the one a totally unsupported patient would choose naturally, provided that patient is capable of maintaining the pattern.

According to textbooks of physiology, the choice of breathing pattern is governed by either work of breathing or the force needed to maintain a pattern. ASV uses the original equation by Otis (Otis 1950) and calculates the optimal rate based on operator entries of %MinVol and the IBW (based on the Patient height setting) as well as on the measurement of RC_{exp} (see Section D.4).

For example, with the 70 kg patient, a setting of 100 %MinVol, and a measured RC_{exp} of 0.5 s, the optimal rate is 15 b/min according to Otis' equation.

Once the optimal rate is determined, the target V_t is calculated as:

$$V_t = \text{target MinVol} / \text{optimal rate} \quad (4)$$

In the example of the 70 kg patient, the target V_t becomes 467 ml (see Section D.4 for details).

Figure D-9 summarizes the calculations done in the previous subsections and shows the position of the target breathing pattern as well as the safety limits imposed by the lung-protective rules strategy.

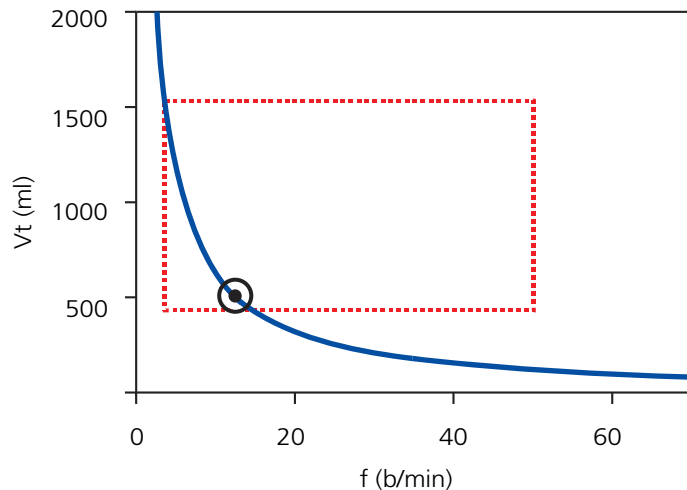


Figure D-9. Anatomy of the ASV target graphics window.

The rectangle shows the safety limits; the circle shows the target breath pattern.

D.3.4.1 Initial breaths: How ASV starts

The question is, how to achieve the target values in a given patient if it is not known whether or not the patient can breathe spontaneously. For this purpose, ASV employs a synchronized intermittent mandatory pressure ventilation mode.

Every breath triggered by the patient is pressure-supported and flow-cycled, i.e., the transition to exhalation is made based on flow. In contrast, if the patient does not trigger the breath, the delivery of the breath is pressure-preset and time-cycled.

The following controls can be set by the operator:

- PEEP/CPAP
- Oxygen
- P-ramp

-
- ETS
 - Trigger type and sensitivity

The following controls are adjusted automatically by ASV and thus cannot be adjusted by the operator:

- SIMV rate: to change total respiratory rate
- Inspiratory pressure level: to change inspiratory volume
- Inspiratory time: to allow gas flow into the lungs
- Startup breath pattern

To safely start ASV, the operator inputs the Patient height setting, which is used to calculate the IBW.

Three initial test breaths are delivered. The resulting rate and tidal volume are measured and compared with the target values. ASV then responds according to the differences between the actual and target V_t as well as the actual and target rates.

D.3.4.2 Approaching the target

Figure D-10 shows a possible scenario after the three initial test breaths. The actual breath pattern, which is plotted as a cross, shows clear deviation from the target. The task of ASV is now to move the cross as close to the circle as possible.

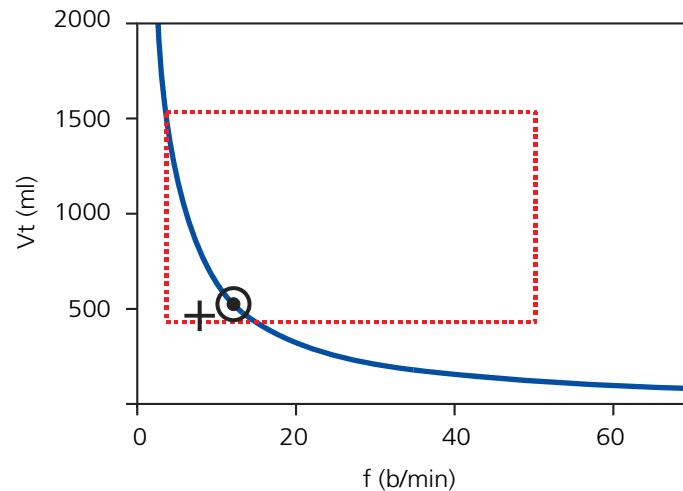


Figure D-10. Example of a situation after the three initial breaths. The cross marks the actual measured values for V_t and rate.

To achieve the target, the following strategy is used:

- If actual $V_t <$ target V_t , the inspiratory pressure is increased.
- If actual $V_t >$ target V_t , the inspiratory pressure is decreased.
- If actual $V_t =$ target V_t , the inspiratory pressure is left unchanged.
- If actual rate $<$ target rate, the SIMV rate is increased.
- If actual rate $>$ target rate, the SIMV rate is decreased.
- If actual rate $=$ target rate, the SIMV rate is left unchanged.

As a result, the cross in Figure D-10 moves toward the circle. The actual V_t is calculated as the average of inspiratory and expiratory volumes of the last 8 breaths. This definition compensates in parts for leaks in the breathing circuit, including the endotracheal tube.

D.3.5 Dynamic adjustment of lung protection

The operator preset values are not changed by ASV, and the corresponding safety limits remain as defined above. However, if the respiratory system mechanics change, the safety limits change accordingly and as defined in Section D.3.3. The safety limits are updated on a breath-by-breath basis.

For example, if the lungs stiffen, the high V_t limit is lowered proportionally, and the high Rate limit is increased according to Equation 5.

This dynamic adjustment ensures that ASV applies a safe breathing pattern at all times. In graphical terms, the dotted rectangle changes as shown in Figure D-11.

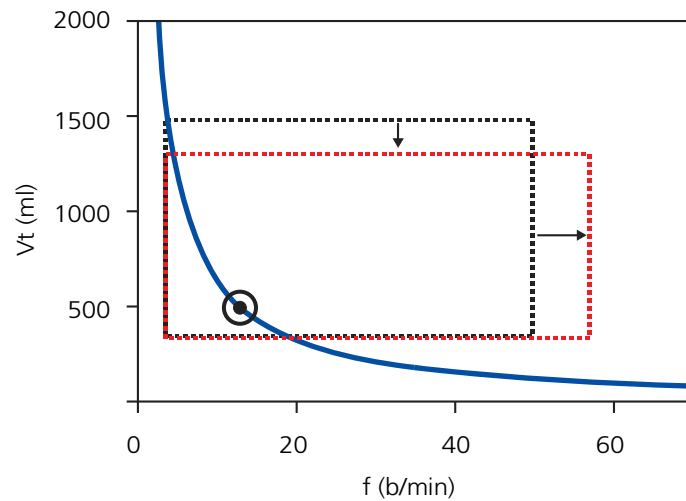


Figure D-11. Lung-protective limits are changed dynamically and according to the respiratory system mechanics. However, the limits derived from the operator input are never violated.

D.3.6 Dynamic adjustment of optimal breath pattern

Once calculated, the optimal breath pattern is revised with each breath according to the measurements of RC_{exp} . Otis' equation is applied and a new target breathing pattern is calculated. Under steady-state conditions, the targets do not change. However, if the patient's respiratory system mechanics change, the target values also change.

For example, if the bronchi of our normal 70 kg sample patient (being ventilated at 15 b/min and with a V_t of 467 ml) constrict due to asthma, the expiratory resistance increases to values higher than 5 $\text{cmH}_2\text{O/l/s}$. For this reason, more time is needed during exhalation for the lungs to reach the end-expiratory equilibrium position. Technically speaking, RC_{exp} has increased and this increase requires a longer expiratory time. For a given minute ventilation, this calls for an increase in V_t and a decrease in rate (longer expiratory time). Otis' equation yields the following new targets: $f = 11$ b/min and $V_t = 636$ ml. Figure D-12 shows the change. Note also that the increase in resistance results in a decrease in the volume/pressure ratio (V/P). The changes in RC_{exp} and dynamic compliance affect the safety limits accordingly and with each breath (see previous subsection).

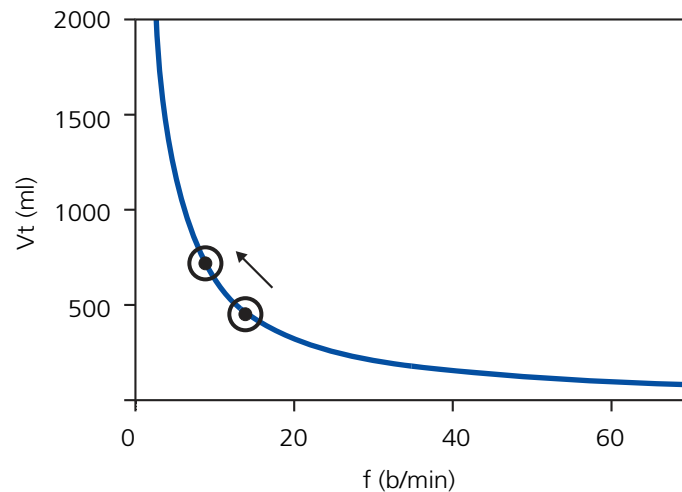


Figure D-12. Changes of target values in bronchoconstriction. For clarity, the safety limits are omitted. For clinical examples, see Belliato 2000.

D.4 Minimum work of breathing (Otis' equation)

Otis' basic question was: how do mammals choose their breathing pattern and on what parameters does it depend (Otis 1950)? The same question was investigated years before by Rohrer and a very similar result was obtained (Rohrer 1925). The hypothesis was that the breath pattern with the least work of breathing (WOB) is chosen by mammals. Figure D-13 below shows the relationship between rate and WOB graphically, for resistive load, elastic load, and total load to breathing.

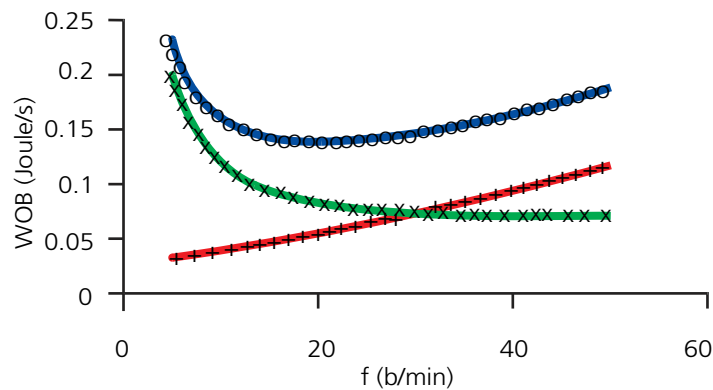


Figure D-13. Three different relationships between rate and WOB are plotted for a hypothetical lung: (+) purely resistive load causes WOB to rise with rate, (x) purely elastic load creates highest load at low rates, (o) the total lung shows a clear minimum which can be calculated according to the equation below.

The following equation was found to represent the rate where WOB is minimum:

$$f = \frac{\sqrt{1 + 2a \times RCe \times (\text{MinVol} - f \times Vd) / (Vd)} - 1}{a \times RCe}$$

where a is a factor that depends on the flow waveform. For sinusoidal flows, a is $2\pi^2/60$.

The corresponding tidal volume is calculated as:

$$V_t = \text{MinVol}/f$$

Example: A 70 kg male patient with normal lungs ($R_{\text{total}} = 5 \text{ cmH}_2\text{O}/\text{l/s}$, expiratory resistance hose and valve = $5 \text{ cmH}_2\text{O}/\text{l/s}$, $C_{\text{rs}} = 50 \text{ ml/cmH}_2\text{O}$) may have a measured R_{Cexp} of 0.5 s, an estimated V_{Daw} of 154 ml, and an operator-set %MinVol of 100%. With these values, the target MinVol becomes

$$\text{MinVol} = 100\% \times 70 \text{ kg} \times 0.1 \text{ l/min/kg} = 7 \text{ l/min}$$

Next, Otis' equation is applied with the following parameters:

$$\text{MinVol} = 7 \text{ l/min}$$

$$V_{\text{Daw}} = 154 \text{ ml}$$

$$R_{\text{Cexp}} = 0.5\text{s}$$

$$a = 2\pi^2/60$$

$$f = 10 \text{ b/min (determined using Table D-6 or Table D-7)}$$

The result is a new rate $f(1)$

$$f(1) = 15 \text{ b/min}$$

This rate is again inserted into Otis' equation, the calculation is performed again, and the next estimate for rate $f(2)$ is obtained. This procedure is repeated until the difference between subsequent results for rate (f) becomes lower than 0.5 b/min. In the present example, one iteration step is sufficient, i.e.,

$$f_{\text{target}} = 15 \text{ b/min}$$

Finally, the target tidal volume is obtained by dividing MinVol by f :

$$V_{\text{target}} = 7000 \text{ ml/min} / 15 \text{ b/min} = 467 \text{ ml}$$

D.5 ASV technical data

Table D-5 lists technical data related to ASV. Underlined parameters are operator-set in the ASV mode.

Table D-5. ASV technical data

ASV-related operator settings	
<u>%MinVol</u>	25 to 350%
<u>Patient height</u>	130 to 250 cm / 50 to 100 in. (adult) 30 to 150 cm / 12 to 60 in. (pediatric)
Internal calculations	
IBW	In kg, calculated based on Patient height and Gender (see Section 4.2)
MinVol (target)	In l/min, target minute volume is calculated as: $\text{IBW (in kg)} \times \text{NormMinVent (in l/kg/min)} \times \frac{\% \text{MinVol}}{100}$ where NormMinVent is the normal minute ventilation from Figure D-6.
fTotal	In b/min, calculated on the basis of Otis' equation
VDaw	2.2 ml/kg IBW
Vt (target)	MinVol/ f(target)
ASV monitor	
Target values (numerical)	MinVol, Vt, fTotal
Current achieved values (numerical)	MinVol, Vt, fTotal
Status of patient (numerical)	fSpont, fControl, PInsp

Table D-5. ASV technical data (continued)

Graphics display (curve)	f versus Vt, target value, actual value, safety boundaries
Alarms	
All HAMILTON-G5 alarms are functional except apnea alarms	See Section 6
Special	ASV: Check hi press limit, Initialization failed, ASV: Cannot meet target
Performance specifications	
Response time (90% of steady state)	< 1 min (typical)
Overshoot/undershoot	< 20%
Maximum pressure change per breath	2 cmH ₂ O
Lung-protective rules	
Maximum Vt	Depends on high <u>Pressure</u> alarm limit and volume/pressure ratio (V/P) However, normally MinVol/5, but always < 22 x IBW
Minimum Vt	4.4 x IBW
Maximum machine rate	22 b/min x %MinVol/100 (adults) 45 b/min x %MinVol/100 (pediatrics) but always < 60 b/min
Minimum target rate	5 to 15 b/min
Maximum P _{insp}	High <u>Pressure</u> alarm limit - 10 cmH ₂ O
Minimum P _{insp}	5 cmH ₂ O above <u>PEEP/CPAP</u>

Table D-5. ASV technical data (continued)

Minimum inspiratory time (TI)	0.5 s or RCexp, whichever is longer
Maximum inspiratory time (TI)	2 s
Minimum expiratory time (Te)	2 x RCexp
Maximum expiratory time (Te)	12 s
I:E range	1:4 to 1:1

D.6 Initialization of ventilation

When ASV is started, the HAMILTON-G5 delivers three test breaths in the synchronized intermittent mandatory pressure ventilation mode. The HAMILTON-G5 automatically selects the values for SIMV rate, inspiratory time (TI), and inspiratory pressure (P_{insp}) based on the calculated IBW, which is determined from the operator-set Patient height and Gender settings, and according to Table D-6 and Table D-7.

Table D-6. Initial breath pattern for Adult settings

IBW (kg)	P _{insp} (cmH ₂ O)	TI (s)	SIMV rate (b/min)	Minimum target rate (b/min)
30 to 39	15	1	14	7
40 to 59	15	1	12	6
60 to 89	15	1	10	5
90 to 99	18	1.5	10	5
≥ 100	20	1.5	10	5

Table D-7. Initial breath pattern for Pediatric settings

IBW (kg)	P insp (cmH ₂ O)	TI (s)	SIMV rate (b/min)	Minimum target rate (b/min)
3 to 5	15	0.4	30	15
6 to 8	15	0.6	25	12
9 to 11	15	0.6	20	10
12 to 14	15	0.7	20	10
15 to 20	15	0.8	20	10
21 to 23	15	0.9	15	7
24 to 29	15	1	15	7

D.7 References

- **Hewlett AM, Platt AS, Terry VG.** Mandatory minute volume. A new concept in weaning from mechanical ventilation. *Anaesthesia* 1977, 32:163-9.
- **Radford EP Jr.** Ventilation standards for use in artificial respiration. *N Engl J Med* 1954, 251:877-83.
- **Otis AB, Fenn WO, Rahn H.** Mechanics of breathing in man. *J Appl Physiol* 1950, 2:592-607.
- **Marini JJ, Crooke PS, Truwit JD.** Determinants and limits of pressure-preset ventilation: a mathematical model of pressure control. *J Appl Physiol* 1989, 67:1081-92.
- **Slutsky AS.** Consensus conference on mechanical ventilation- January 28-30, 1993 at Northbrook, Illinois, USA. *Int Care Med* 1994, 20:64-79.
- **Lourens MS, Van den Berg BV, Aerts JGJ, Verbraak AFM, Hoogsteden HC, Bogtaard JM.** Expiratory time constants in mechanically ventilated patients with and without COPD. *Int Care Med* 2000, 26:1612-18.

-
- **Quan SF, Parides GC, Knoper ST.** Mandatory Minute Volume (MMV) Ventilation: An Overview. *Resp Care* 1990, 35:898-905.
 - **Belliato M, Maggio M, Neri S, Via G, Fusilli N, Olivei M, Iotti G, Braschi A.** Evaluation of the adaptive support ventilation (ASV) mode in paralyzed patients. *Intensive Care Med* 2000, 26, Suppl. 3:S327.
 -**more** and updated references on www.hamilton-medical.com