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14. ABSTRACT Aeromedical transport of critically ill patients requires continued, accurate performance of equipment at altitude. Changes in barometric pressure can affect the performance of mechanical ventilators calibrated for operation at sea level. Deploying ventilators that can maintain a consistent tidal volume (VT) delivery at various altitudes is imperative for lung protection when transporting wounded war fighters to each echelon of care. Three ventilators (Impact 731, Hamilton T1, and CareFusion Revel) were tested at pediatric (50 and 100 mL) and adult (250Y750 mL) tidal VTs at 0 and 20 cm H2O positive end expiratory pressure and at inspired oxygen of 0.21 and 1.0. Airway pressure, volume, and flow were measured at sea level as well as at 8,000, 16,000, and 22,000 ft (corresponding to barometric pressures of 760, 564, 412, and 321 mm Hg) using a calibrated pneumotachograph connected to a training test lung in an altitude chamber. Set VTand delivered VTas well as changes in VT at each altitude were compared by t test. The T1 delivered VTwithin 10% of set VTat 8,000 ft. The mean VTwas less than set VTat sea level as a result of circuit compressible volume with the Revel and the 731. Changes in VT varied widely among the devices at sea level and at altitude. Increasing altitudes resulted in larger VT than set for the Revel and the T1. The 731 compensated for changes in altitude delivered VTwithin 10% at the adult settings at all altitudes. Altitude compensation is an active software algorithm. Only the 731 actively accounts for changes in barometric pressure to maintain the set VT at all tested altitudes.					
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Performance of portable ventilators at altitude

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BACKGROUND:	Aeromedical transport of critically ill patients requires continued, accurate performance of equipment at altitude. Changes in barometric pressure can affect the performance of mechanical ventilators calibrated for operation at sea level. Deploying ventilators that can maintain a consistent tidal volume (VT) delivery at various altitudes is imperative for lung protection when transporting wounded war fighters to each echelon of care.
METHODS:	Three ventilators (Impact 731, Hamilton T1, and CareFusion Revel) were tested at pediatric (50 and 100 mL) and adult (250–750 mL) tidal VTs at 0 and 20 cm H ₂ O positive end expiratory pressure and at inspired oxygen of 0.21 and 1.0. Airway pressure, volume, and flow were measured at sea level as well as at 8,000, 16,000, and 22,000 ft (corresponding to barometric pressures of 760, 564, 412, and 321 mm Hg) using a calibrated pneumotachograph connected to a training test lung in an altitude chamber. Set VT and delivered VT as well as changes in VT at each altitude were compared by <i>t</i> test.
RESULTS:	The T1 delivered VT within 10% of set VT at 8,000 ft. The mean VT was less than set VT at sea level as a result of circuit compressible volume with the Revel and the 731. Changes in VT varied widely among the devices at sea level and at altitude. Increasing altitudes resulted in larger VT than set for the Revel and the T1. The 731 compensated for changes in altitude delivered VT within 10% at the adult settings at all altitudes.
CONCLUSION:	Altitude compensation is an active software algorithm. Only the 731 actively accounts for changes in barometric pressure to maintain the set VT at all tested altitudes. (<i>J Trauma Acute Care Surg.</i> 2014;77: S151–S155. Copyright © 2014 by Lippincott Williams & Wilkins)
KEY WORDS:	Portable ventilators; altitude performance; aeromedical evacuation.

Safe transport of critically ill and injured patients during aeromedical evacuation requires equipment that performs accurately at altitude. Hypobaric conditions alter gas characteristics and can affect the performance of mechanical ventilators that are normally calibrated for use at sea level. Increased altitude changes how gas moves through the ventilator's measuring mechanisms, which can alter flow measurement, resulting in inaccurate ventilator settings being delivered to the patient. Since the standard of care for lung protection is VT delivery of 6 mL/kg predicted body weight, the effects of hypobaric gas density changes could increase delivered VT and induce or exacerbate lung injury.¹ Many patients transported by the Air Force Critical Care Transport Teams (CCATT) have acute lung injury or adult respiratory distress syndrome, so ensuring accurate VT delivery is critical to maintaining lung protection and patient safety. Excessive VT may have a negative effect on these patients because of a left shift in the oxyhemoglobin dissociation curve, hypocarbia, cardiac arrhythmias, decreased cerebral blood flow, and hypokalemia. Deploying ventilators that can maintain a consistent VT delivery at various altitudes is imperative for lung protection

when transporting wounded war fighters to each echelon of care. We evaluated the VT delivered by three portable ventilators, either currently in use or being considered for aeromedical transport use, in a bench model at sea level and at simulated altitudes.

Devices

We evaluated one device each: 731 (Impact Instrumentation, West Caldwell, NJ), T-1 (Hamilton Medical, Reno, NV), and Revel (Carefusion, San Diego, CA). Preuse calibration of the ventilators, required by the manufacturer, was done before testing. The performance and physical characteristics of the devices are described in Table 1.

MATERIALS AND METHODS

The study was conducted at Wright-Patterson Air Force Base in a human-rated altitude chamber at sea level as well as at altitudes of 8,000, 16,000, and 22,000 ft, corresponding to barometric pressures of 760, 565, 412, and 321 mm Hg. An altitude of 8,000 ft was chosen to represent a simulated cabin altitude during CCATT flight. An altitude of 22,000 was chosen to represent the upper limit of crew functionality in the case of aircraft decompression and conditions of Special Forces mission requirements.

At sea level and each altitude, the ventilators were connected to a two-chamber test lung (TTL, Michigan Instruments, Grand Rapids, MI) via the manufacturer-supplied circuit and evaluated using the combinations of ventilator settings shown in Table 2, using pediatric and adult lung models shown in Table 3. A Fleisch pneumotachograph (Series

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TABLE 1. Comparison of the Physical and Functional Properties of the Ventilators Included in the Evaluation

Ventilator	Impact 731	Hamilton T1	CareFusion Revel
Weight, kg	4.4	6.5	4.5
Dimensions (W × L × D), cm	20.3 × 31.8 × 11.4	31 × 30 × 21	28.7 × 18 × 8.4
Breath types	Volume Pressure	Pressure PRVC	Volume Pressure PRVC
Modes	Assist control SIMV Pressure support CPAP	Assist control SIMV Pressure support CPAP ASV DuoPAP APRV	Assist control SIMV Pressure support CPAP
VT range, mL	50–1,500	20–2,000	50–2,000
PEEP range, cm H ₂ O	0–25	0–35	0–20
Breath rate, breaths per minute	1–60	1–80	1–80
Volume monitoring	Inspired	Inspired and expired	Inspired and expired
FIO ₂ range	0.21–1.0	0.21–1.0	0.21–1.0
Internal air source	Compressor	Blower	Blower
Altitude compensation, ft	Up to 25,000	Up to 13,120	Up to 10,600

4700, Hans Rudolph, Shawnee, KS) was connected between the ventilator circuit and the test lung, and the signals for airway pressure, flow, and volume were collected on a breath-to-breath basis by a research data collection system (RSS 100, Hans Rudolph, Shawnee, KS) and recorded to a personal computer for later analysis. After a 1-minute stabilization period, a minimum of 1 minute of data were collected at each combination of lung model and ventilator settings. All tests were performed at each altitude a minimum of two times. At sea level and each altitude, barometric pressure was verified, and the measurement system was calibrated using a 3-L super syringe.

RESULTS

Changes in VT varied widely among the devices at sea level and at altitude. From sea level to 22,000 ft, VT increase ranged from 2% to 19% at the pediatric settings and 5% to 33% at the adult settings, with the T1. The largest increase occurred at the 250-mL setting. Most of the volumes greater than 10% of set VT with the T1 were at the 250-mL VT settings. The T1 displayed a critical alarm and delivered VT from 8% to 40% lower than set VT at the 500-mL/20-cm H₂O positive end expiratory pressure (PEEP) setting at 22,000 ft and at the 750-mL/20-cm H₂O PEEP setting at both 16,000 and 22,000 ft.

We subsequently tested another T1 to determine whether the critical alarm could be reproduced. As 15,000 ft during the first test and 8,000 ft during the second test, the device displayed a “technical event” alarm with a “ventilation canceled” message and ceased to ventilate. The device was unable to be restarted until descending to lower altitudes. The T1 was the only device that consistently delivered VT within the American Society for Testing and Materials (ASTM) standard with all settings at sea level. The Revel VT increase ranged from 22% to 32% at the pediatric settings and 30% to 39% at the adult settings. The increases were consistent across all ventilator settings and lung models. Nearly all VTs delivered by the Revel at sea level and 8,000 ft were less than the 10% ASTM standard. All VTs with the adult settings at 16,000 ft and the pediatric settings at 22,000 ft were within 10% of set VT. The baseline VT at sea level, lower than ASTM-acceptable VT, coupled with no compensation for altitude allowed the delivered VT to be within 10% of set VT at 16,000 ft at the adult settings. All VTs with the adult settings at 22,000 ft were greater than 10% of set VT. The 731-delivered VTs decreased with increases in altitude. The VT decrease ranged from 9% to 21% at the pediatric settings and 1% to 7% at the adult settings. All but one of the delivered VTs using the pediatric settings with the 731 were less than the 10% ASTM standard at sea level and all altitudes, with the exception of the 250-mL VT setting. With the restrictive lung model, the 731-delivered VTs were within 10%

TABLE 2. Pediatric and Adult Ventilator Settings Used in the Evaluation

Ventilator Settings				
Lung Model	Respiratory Rate	VT, mL	PEEP, cm H ₂ O	FIO ₂
Pediatric	30	50 and 100	0 and 10	0.21 and 1.0
Adult	15	500 and 750	0 and 20	0.21 and 1.0

TABLE 3. Pediatric and Adult Lung Models

Lung Model	Lung Compliance	Airway Resistance
Pediatric	0.01 L/cm H ₂ O	20 cm H ₂ O/L/s
Adult normal	0.1 L/cm H ₂ O	5 cm H ₂ O/L/s
Adult restrictive	0.02 L/cm H ₂ O	5 cm H ₂ O/L/s

of set VT using the adult settings. No VTs were greater than 10% of set VT with this device.

Each of the ventilators delivered some VTs that were outside the ASTM standard of $\pm 10\%$ of the set VT.² The most common occurrences were with the adult settings with the T1, the pediatric settings with the 731, and with both pediatric and adult settings with the Revel.

Figures 1 and 2 show the measured VT \pm SD at each VT setting using 0-cm H₂O PEEP and fractional inspired oxygen (FIO₂) of 0.21. The addition of PEEP or the use of an FIO₂ of 1.0 did not demonstrably affect VT changes at sea level or at altitude with any of the ventilators. Respiratory rate was not affected by increases in altitude.

All differences in VT from baseline to each altitude were statistically significant ($p < 0.01$) but not necessarily clinically significant. Clinical significance is defined as those VTs that were outside the $\pm 10\%$ ASTM threshold for accuracy.

DISCUSSION

The findings of this study show that differences remain among ventilators with respect to VT delivery at altitude and at sea level at selected settings. The evaluation of changes in VT in our current project is twofold: (1) measuring the percentage change in delivered VT with increases in altitude and (2) determining if the delivered VTs are within the 10% ASTM standard.

Several laboratory evaluations of portable ventilator performance at sea level have been performed in the past decade. The two most recent were by Chipman et al.³ and our group.⁴ The study of Chipman et al. evaluated the performance of 15 portable ventilators at different combinations of airway resistance and lung compliance and found that a number of the devices delivered VTs that were outside the $\pm 10\%$ of the set VT. Our group evaluated the performance of four of the newest portable ventilators, including the T1 and the 731, and found that, as in our current evaluation, with a few exceptions, the devices delivered VTs that were within the $\pm 10\%$ threshold for accuracy at sea level.

Published works evaluating the performance of mechanical ventilators at altitude date back to the 1960s. Kirby

et al.⁵ evaluated the Bird Mark VIII respirator at various altitudes from sea level to 34,000 ft in an altitude chamber. Device settings were set at sea level and kept constant through testing at each altitude. The baseline VT was 705 mL at sea level and increased by 38% at 34,000 ft to a VT of 1,144 mL. Interestingly, the device's respiratory rate steadily decreased at each altitude with increased VT, keeping minute ventilation relatively constant. Although inspiratory time shortened with decreasing barometric pressure, VT increased because of increased gas flow as a result of the lower gas density at altitude. Devices such as the Bird Mark VIII that use pressure-controlled breath delivery keep inspiratory pressure constant, and lower density gas at altitude flows through a fixed orifice, resulting in larger VT.

Similarly, Thomas and Brimacombe⁶ evaluated the Drager Oxylog ventilator in an altitude chamber at sea level and altitudes of 6,700 and 30,000 ft using normal and restrictive lung models. With the normal lung model, VT increased by 106% from sea level to 30,000 ft. The restrictive lung model produced similar increases in VT but to a slightly lesser degree. As with the study conducted by Kirby et al., respiratory rate decreased in response to increasing altitude, but the increase in VT was so large that minute volume increased progressively from sea level to 30,000 ft. Roeggla et al.⁷ found similar percentage increases in minute ventilation with the same ventilator from sea level to an altitude of 9,800 ft.

In more recent studies, Flynn and Singh⁸ evaluated the Oxylog 1000, 2000, and 3000 ventilators using normal, restrictive, and obstructive lung models over a range of altitudes from sea level to 10,000 ft. The authors found that the evaluation results were similar to previous evaluations of the Oxylog 1000, with increases in VT of 68% and decreases in respiratory rate of 28% at 10,000 ft. The Oxylog 2000 experienced a 29% increase in VT at the same altitude but with no decrease in respiratory rate. The Oxylog 3000 experienced no change in VT at any altitude up to 10,000 ft because of the incorporation of an internal pressure sensor that measures barometric pressure and corrects gas flow accordingly. The device did not have any change in respiratory rate during the evaluation.

Rodriguez et al.⁹ evaluated two ventilators, Impact 754 and Pulmonetics LTV-1000, used by the United States Air Force

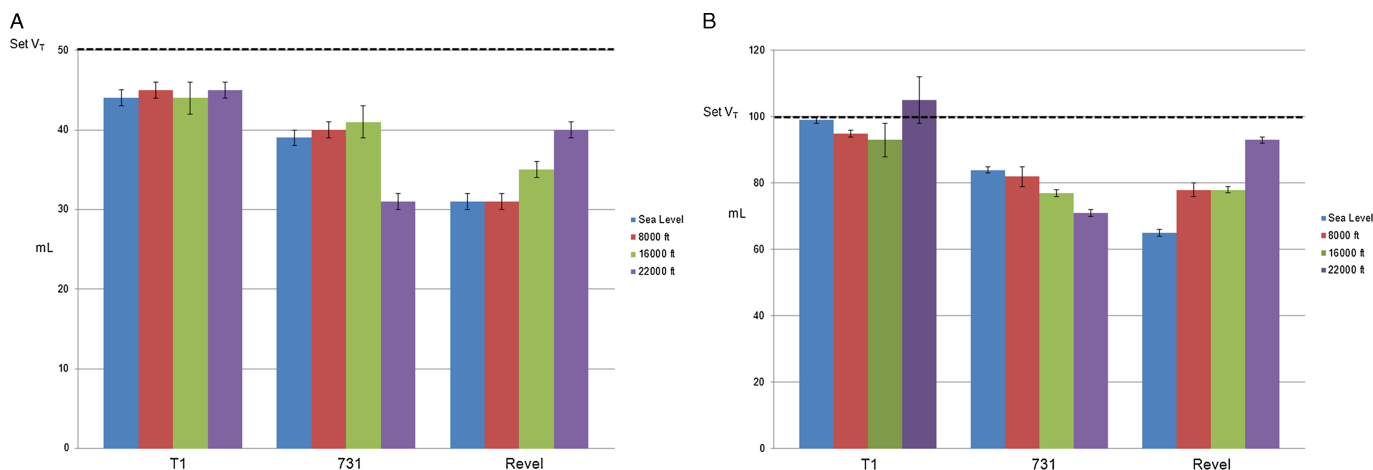


Figure 1. A, Delivered VT at 50 mL, 0 cm H₂O PEEP settings. B, Delivered VT at 100 mL, 0 cm H₂O PEEP settings.

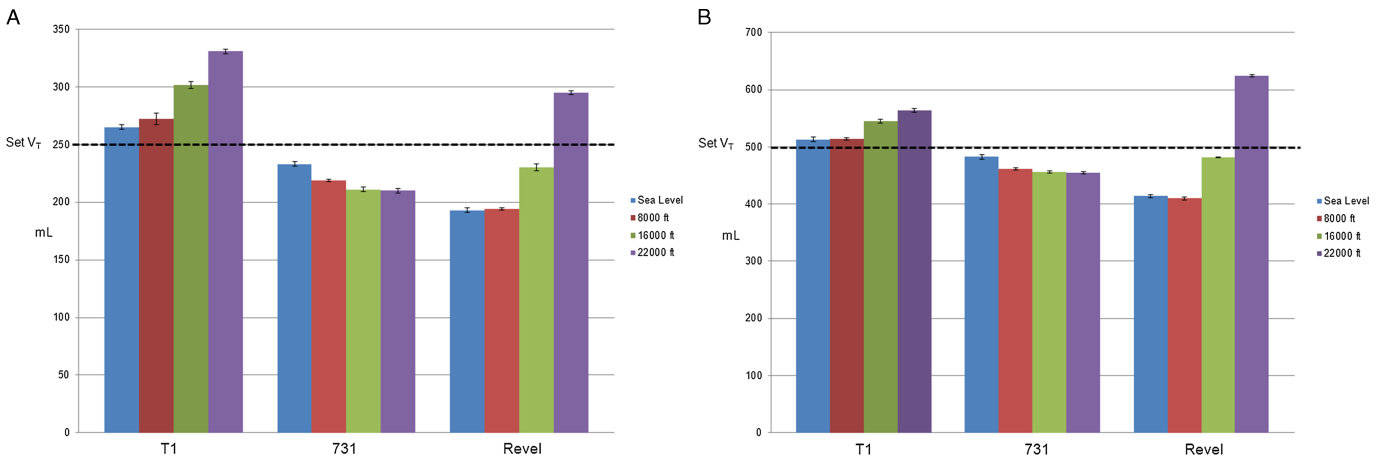


Figure 2. A, Delivered VT at 250 mL, 0 cm H₂O PEEP settings. B, Delivered VT at 500 mL, 0 cm H₂O PEEP settings.

CCATT at a range of altitudes from sea level to 15,000 ft in an altitude chamber. The study results showed that the 754-delivered VT remained within 10% of set VT at all altitudes. The delivered VT increased 30% at 15,000 ft with the LTV-1000. At 8,000 ft, the VT increase with the LTV-1000 was less than 10% of set VT. The 754 is compressor driven and contains an internal pressure sensor to monitor barometric pressure and adjust VT accordingly. The LTV-1000 is constant-speed turbine driven and has a flow control valve to deliver gas flow. Decreases in gas density at altitude causes the turbine speed to increase to maintain a constant pressure across the control valve, which increases delivered volume.

In two recent studies, Tourtier et al.^{10,11} published the results of performance evaluations of the T-BirdVSO₂ and the LTV-1000 at ranges of altitudes from sea level to 9,800 ft using lung models of adult respiratory distress syndrome and severe asthma. The T-BirdVSO₂ showed greater than 10% decreases in VT, and the LTV-1000 showed increases up to 20% regardless of the lung model.

Our study is the first to evaluate the effect of altitude on VT delivery of three of the newest portable ventilators (Fig. 3). Each device has different mechanisms for monitoring and delivering VT. The Impact 731 is compressor driven, uses both volume-controlled and pressure-controlled breath types, and

measures the volume exiting the ventilator via a single-limb circuit to determine delivered VT. The device has an internal pressure sensor that monitors ambient pressure and adjusts delivered volume in response to barometric pressure changes.

The Hamilton T1 is blower driven and measures both inspired and expired VT as gas exits and re-enters the device via a dual-limb or coaxial circuit. The T1 does not allow for traditional volume control ventilation; all breaths are pressure controlled. This explains the VT overshoot at the 250-mL setting in the normal lung model. With pressure-controlled/volume-targeted breaths, the device is targeting 250 mL but at a lung compliance of 100 mL/cm H₂O, and the minimum pressure the device can deliver is 5 cm H₂O; delivering that volume could not be achieved. Delivered VT is determined by comparing measured inspired and expired VT and using those volumes to adjust the pressure to deliver the set target VT. The operator's manual states that the device will operate as intended up to an altitude of 13,123 ft. The pressure deviations at a range of ventilator pressures up to this altitude were listed in the manual, but accuracy of the delivered VT was not noted.

The CareFusion Revel is blower driven and, like the LTV-1000, uses a flow control valve to deliver gas flow. Pressure and flow are monitored by a pressure differential transducer across

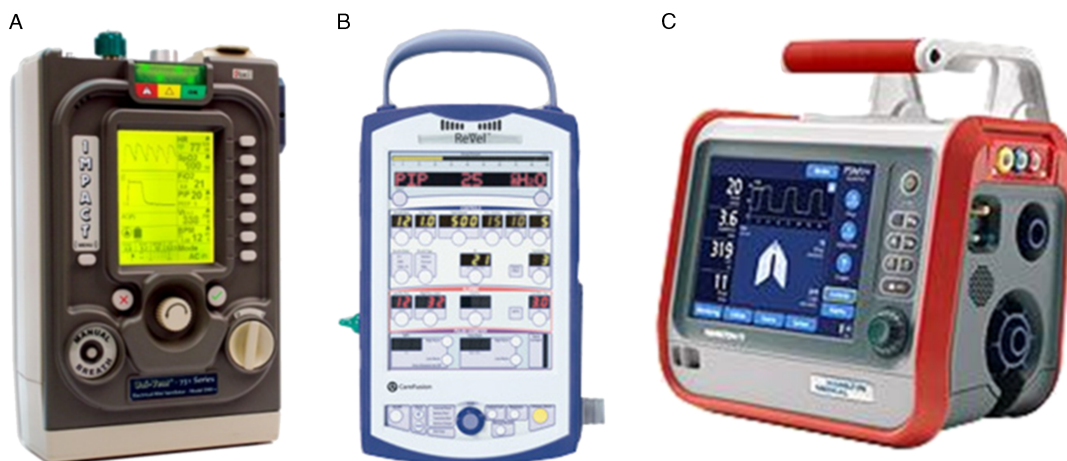


Figure 3. A, Impact 731 ventilator. B, Hamilton T1 ventilator. C, CareFusion Revel ventilator.

a fixed orifice flow transducer at the patient wye. Pressure and flow are transmitted to the ventilator, where delivered volume is determined and adjusted to deliver set VT. With increases in altitude and associated decreases in gas density, the blower speed must increase to maintain the constant pressure drop across the flow control valve that increases gas flow, resulting in a larger delivered VT than set VT. The operator's manual states that the device will operate up to 10,600 ft, but VT accuracy at altitude is not specified.

CONCLUSION

The Impact 731 ventilator delivered VTs that were within the ASTM standards at the adult settings at all altitudes. Neither the Revel nor the T1 has mechanisms for VT compensation with increases in altitude. Many of the pediatric VTs delivered by the 731 were not within the $\pm 10\%$ standard but were always less than the set VT. The 731 tended to overcompensate and deliver progressively lower VT at all settings with increases in altitude. Interestingly, the Revel delivered VTs that were less than the ASTM standard at both sea level and 8,000 ft, which can partly be attributed to compressible volume lost in the ventilator circuit. Compressible volume is created during inspiration, when the pressure required to deliver the set VT expands the ventilator circuit, resulting in part of the delivered VT being trapped in the circuit and not reaching the patient's lungs.

The T1 delivered VTs that were much greater than set VT at the highest altitude. The T1 performed well at the lower altitudes, with the exception of the 250-mL settings, because of the way the pressure-controlled, volume-targeted mode delivers volume, as detailed in the Discussion section. The device had more VTs that were progressively greater than the ASTM standard at 16,000 and 22,000 ft. At altitudes above 8,000 ft, the performance was inconsistent between the T1s we tested, and the potential for the device to shut down at higher altitudes is concerning. Aeromedical evacuation crews must be aware of the capabilities and limitations of the ventilators they are using to care for patients at sea level and especially at higher altitudes with the Special Forces unpressurized aircraft and in the case of pressurized aircraft decompression.

AUTHORSHIP

T.Bl. conducted literature search, study design, data collection, data analysis, data interpretation, writing, revisions, and submission. T.Br. conducted study design, data collection, data analysis, data interpretation, and critical review of the manuscript. D.R.J. conducted data collection, data analysis, data interpretation, and critical review of the manuscript. R.B. conducted literature search, study design, data analysis, data interpretation, writing, and critical review of the manuscript.

DISCLOSURE

R.B. has received honoraria from Covidien, Ikaria, and Bayer. The remaining authors declare no conflicts of interest. No funding for this work was received from the National Institutes of Health, Wellcome Trust, or HHMI.

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