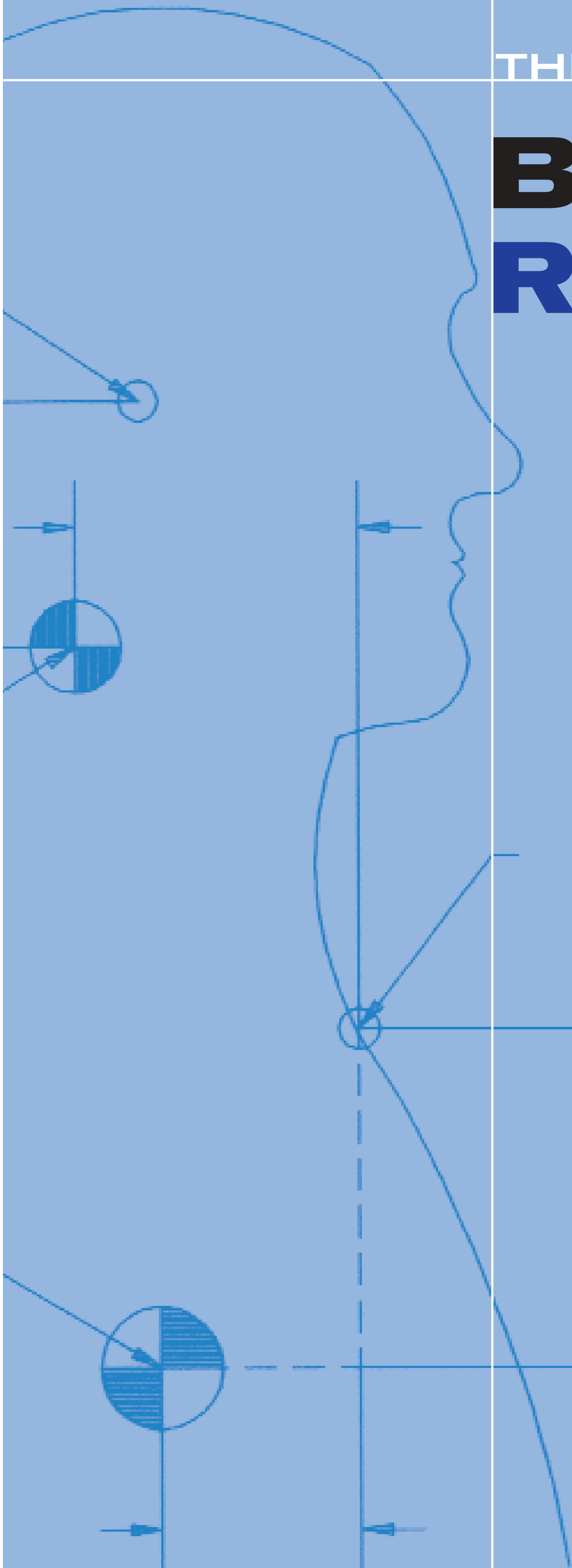


THE TRUE WORK OF

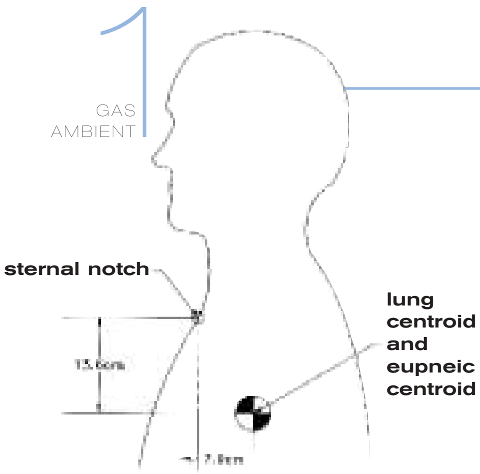
Breathing in Rebreathers

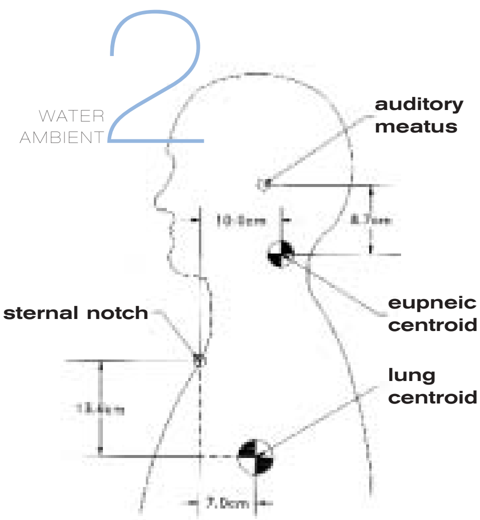
by Jack Kellon

One of the most difficult concepts to convey to new rebreather users is the difference between what the diver perceives as low work of breathing and true low work of breathing. The reason for the disparity can best be illustrated by the change in sensation between using a single-hose regulator and the chipmunk cheek effect of breathing through a double-hose regulator while in a vertical or supine position.

It's only natural for a diver to equate the pressure at the mouthpiece that produces cheek movement with resistance to breathing, but such is not the case. Negative pressures at the mouthpiece create the same effect, but are not as noticeable because of the support provided by teeth when the cheeks are drawn inward. The problem is the difference between what the diver's cheeks are telling him and what the lungs require to operate as closely as possible to the conditions under which the diaphragm muscles, which drive the lungs, developed.

Any inherent restriction to gas flow in a breathing apparatus, such as the restriction of passing breathing gases through a scrubber, produces some degree of hypoventilation. These flow-restrictive conditions become worse as depth increases, when the density of gas being moved with each breath is greater. The same degree of restriction in any apparatus would manifest itself equally in





Perception of comfortable breathing loads, or eupnea, changes as soon as a diver enters water. The eupneic centroid and lung centroid coincide on land (top). However, in water, differential pressure in the water column between the mouth and the lung centroid cause the eupneic centroid to shift toward the mouth (bottom).

the water or in a dry chamber at an equal depth. This is the breathing resistance that divers are familiar with, and it's intuitive. It's the type of resistance the divers think they're dealing with whenever they feel pressure differentials at the cheeks.

Additions to work of breathing that generally are not familiar to divers are unit-induced elastance and hydrostatic lung loading. Elastance is the resistance to an increase in breathing system volume, such as filling the counterlung. Hydrostatic lung loading is the negative or positive pressure that must be generated by the diver's lungs to overcome the difference in the water column between the lung centroid and either the regulator second stage or the lowest point of the entrapped gas volume in the counterlung.

A diver's perception of comfortable breathing loads, or eupnea, changes as soon as he is immersed in water (see figures above). In air, there is an almost immeasurable pressure difference between the mouth and the centroid of the mean pressure exerted on the thorax. The eupneic centroid and lung centroid coincide in this normal state, and the breathing muscles have developed over eons to deal with this condition. However, in water, because of the differential pressure in the water column between the mouth and the lung centroid, the eupneic centroid in which breathing is perceived to be the easiest immediately shifts because of pressures experienced at the mouth . This explains why a diver thinks that a single-hose regulator breathes better than a double-hose regulator in the upright position. A second stage regulator diaphragm located at the mouth is obviously closer in the water column to the eupneic centroid than is a double-hose regulator located halfway down the back. Yet the true work of breathing is substantially higher with the single-hose regulator.

The amount of work expended by the breathing muscles trying to overcome the pressure differential in the water column between the mouth and the lung centroid contributes substantially to the phenomenon known as decompression fatigue. The use of a double-hose regulator in this instance would result in much lower work of breathing and better lung ventilation during decompression. The same effect can be achieved with a single-hose regulator by decompressing in the prone position, where the second stage diaphragm is closer to the depth of the lung centroid in the water column.

The use of a rebreather brings the importance of hydrostatic lung loading to a higher plateau. Not only will the diver encounter considerable pressure differences between the gas in the counterlung and the lung centroid, but the differences will vary throughout each breath and with changing tidal volumes as well as diver position. This is caused when the greatest depth of the entrapped gas in the counterlung changes its vertical position in the water column with the volumetric changes encountered during a breath.

The gradient of elastance caused by varying hydrostatic lung loading during the breath causes a breathing muscle response that is never encountered in nature while breathing in ambient air. The amount of gradient hydrostatic lung loading or dynamic elastance alone may well account for more than half the true total work of breathing. Obviously, all lung loading, and particularly gradient differential lung loading, should be avoided both for hypoventilation and fatigue considerations.

Negative lung loading has been shown to create more hypoventilation and fatigue than positive lung loading, which creates fatigue only. The rule is, positive lung loading is better than negative lung loading, but low hydrostatic lung loading and the reduction of lung loading variances are best of all. Reduction of unit-induced hypoventilation produces a marked reduction in retained carbon dioxide levels. The lower the retained carbon dioxide level, the less likely the diver is to experience oxygen toxicity and decompression illness.

LOADING RANGES ►

Vertical and Prone Lung Loading Ranges

FIGURE A

Over-the-shoulder split bag (inhalation and exhalation) counterlungs, such as those used on the Mk6 semiclosed and Mk19 fully closed mixed gas rebreathers, reduce perceived work of breathing in both vertical and swimming positions. This is because the breath put into the bags remains fairly close to the eupneic centroid longer than with most other types of counterlungs associated with active addition operating systems that allow a diver to breathe off the "top" of the counterlung. It produces less true work of breathing than non-weight compensated back-mounted counterlungs in the swimming position, but more than weight-compensated or chest-mounted counterlungs.

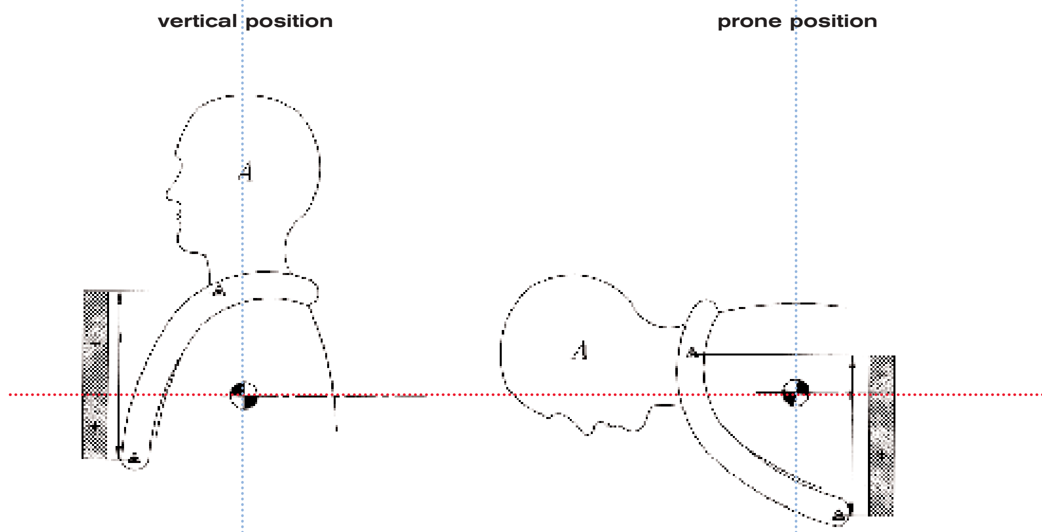


FIGURE B

Chest-mounted counterlungs produce considerable maximum lung loading in both the vertical and swimming positions, but only about one-third of it is negative in the vertical position and none of it is negative in the prone position.

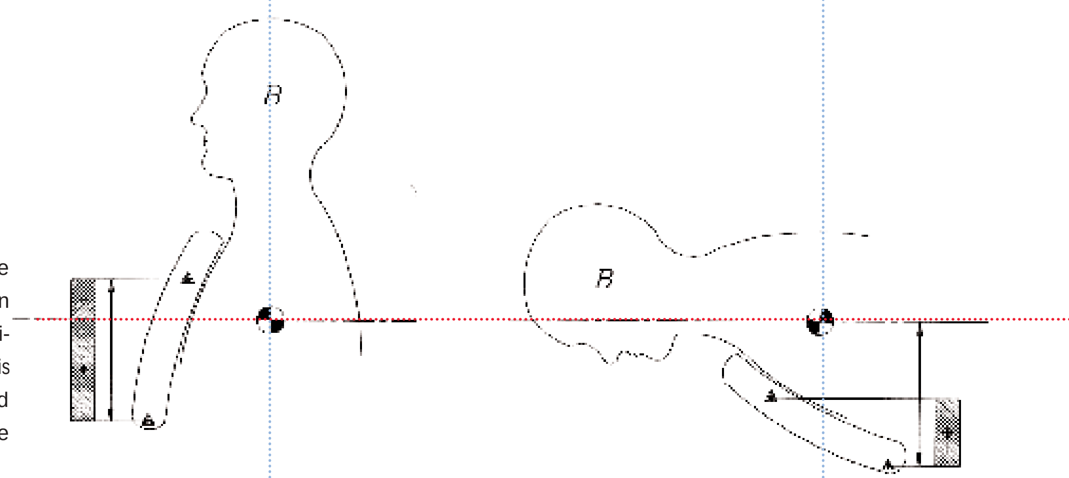
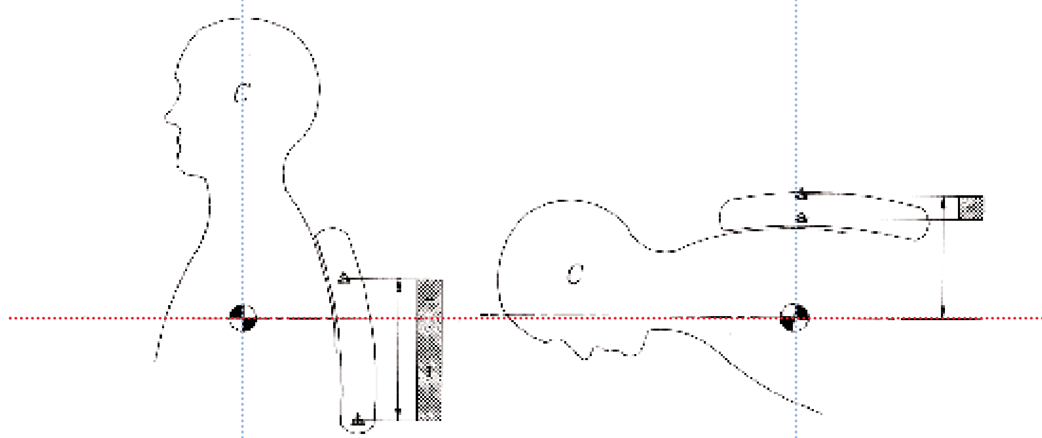


FIGURE C

Back-mounted bag-type counterlungs function about the same as chest-mounted counterlungs in the vertical position and produce far worse maximum lung loading in the prone position. Although the range of change is relatively small, it is all negative lung loading, which produces considerable hypoventilation.



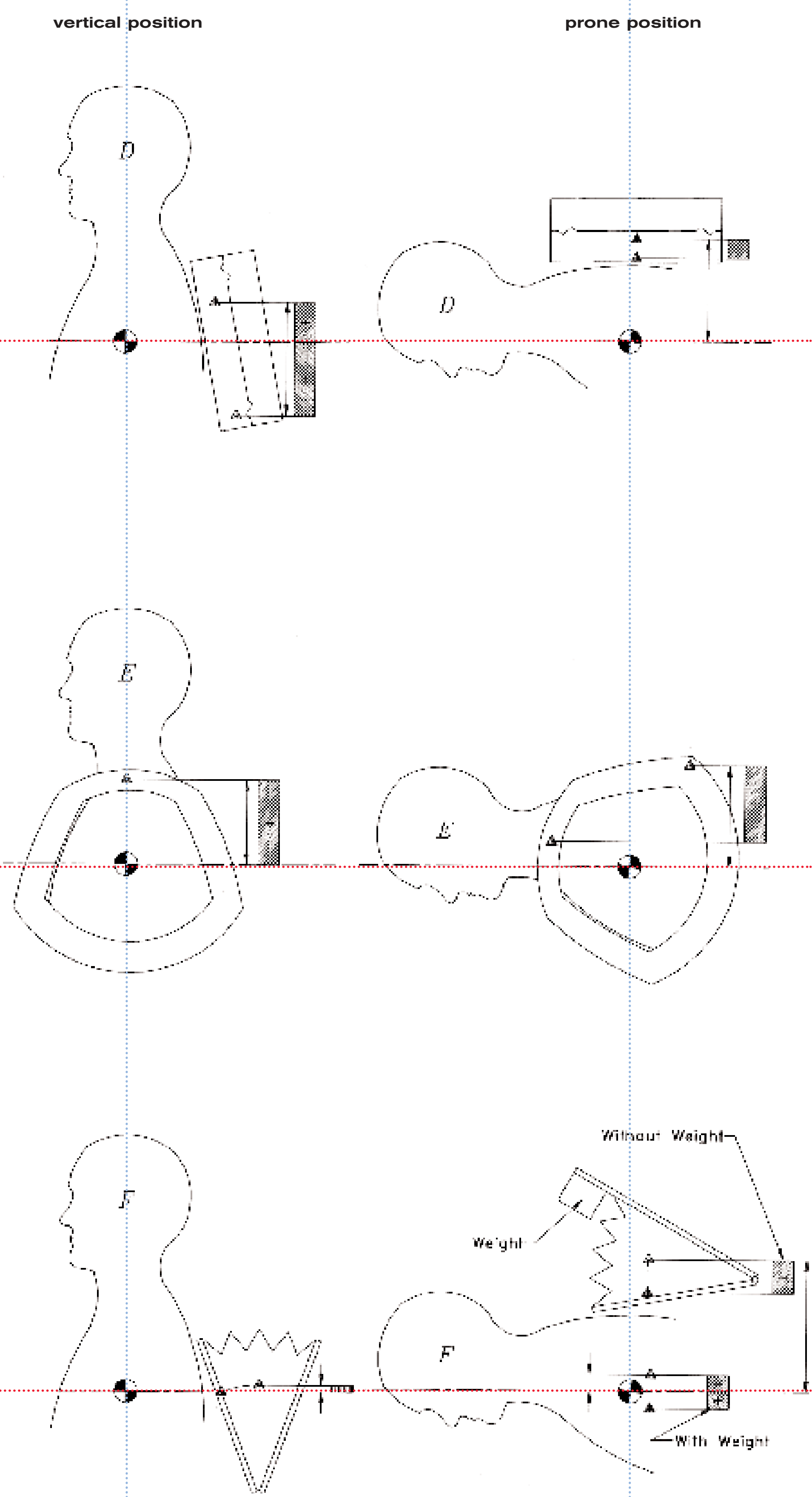


FIGURE D
Diaphragm counterlungs, such as those used on BioMarine CCR-1000 and its various descendants (the Mk15 and Mk16), have lung-loading characteristics that are almost identical to those of back-mounted bags except that their round shape reduces the time spent close to the lung loading extremes at the start and end of each breath.

FIGURE E
Toroidal-split counterlungs provide even more perceptively easy breathing than over-the-shoulder bags in both the vertical and swimming positions, but perform poorly in terms of negative lung loading in the vertical position.

FIGURE F
Bellows-type counterlungs produce the highest perceived work of breathing even though they produce the lowest true work of breathing in the vertical position with or without a counterweight. In the swimming position, the range of lung loading change is small but exclusively in the high negative loading area. To counteract this, a weight at the end of a movable slide on the bellows artificially drives the counterlung centroid closer to the lung centroid. Since buoyancy and gravity act in the same axis, the same type of assist occurs in the supine position. A counterweighted bellows counterlung produces the lowest true work of breathing because of hydrostatic lung loading and varying unit-induced elastance. The gains in reduced hypoventilation and lower breathing muscle fatigue over any other type of counterlung are substantial and are well worth the inconvenience of higher perceived work of breathing in the vertical position with a mouthpiece or the use of a full face mask to eliminate the pressure differential between the interior and the exterior of the diver's cheeks. ■

Jack Kellon, an engineer with Cochran Undersea Technology, Richardson, Texas, has been designing and testing rebreathes for more than 30 years.