
Transcranial Doppler Protocols and Procedures: Vasomotor Reactivity

Brenda Rinsky

Introduction

Evaluating cerebral vasomotor reactivity (VMR) using TCD provides information about cerebrovascular capacity and has utility in assessing stroke risk. It is relatively easy to perform, reliable, safe, inexpensive, and well-tolerated. While there is no significant change in the large vessel diameter with increased PCO₂, the arterioles dilate or contract as needed to maintain constant brain blood flow. CO₂ inhalation or breath-holding are used to evaluate the arteriolar function and provide a “stress” test for the collateral circulation during carotid high-grade stenosis or occlusion. Various methods are available to monitor intracranial hemodynamics using vasomotor reactivity. This protocol will describe the two most widely used VMR measurement techniques:

1. CO₂ challenge – This study requires inhalation of 5% medical grade CO₂, 95% O₂ gas mixture and a dedicated gas delivery system.
2. Breath-holding – This study requires the patient to hold their own breath for 30 seconds.

B. Rinsky (✉)

Neurovascular Ultrasound Laboratory, Department of Neurology,
Cedars-Sinai Medical Center, Los Angeles, CA, USA
e-mail: Brenda.rinsky@cshs.org

Indications for Vasomotor Reactivity and Breath-Holding [1, 2, 3]

1. Evaluate the adequacy of collateral flow pathways due to carotid artery high-grade stenosis or occlusions
2. Assess hemodynamic insufficiency in patients who may benefit from cerebral re-vascularization
3. Pre-operative assessment of hemodynamic risk from carotid stenosis or occlusion prior to:
 - (a) Carotid Endarterectomy (CEA)
 - (b) Coronary Bypass Grafts (CABG)
 - (c) Cardiothoracic surgeries such as TEVAR, circulatory arrest, carotid bypass, aortic replacement/repair

The CO₂ inhalation method is performed using dedicated non-imaging TCD equipment with dual-channel capabilities. Many of the equipment manufacturers now have vasomotor reactivity software programs with calculation packages for both CO₂ and breath-holding. The programs demonstrate velocity and pulsatility index trends and can accommodate the inclusion of PCO₂ and blood pressure readings for proof of change over time. Capnometry will serve to display changes in end tidal PCO₂ throughout the procedure.

The equipment requirements are a source for medical grade 5% CO₂, 95% O₂ carbogen mixture [1], a storage tank, and a dedicated delivery system that is effective and patient friendly. Compared to breath-holding there are increased costs involved in putting together the initial system. The gas tanks can be rented or owned. The small, portable “E” tank can provide gas for between 5 and 10 studies before needing to be refilled. The larger capacity “H” tank will need to be secured to the wall and is not portable. Gas refills are relatively inexpensive, and obtaining the gas, tank, and regulators can be arranged through “Cylinder Management” in most hospital settings. Independent companies like Air West, Inc. and Praxair, Inc. are located across the United States and can provide gas, tanks, regulators, and flow meters. The delivery system is semi-disposable, but mouth and nose pieces should be disposed of after each use. The advantage of using a delivery system is that it provides a quantifiable result that is not dependent on the patient’s

ability to breath-hold. Both hypercapnia and hypocapnia can be demonstrated in the same trending program allowing for visual documentation of both hyper, and hypocapnia. With the assistance of respiratory therapy, even ventilated patients can be safely tested. The CO₂ inhalation method demonstrates velocity trending over time and produces reliable, reproducible results. The patient can breathe and participate throughout the entire study.

CO₂ Delivery System Set Up: (Courtesy of Cedars-Sinai Medical Center)

- (a) Universal or multi-airway adapters (small and large)
- (b) (1) each male/female one-way valve or aerosol “TEE” with built-in one-way valves
- (c) (1) Aerosol “Tee” adapter (top load or side load depending on capnometry)
- (d) Disposable mouthpiece and nose clip, or full-face mask if tolerated
- (e) Corrugated tubing – ≤ 1 ft.
- (f) Large air mix bag with “Y” adapter
- (g) Small bore oxygen tubing that fits flow meter and “Y” adapter
- (h) Nipple- connects the oxygen tubing to the air mix bag
- (i) 22-micron filter
- (j) Flow meter
- (k) Christmas tree adaptor – connects the small-bore tubing from the tank to the nipple
- (l) Regulator – Specific for carbogen gas mixture

Starting with the tank: Attach the regulator and flow meter onto the tank. Connect one side of the small-bore tubing to the Christmas tree adaptor on the flow meter and connect the other side to the nipple attached to one side of the “Y” in the air bag. Connect the corrugated tubing to the other port in the “Y”. This system is comprised of small parts that can be purchased through the hospital purchasing dept., respiratory therapy group, or directly through the vendors. There is a filter in the bag that allows room air to mix with the CO₂ and O₂ gas mixture. Now connect the corrugated tubing into the male one-way valve and then fit the male one-way



Fig. 1 CO₂ delivery system without capnometry in place – Original delivery system developed by Brenda Rinsky, RDMS, RVT, NVS

valve into one end of the aerosol TEE adaptor. The female one-way valve will fit onto the opened top of the TEE adaptor. This keeps the patient from re-breathing. It may be possible to purchase a TEE adaptor that has built-in male and female valves for ease of use and reduced costs. If using a top loading capnometer, attach into the end of the aerosol TEE adaptor on the side of the patient's mouth. Universal adaptors can be used if the diameter of the TEE adaptor, micron filter, or mouthpieces are different. If using a side-loading capnometer, choose a side-load TEE adaptor. Attach the mouthpiece into the open end of the TEE adaptor. The delivery system is now in place (Fig. 1).

Procedure

Performance of a complete TCD prior to VMR testing can be an important way to identify collateral flow pathways and to determine if the bone windows will be acoustically sufficient. Place the stationary headband around the patient's head making sure to slide the back of the band down around the back of the neck. Tighten the headband so that it is snug, but not painful. Add a generous amount of gel and attach each transducer. Avoid bi-directional flow from the bifurcation by setting the depth between

45 and 55 mm in the bilateral M1 portion of the Middle Cerebral Arteries (MCA). Adjust the power and gain settings to obtain a quality Doppler signal and maintain that the envelop fits well around the spectral waveform. Adjust the transducer angle to obtain the highest velocity. A weak waveform can be monitored, but the transducer may need constant adjustment during the procedure. Adjust the scale so the systolic peak is clear of the top of the screen. This can be achieved by lowering the zero line toward the bottom of the screen or increasing the scale to avoid aliasing of the peak systolic velocity during hypercapnia. Be sure the bilateral scale and choice of sampling depth are symmetric for a true side-to-side comparison.

To begin the study, power up and calibrate the capnograph. Place the disposable mouthpiece into the patient's mouth and place the nose clip over the nostrils to eliminate breathing through the nose during the study. Attach the capnograph into either the side port, or top port near the mouthpiece. Trend the velocities for 1–3 minutes, allowing the patient to relax and calm down, waiting for the velocities to become stable. Do not connect in the delivery system until after a baseline waveform has been saved or marked if trending (Fig. 2). Normal entidal CO₂ is between 35 and 40

Baseline PCO₂ 36 torr

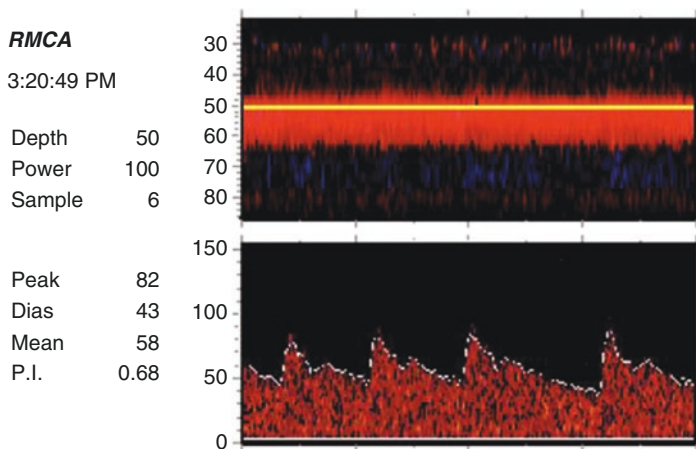


Fig. 2 Baseline velocity and end-tidal PCO₂

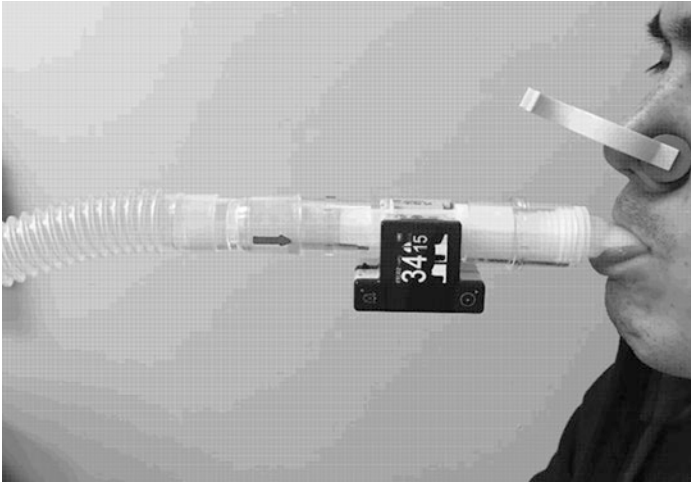


Fig. 3 Aerosol TEE connected to the corrugated tubing and capnometry. Female one-way valve is not in view

mmhg. Note the patient's baseline end-tidal CO₂. At this point, attach the nose clip and delivery system consisting of the inflow aerosol TEE adaptor that has been previously fitted with the one-way valves and corrugated tubing to the patient's mouthpiece (Fig. 3).

After the baseline velocity has been established, open the valve on the CO₂ tank and set the flow meter to between 8 and 12 liters to begin CO₂ inhalation. The flow meter can be adjusted according to how deeply the patient inhales. The gas mixture bag should collapse almost completely during inhalation and then refill again during exhalation. Have the patient take in deep, slow breaths through the mouthpiece into their upper chest. The CO₂ gas will begin to build up in the lungs and in normal circumstances, the velocities will increase as the arterioles begin to dilate producing an increase in cerebral blood flow. The diastolic component of the waveform will also increase as the pulsatility indices will decrease. This portion of the study will take up to 3 minutes to perform. Keep the patient calm and try to slow their breathing. As the CO₂ increases, the patient's respiratory drive will engage, forcing the

Co2 Maximum Inhalation PCO2 42 torr

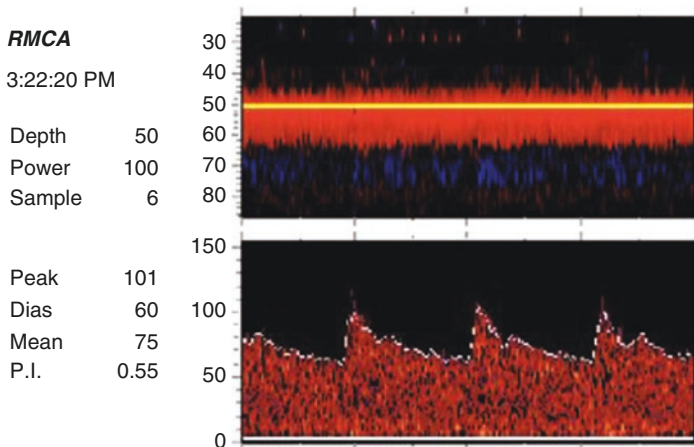


Fig. 4 CO₂ inhalation causes arteriolar dilatation, increasing the velocity and decreasing the pulsatility indices

patient to breathe rapidly to eliminate the excess CO₂. Maximum velocity is achieved when the velocities become stable and no longer increase. Save the waveforms or mark the event and note the end-tidal CO₂ (Fig. 4). The objective is to increase the PCO₂ approximately 20% from the baseline Torr. Turn the CO₂ gas off at the regulator and tank. Remove the gas delivery apparatus to allow the CO₂ to normalize while the patient breaths room air. The nose clip can be left in place. Make sure the end-tidal reading from the capnometer returns to baseline for at least 30 seconds before proceeding with the next step.

Hypocapnia starts with the patient breathing rapidly and consistently through the mouth. Demonstrating how to hyperventilate in a controlled fashion will enhance the patient's ability to perform this part of the testing. Have the patient breathe rhythmically with the objective of decreasing the end-tidal CO₂ to approximately 20% of baseline Torr. The velocities will decrease as the arterioles constrict, decreasing cerebral blood flow. The pulsatility

HVT Minimum P_{CO2} 19 torr

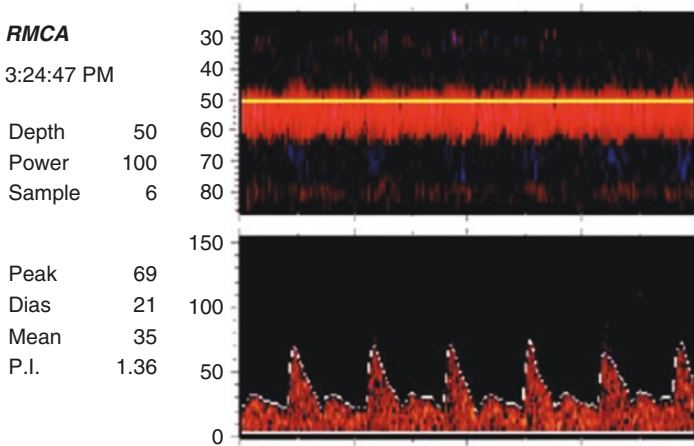


Fig. 5 Hyperventilation constricts the arterioles causing decreased velocity and increased pulsatility indices

indices will increase significantly. Save the waveforms once again and note the final end-tidal CO₂ (Fig. 5). Remove the nose clip. Allow the end-tidal CO₂ to go back to baseline once again before allowing the patient to sit up. The study is now complete.

Alternate Procedure Without Capnometry

Allow 1–3 minutes for the patient to relax and become calm. Acquire the MCA velocities making sure to keep the envelop on for monitoring both the velocities and Pulsatility indices. Adjust the scale and sample depth to avoid aliasing. Capture the baseline velocities. Follow the CO₂ inhalation and hyperventilation directions as described above. Without capnometry to gage whether the end-tidal P_{CO2} has effectively increased or decreased, it will be very important to monitor the waveforms closely. Once the velocities are stable

and no longer changing, then save the maximum velocity for hypercapnia, and the minimum velocity for hypocapnia.

Although highly unlikely, should the patient experience neurologic change or respiratory distress, immediately turn off the gas, remove the mouthpiece and nose clip, and allow the patient to breathe room air. Evaluate the patient when they return to their baseline CO₂. The gas will exit the lungs very quickly, and the patient should recover back to their normal state. If the symptoms persist, get immediate medical assistance.

Several of the TCD equipment manufacturers now have automated VMR and breath holding calculation programs. Although the procedure is the same, the equipment will automatically calculate the vasomotor reactivity.

Calculations [3]

$$1. \% \text{Change in } PCO_2 = \frac{PCO_2 \text{ at Maximum (CO}_2 \text{ inhalation)} - PCO_2 \text{ at Minimum (HVT)}}{PCO_2 \text{ at Baseline}} \times 100$$

$$2. \% \text{Change in VMR} = \frac{(\text{CO}_2 \text{ inhalation) Maximum Velocity} - (\text{HVT) Minimum Velocity}}{\text{Baseline Velocity}} \times 100$$

Results

≤/ < 15%	Exhausted VMR
16–38%	Severely reduced VMR
39–69%	Mild to moderately reduced VMR
> 70%	Normal VMR
Paradoxical Effect	Velocities drop during hypercapnia and increase during hyperventilation. This is consistent with exhausted VMR and the steal effect is reported in the interpretation

Breath-Holding Method

Breath holding is used to establish a state of hypercapnia. Like the CO₂ challenge, it is used to evaluate the effects of carotid stenosis or occlusion on the cerebral circulation. By having the patient hold their own breath, the buildup of natural CO₂ in the lungs replaces the need for inhalation of additional CO₂. Storing CO₂ gas is not required reducing overall costs, and eliminating the need for a gas delivery system. Unfortunately, this technique is also very dependent upon the patient's ability to follow instructions and cooperate fully. Results may be limited depending on the patient's mental status, respiratory status, and breath-holding capabilities.

Generally, breath-holding is performed using dedicated non-imaging TCD equipment with dual-channel capabilities. Once the initial TCD is completed, set the stationary head gear up for unilateral or bilateral monitoring as previously described in the CO₂ inhalation section. Because this study requires accurate timing, be sure to have access to a stopwatch or clock with a second hand.

Procedure [2]

1. The patient should begin the study in a state of normal breathing. Record or save the MCA baseline velocity(s) once they are stable
2. Begin hyperventilation and continue for 2 minutes, record or save the MCA velocity(s) at 2 minutes
3. Let the patient return to normal breathing for 4 minutes
4. Start breath-holding after normal respiration. The patient should avoid taking in a deep breath before they stop breathing. The established time to breath-hold is for 30 seconds. After 30 seconds, allow the patient to breath and then wait 4 seconds before saving the final velocity (s)
5. The patient can breathe normally, the testing is now complete
6. Record the time that the breath was held and calculate the results

Calculations [2]

- $$\text{BHI} = \frac{\text{MFV end} - \text{MFV baseline}}{\text{MFV baseline}} \times \frac{100}{\text{Seconds of breath - holding}}$$
- $$\Delta V_{\text{MCA}}/\Delta t = \text{increase in } V_{\text{MCA}} \text{ during breath-holding} / t = \text{Time of breath-holding}$$

Results

>0.6:	Normal VMR
0.02–0.6:	Impaired VMR
<0.02:	Severely impaired VMR

References

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