Bilateral Diaphragmatic Paralysis following Topical Cardiac Hypothermia

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Topical cardiac hypothermia has been shown to be a safe and effective means of providing protection for the ischemic myocardium during aortic cross-clamping. We report herein two cases of postoperative bilateral diaphragmatic paralysis which we believe resulted from hypothermic injury to the phrenic nerves. After open-heart surgery, both patients experienced prolonged weaning from assisted ventilation and severe orthopnea. Return of normal diaphragmatic and phrenic motor function was demonstrated in one patient ten months after surgery. Failure to correctly interpret the respiratory failure and orthopnea led to confusion and erroneous types of therapy. Awareness of this complication should lead to improved care and postoperative management of patients.

Topical cardiac hypothermia produced by filling the pericardial sac with cold physiologic saline solution or saline ice slush is an effective and widely employed technique for providing myocardial protection during aortic cross-clamping during cardiopulmonary bypass. We report two cases of bilateral diaphragmatic paralysis which we believe directly resulted from ice slush hypothermic injury to the phrenic nerves during cardiopulmonary bypass.

CASE REPORTS

CASE 1

A 49-year-old man with chronic angina pectoris underwent triple aortocoronary bypass surgery in October 1981. Hypothermia induced with an ice slush was used for approximately 45 minutes during cardiopulmonary bypass and aortic cross-clamping. During the immediate postoperative period, the patient remained dependent on a ventilator and unable to tolerate even short periods of time breathing 100 percent oxygen via a "T" adapter. Further attempts at discontinuation of mechanical ventilation were unsuccessful until the third postoperative day, when the patient was successfully weaned and extubated; however, over the next several days, he complained of severe and persistent orthopnea.

No evidence of congestive heart failure was noted on physical examination. Posteroanterior and lateral chest roentgenograms taken at full inspiration showed bibasilar atelectasis and elevation of both hemidiaphragms compared to the preoperative chest roentgenograms. The patient's orthopnea, severe enough to require sitting bolt upright to sleep, persisted despite aggressive pulmonary toilet and empiric treatment with digitals, diuretics, and nitrates. Studies of pulmonary function performed 14 days after surgery demonstrated a severe restrictive defect (Table 1). A radionuclide angiographic study demonstrated a left ventricular ejection fraction of 0.64 with normal left ventricular wall motion. Fluoroscopic examination of diaphragmatic motion during sniffing ("sniff test") was interpreted as showing appropriate downward diaphragmatic motion bilaterally.

On the 20th postoperative day, paradoxical inward motion of the abdominal wall during inspiration, as well as extreme air-hunger and cyanosis, were noted with the patient lying supine. Studies of phrenic nerve conduction showed latencies of 11 msec and 12 msec (normal, 6 to 9 msec), with amplitudes of 60 μV and 70 μV (normal, 400 to 1,200 μV), for the right and left phrenic nerves, respectively. Measurements of transdiaphragmatic pressure (Pdi) made with latex-balloon-tipped catheters placed in the stomach and esophagus demonstrated a Pdi of zero generated during both resting tidal

| Table 1—Serial Studies of Pulmonary Function and Phrenic Nerve Conduction in Case 1* |
|-----------------|-------|-------|-------|-------|
| Data†          | 3 wk  | 3 mo  | 5 mo  | 10 mo |
| FVC, L         | 1.32 (32) | 0.60 (15) | 1.18 (44) | 2.30 (56) |
| FEV1, L        | 1.06 (32) | 0.30 (9) | 1.32 (40) | 1.50 (45) |
| FRC, L         | 1.89 (59) | 1.38 (43) | 1.78 (56) | 2.40 (75) |
| RV, L          | 1.09 (55) | 1.13 (57) | 1.12 (57) | 1.84 (76) |
| TLC, L         | 2.77 (45) | 2.44 (40) | 3.06 (50) | 4.70 (76) |
| Dco            | mL/min/mm Hg 11.1 (36) | ... | ... | 20.8 (68) |
| Right phrenic latency, msec | ... | ... | 11 | 9.0 |
| Right phrenic amplitude, μV | 60 | ... | ... | 320 |
| Left phrenic latency, msec | 12 | ... | ... | 9.2 |
| Left phrenic amplitude, μV | 70 | ... | ... | 320 |
| Pdi, cm H2O    | 0 | 0 | 12-14 | 22-24 |

*Data within parentheses are percentages of predicted.
†FVC, forced vital capacity; FEV1, forced expiratory volume in one second; FRC, functional residual capacity; RV, residual volume; and Dco diffusing capacity.

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inspiration and maximal inspiration to total lung capacity (TLC) (Fig 1). The patient was later discharged without specific therapy for his bilateral diaphragmatic paralysis, and he continued to note severe orthopnea, but little or no dyspnea while walking.

Three months after surgery, the patient's symptoms had not improved, and repeat studies of pulmonary function and measurements of Pdi likewise showed no improvement (Fig 1; Table I). His orthopnea persisted and five months after surgery, the Pdi had increased to 12 to 15 cm H2O with maximum inspiration to TLC. The patient's orthopnea gradually disappeared, and ten months after surgery, his Pdi was 10 cm H2O with resting tidal inspiration and 22 to 24 cm H2O with inspiration to TLC. Phrenic nerve conduction approached normal, with latencies of 9.0 msec and 9.2 msec on the right and left, respectively, and amplitudes of 320 μV bilaterally. Pulmonary volumes also showed significant improvement from prior studies.

**CASE 2**

A 44-year-old man with long-standing insulin-dependent diabetes mellitus and unstable angina underwent triple aortocoronary bypass surgery in November 1981. During cardiopulmonary bypass, ice slush was packed into the pericardial sac to provide topical cardiac hypothermia for approximately 50 minutes. The patient was extubated approximately 36 hours after surgery, but experienced marked dyspnea within 30 minutes of extubation. Continuous positive airway pressure of 8 cm H2O by mask was begun, but the patient's extreme dyspnea and hypoxemia persisted, necessitating reintubation of the endotracheal tube and reintroduction of assisted ventilation. He was finally successfully weaned from mechanical ventilation 49 days after surgery; arterial blood gas levels while breathing 40 percent oxygen showed a pH of 7.41, arterial oxygen pressure (PaO2) of 106 mm Hg, and arterial carbon dioxide tension (PaCO2) of 45 mm Hg.

Nine days after surgery, the patient noted extreme shortness of breath while walking, which gradually worsened to include shortness of breath at rest; he was also severely orthopneic and had to sit upright to sleep. No signs of congestive heart failure were noted, other than coarse bibasilar rales. Daily chest roentgenograms failed to display any abnormalities other than persistent bibasilar atelectasis. Fluoroscopic examination of the hemidiaphragms during sniffing and deep inspiration was interpreted as showing normal descending movement for both hemidiaphragms. Twelve days after surgery, paradoxic motion of the abdominal wall with inspiration was seen, and bilateral diaphragmatic paralysis was suspected. Studies of Pdi using esophageal and gastric balloon catheters demonstrated zero Pdi generation during both tidal breathing and maximum inspiration to TLC (Fig 2). Adequate studies of phrenic nerve conduction could not be obtained because of technical difficulties. The patient was eventually discharged with the diagnosis of bilateral diaphragmatic paralysis, and he continued to note severe persistent orthopnea, as well as exertional dyspnea. The patient declined further studies of Pdi and phrenic nerve conduction. Six months after surgery, he suffered cardiopulmonary arrest and died. He had continued to complain of orthopnea and exertional dyspnea up to the time of his death.

**DISCUSSION**

Topical cardiac hypothermia using iced physiologic saline solution, saline slush, or ice chips is commonly employed to provide low-temperature protection for the myocardium during cardiopulmonary bypass when coronary blood flow is interrupted. Several investigators have confirmed its efficacy in protecting the myocardium from ischemic injury.13 Reports of adverse effects have been rare; however, the intimate anatomic relationship of the phrenic nerves to the heart and pericardium would seem to place them at increased risk of injury during open-heart surgery. Cold temperatures from ice slush or chips filling the pericardial sac may unavoidably be transmitted through the pericardium to the closely apposed phrenic nerves. Scannell4 was the first to recognize this

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**Figure 1.** Recordings of Pdi (case 1). At three weeks after surgery, there is no rise in Pdi above baseline with inspiration to TLC. Note fall in intragastic pressure (Pga) with each inspiration. At three months, Pdi is still zero at TLC. At five months, Pdi is now 12 to 14 cm H2O at TLC. At ten months, Pdi has increased to 22 to 24 cm H2O at TLC. Also note elevation of Pga above baseline at TLC. (Upward deflections on spirograms are with inspiration; upward deflections on pressure tracings are positive.) Pes, Esophageal pressure.
population of patients undergoing open-heart surgery in our hospital.

The first indication, albeit nonspecific, of phrenic nerve injury and diaphragmatic dysfunction was the difficulty in weaning both patients from assisted ventilation. Both noted severe orthopnea immediately after weaning from the ventilator; paradoxic motion of the abdominal wall with inspiration was the first relatively specific sign pointing toward bilateral diaphragmatic paralysis. The length of time from weaning from the ventilator to the first suspicion of diaphragmatic paralysis in these patients underscores the high index of suspicion needed to diagnose such patients. Their principal symptoms of orthopnea and exertional dyspnea could easily be attributed to much more common postoperative problems, such as congestive heart failure, anxiety, atelectasis, preexisting chronic pulmonary disease, and others.

Not surprisingly, fluoroscopic examination of diaphragmatic motion was misleading. Performance of a “sniff” during fluoroscopic visualization of the diaphragmatic dome will produce paradoxic upward movement in unilateral diaphragmatic paralysis; however, for a number of reasons, in bilateral paralysis, fluoroscopic examination is usually fruitless. In such a circumstance, the only reliable test available for the definitive diagnosis of diaphragmatic paresis or paralysis is measurements of Pdi. The measurement of Pdi with properly placed esophageal and gastric catheters should reveal a fall in esophageal pressure (which closely reflects intrapleural pressure) with each inspiration. Intragastric pressures should rise as a result of diaphragmatic contraction producing compression of intra-abdominal contents. The absolute magnitude of increases in intragastric pressure may vary greatly, depending on the compressibility of intra-abdominal organs and gas, the tone of the abdominal wall muscles, and so on; a fall in intragastric pressure with inspiration does not normally occur. Both of our patients failed to show development of measurable Pdi with inspiration to TLC (normal, 25 to 40 cm H₂O); both patients had characteristic decreases in intragastric pressure with inspiration, the physiologic correlate of the paradoxic abdominal motion. Comparison of spirometric data obtained with the subject supine and upright may show marked decreases in pulmonary volumes in those with unilateral or bilateral diaphragmatic paralysis. Supine spirometric studies were not performed in our patients, due to their inability to lie supine for longer than a few seconds.

The prognosis for recovery of phrenic nerve and diaphragmatic function in such patients appears to be highly variable. Irisawa and colleagues reported symptomatic recovery after 1/2 months in their patient; the degree of nerve injury was not described. Chandler and co-workers documented recovery over
5 to 12 months in three patients. This highly variable prognosis may be a reflection of a spectrum of microscopic changes that may result from “frostbitten” phrenic nerves. Injury with mild demyelinative changes and little or no axonal damage would be expected to have the best prognosis and the most rapid recovery. The mild histologic changes seen by Marco et al in the canine phrenic nerve model, with complete recovery in 62 days or less, supports this concept. The slow recoveries (eight to ten months) of our patient and the three patients of Chandler et al suggest more serious phrenic nerve injury, perhaps significant axonal disruption in addition to demyelination.

In conclusion, bilateral diaphragmatic paralysis may follow open-heart surgery that employs topical cardiac hypothermia, probably as a result of hypothermic injury to the phrenic nerves, rather than mechanical trauma. Otherwise unexplained orthopnea, exertional dyspnea, prolonged weaning from a ventilator, or paradoxical abdominal wall motion should raise a high index of suspicion of this complication in such patients.

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