David S. Warner, M.D., Editor

Venous Air Embolism

A Warning Not to Be Complacent—We Should Listen to the Drumbeat of History

Maurice S. Albin, M.D., M.Sc. (Anes.)*

Clinical Considerations Concerning Detection of Venous Air Embolism. By Maurice S. Albin, Robert G. Carroll, Joseph C. Maroon. Neurosurgery 1978; 3:380–84. Abstract used with permission from the Congress of Neurological Surgeons, copyright 1978.

ABSTRACT:

Venous air embolism during neurosurgical procedures (detected by Doppler ultrasound and aspiration *via* a right atrial catheter) was noted in 100 of 400 patients in the sitting position, 5 of 60 patients in the lateral position, 7 of 48 patients in the supine position, and 1 of 10 patients in the monitored prone position. We confirmed venous air embolism in many of these patients by using serial technetium-microaggregated albumin lung scans. Gravitational gradients from the venous portal of entrance to the right side of the heart were as small as 5.0 cm, with aspiration of 200 ml of air occurring. Doppler ultrasonic air bubble detection and aspiration through a previously inserted right atrial catheter are critical factors in the diagnosis and treatment of this condition.

IN 1837, John Rose Cormack (1815–1882), President of The Royal Medical Society of Edinburg, Scotland, published a 56-page thesis[1] to qualify for the Doctor of Medicine degree. This thesis was titled "Air in the Organ of Circulation." The concept of right heart airlock, the "hissing gurgling sound" when a large vein is divided, and the rapid cardiovascular collapse of the patient, as well as venous air embolism (VAE) during parturition because of the turgid uterus and uterine sinuses, is touched upon. More than 40 physician-surgeons are mentioned who have reported VAE in one or more cases in that era. It must be stressed that before use of sulfuric ether as an anesthetic agent by Morton in 1846 at the Massachusetts General Hospital (Boston, Massachusetts), surgery in general was extremely rapid, and veins were often opened in the rush to complete the case. From 1811 through 1885, I have documented more than 50 reports on VAE, with death resulting in the overwhelming majority of cases.[2] Two landmark works must be mentioned, the first by a Frenchman, Jean Zulema Amussat (1884–1908) who wrote a seminal 255-page book on the subject in 1856 (figs. 1 and 2).[3]

The second surgeon was Nicolas Senn (1844–1908), an American and Professor of Surgery at Rush Medical College and the University of Chicago, Illinois, who published a 115-page dissertation on VAE in 1885 (fig. 3).[4]

Amussat and Senn together collected and reviewed more than 250 case reports, described hundreds of animal experiments performed to determine the pathophysiology of VAE, and mentioned treatment modes including cannulation and aspiration of the right side of the heart. They also identified changes in the heart tones that we now call the "mill-wheel" murmur, and noted the cyanosis, gasping respiration, and cardiovascular collapse that are the major signs of severe VAE as well as the air lock due to air bubble accumulation that causes overdistention of the right side of the heart. These two surgeon-scientists documented the finding that the develop-

* Professor, Department of Anesthesiology, University of Alabama at Birmingham, Birmingham, Alabama.

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Address correspondence to Dr. Albin: Department of Anesthesiology, University of Alabama at Birmingham, JT 845, 619 19th Street South, Birmingham, Alabama. malbin@uab.edu. This article may be accessed for personal use at no charge through the Journal Web site, www.anesthesiology.org.

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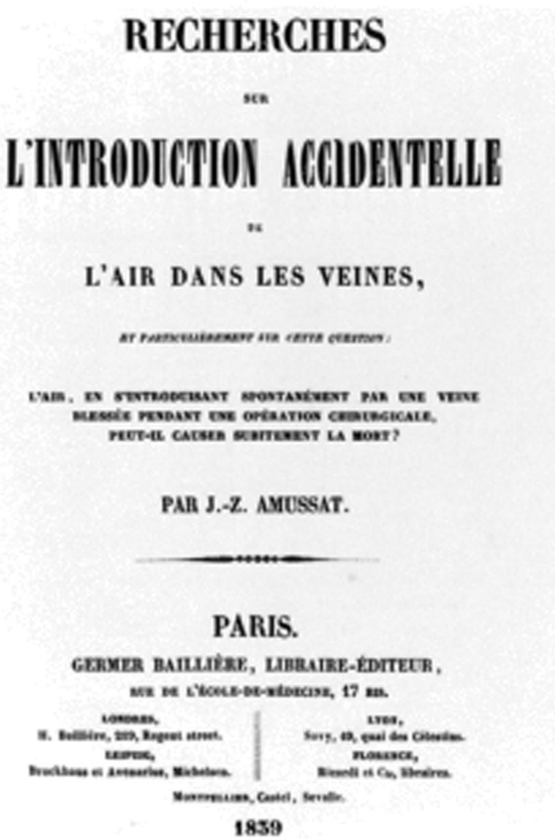

RECHERCHES

SUR

L'INTRODUCTION ACCIDENTELLE

DE

L'AIR DANS LES VEINES,

ET PARTICULIÈREMENT SUR CETTE QUESTION:

L'AIR, EN S'INTRODUISANT SPONTANÉMENT PAR UNE VEINE BLESSÉE PENDANT UNE OPÉRATION CHIRURGICALE, PEUT-IL CAUSER SUBITEMENT LA MORT?

PAR J.-Z. AMUSSAT.

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1839

Fig. 1. Title page of the seminal 255 page book on venous air embolism by the surgeon Jean Zulema Amussat, published in 1839.

ment of gradients, described by Senn as "the force of gravitation" between the right side of the heart and the incisional area was a critical factor in air entrainment. So we can note that a sophisticated level of understanding concerning VAE

Fig. 2. Jean Zulema Amussat (1796–1855), surgeon, physiologist, urologist, inventor of an ether inhaler.

Fig. 3. Nicolas Senn (1844–1908), Spanish-American War surgeon, Professor of Surgery, University of Chicago and Rush Medical College, and author of the first modern American textbook of surgery.

existed in the 19th century. Amussat also was the inventor of an ether nasal inhaler and was a pioneer in the use of the suprapubic cystotomy as well as lithotripsy and lumbar colotomy.

Returning to the 20th century and our 1978 paper, we were fortunate at that point in time to have available a huge mass of clinical material because of the work of Peter J. Jannetta, M.D., who had over the years developed the technique of vascular decompression of the fifth cranial nerve primarily for tic doloreaux. Dr. Jannetta, the Chair of the Department of Neurosurgery, and I arrived at the University of Pittsburgh School of Medicine in Pittsburgh at approximately the same time, 1971, when I established a neuroanesthesia service. Word of the efficacy of Dr. Jannetta's procedure spread throughout the medical community and the referral load became almost overwhelming, with patients coming to the university on a national and international level and not infrequently averaging 8–10 surgical procedures a week. With rare exceptions, almost all of the vascular decompressions of the fifth cranial nerve (Jannetta procedure) were carried out in the "sitting" position, with knees at the level of the heart as a posterior fossa procedure. Because of the newness of this technique, our neurosurgical operating rooms were not only busy with patients but we were visited by numerous neurosurgeons from all over the world as well as by neuroanesthesiologists wanting to familiarize themselves with the surgical and anesthetic considerations.

Among the neurosurgeons on our staff, we were fortunate to have Joseph Maroon, M.D., who did a postresidency fellowship in neurosurgery in the 1960s at Oxford University in England and who, together with Edmonds-Seal, published

Fig. 4. Dr. Albin in the neuroanesthesia laboratory, University of Pittsburgh, 1978.

the first paper on the neurosurgical application of the precordial Doppler for air-bubble detection.[5] Interestingly, the large number of patient referrals with a purported diagnosis of tic doloreaux often yielded individuals who, after very vigorous diagnostic workup, had pathology other than classic tic doloreaux such as tumors, dental conditions, aneurysms, arteriovenous malformations, temporomandibular joint dysfunction, and other cranial nerve pathology.

With this large amount of patient material, we were fortunate to have staffing with neuroanesthesia fellows and dedicated neuro-nurse anesthetists. This allowed us time to develop clinical studies looking at the problems of the sitting position and the Jannetta surgical technique, as well as stimulating us to go to the laboratory to help further delineate some of these questions (fig. 4).

Beginning with the arrival of Dr. Jannetta in 1971, we developed an anesthesia monitoring protocol that included the insertion of a right atrial line for air aspiration, based on the work of Michenfelder *et al.* in 1966,[6] a radial artery line for monitoring blood pressure and blood gases, a precordial ultrasonic Doppler probe, end-tidal carbon dioxide analysis, and the electrocardiogram.

Our original 1978 paper[7] had several intended and unintended consequences. In terms of the former we were able to delineate with the Te99 lung scans that in cases where more than 25.0 ml of air were aspirated from a right atrial catheter and the patient(s) appeared to be doing well symptomatically, pulmonary perfusion defects, some quite severe, were present as long as 11 days after surgery. An important unintended finding was to reemphasize that VAE occurrence is not limited only to the sitting position, but can occur as well during prone, supine, and lateral surgical procedures,a finding that is in agreement with the numerous examples of VAE reported in the literature in the 19th century. This finding of VAE in the prone position was a stimulus instituting a central registry for these events.[8] As a follow-up, a recent paper by Wills *et al.* indicated the increasing morbidity and mortality during spine instrumentation procedures in the prone position especially in the pediatric age group.[9] The cardiovascular response to VAE was illustrated in the case of the patient who experienced VAE while in the prone position during surgery for an extensive spinal cord ependymoma, with a gravitational gradient of only 7.5 cm. Coincidentally, we had been prepared to do cardiac output determination using indocyanine green as the indicator and found a cardiac index calculated to be 2.78 l/m^2 just before Doppler activation indicated VAE. Within a few minutes after withdrawal of 45 ml of air and the development of arterial hypotension, the cardiac index decreased to 1.22 l/m^2 and returned to baseline preaspiration values after electrocoagulation of epidural veins, which then terminated the entrance of air. The large volume of sitting position cases with accompanying 25% incidence of VAE gave our group an opportunity to go to the laboratory to develop better monitoring and air-bubble aspiration technology.

We had speculated that a larger volume of air might be aspirated were we to use a multiorificed catheter instead of the single orificed catheter pioneered by Michenfelder *et al.* However, the major problem was that there was no testing model available to compare the aspiration efficiency catheters. We then decided to seek a model of the human right atrium. A flexible Silastic®casting (Lilling Hongjia Machinery Industry Co., Ltd., Hunan, China) of the human right atrium was developed to correspond to some *in vivo* human right atrium hemodynamic characteristics including chamber pressures, pulsatility, fluid output, and flow velocity. Using an infusion pump, air was introduced (10 ml in 30 s) into the superior vena cava of the model and aspirated *via* a catheter from different positions within the model atrial chamber. The tests were carried out at atrial inclinations of 60°, 80°, and 90° from the horizontal and compared the aspiration efficiency of a single-orificed 16-gauge catheter to a 16-gauge multiorificed (five apertures) catheter. Optimal air aspiration occurred with the multiorificed catheter tip position within the area 2.0 cm below the junction of the superior vena cava and the atrial chamber at an inclination of 80°. As much as 80% of the incoming air could be aspirated under these conditions. At its optimal position the single-orificed catheter gave a maximum yield of 45–50% aspiration when the tip was positioned 3.0 cm above the superior vena cava and arterial chamber junction. Aspiration of air from mid right atrium (4.5 cm below the superior vena cava-atrial junction) was poor regardless of the type of catheter used or atrial inclination.

This model[10] allowed us to view several interesting phenomenon that took place at 4.5 cm or greater below the superior vena cava-right atrial junction. As stated previously, not only was air aspiration poor in both type of catheters, but we observed a "whipping effect," with the catheter at occasions hitting the inner wall of the atrium with greater force as the distance from the superior vena cava-right atrial junction was extended. This might be a possible explanation for the mechanism of atrial wall perforation with the development of an acute pericardial tamponade. Years later, we convinced the manufacturers of our air aspiration catheter, Cook, Inc., (Bloomington, IN), to produce a multiorificed air aspiration catheter made of silastic material. We did this because we noted that the "whipping effect" was almost completely attenuated and replaced by what we called the "wet noodle response," with the Silastic catheter tip rarely hitting the wall, and if so with almost no apparent force. Unfortunately, we were not able to perform the needed safely and efficacy experiments in animals as was our custom before proceeding with the clinical studies. The entrance of large volumes of air would overwhelm the air-blood vortex that develops from the pulsatory flow pattern throughout the chamber, causing bubble coalescence, and a point is reached where the resulting surface tension overcomes the vortex and an airlock results with the synthetic atrial walls fruitlessly trying to contract and break up the large bubble mass, but to no avail. It is frighteningly dramatic to see this occur in the model and it makes one realize the importance of acting quickly when there is Doppler activation, decreased end tidal carbon dioxide, or the visualization of air using transesophageal echocardiography. As an aid to checking the presence of air bubble in atrial catheter, our neuroanesthesia laboratory developed the Tung air bubble illumination unit.[11] This device is an illuminated box with a magnified glass anterior surface. The box is clamped on a segment of the air aspiration catheter and helps to magnify and illuminate any passing air bubbles.

Our research culminated in the development of the Bunegin-Albin multiorificed air aspiration catheter as well as the Tung air-bubble illumination unit. Hopefully, this research and our paper raised the consciousness of the anesthesiologist to the factors involved in the entrance of air into the veins.

This review of the background and anatomy of our paper indicates that the insidiousness of VAE will always be with us regardless of the surgical position, and that we should take to heart the one-liner written in the year 1450 and found in the beginning of this 1978 paper, *Sooner Slays Ill Air Than Sword!* Perhaps we can counter this last Old English saying with the Latin phrase, Pramonitus, Pramunitus—Forewarned is Forearmed!

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