Michael Bayliss, MD, FRCPC, Jason Andrade, MD, FRCPC, Bobby Heydari, MD, FRCPC, Andrew Ignaszewski, MD, FRCPC

Jeremy Swan and the pulmonary artery catheter: Paving the way for effective hemodynamic monitoring

Despite ongoing debate about cardiac catheterization, there is no question that the use of the Swan-Ganz catheter has contributed greatly to our understanding of cardiovascular physiology and cardiogenic shock.

ABSTRACT: Right heart catheterization is a valuable tool for measuring hemodynamics, gas exchange, and heart-lung interaction. In the past, this procedure was largely limited to the catheterization laboratory because of the equipment and technical skill needed for catheter placement. However, with the development of the flow-directed catheter by Dr Jeremy Swan in 1970, pulmonary catheterization quickly became standard in the critical care setting. Over the years, questions regarding its impact on clinical outcomes and its safety have emerged. Today, routine pulmonary catheterization in critically ill patients and the value of catheterization in selected individuals continues to be debated. However, there is no question that Swan's work has paved the way for much of our current understanding of cardiovascular physiology and that Swan will forever be remembered as one of the true cardiology giants of his time.

Dr Harold James Charles "Jeremy" Swan was born in the small town of Sligo, Ireland, on 1 June 1922. He was the son of two Catholic doctors in a family of four brothers. As a young boy he attended St. Vincent College in Dublin, where his education was interrupted when he lapsed into a coma after being diagnosed with meningitis, a commonly fatal disease in the days before penicillin. His life was saved when his mother provided him with sulfa drugs, the only antibiotic available in that era. He made a full recovery and excelled not only as a scholar but also as a middleweight boxer.

Swan completed his medical training at St. Thomas's Hospital Medical School at the University of London. After graduation he worked for 6 months as a casualty surgeon before joining the Royal Air Force. He spent 2 years with the military serving as a medical director, primarily at a hospital in Iraq. Swan had originally planned to go back to Sligo to join his father in family practice. Unfortunately, his father passed away in 1948 before this could happen, so Swan abandoned these plans and instead embarked upon a research career in cardiovascular physiology in London under the guidance of Dr Henry Barcroft.

In 1951, Swan took a research fellowship at the Mayo Clinic in Rochester, Minnesota, under the direction of Dr Earl Wood. He continued his earlier work in the catheterization laboratory, conducting research on pulmonary hypertension in congenital heart disease and developing techniques for measuring cardiac output and cardiac shunts. He was successful in bringing one of the first research grants to the Mayo Clinic and was a key player in developing the first training program at the institution. During his 14 years at the Mayo Clinic, Swan published over 100 papers and established his reputation as a

Drs Bayliss, Andrade, and Heydari are University of British Columbia cardiology fellows. Dr Ignaszewski is head of St. Paul's Hospital Division of Cardiology, is affiliated with the St. Paul's Hospital Heart Transplantation Program and Heart Failure Program, and is a clinical associate professor in the Division of Cardiology at the University of British Columbia.

brilliant and innovative research scientist.

In 1965, Swan accepted a position at Cedars of Lebanon Hospital in Los Angeles, now known as Cedars-Sinai Hospital. He worked there for the next 22 years and published another 300 papers during this time. His most famous paper, describing the catheter that would ultimately bear his name, was published in 1970 in the *New England Journal of Medicine.*

Throughout Swan's career he was honored with many awards. He was president of the American College of Cardiology in 1973. He received the award for distinguished fellow in 1985, the award for distinguished service in 1999, and the award for distinguished scientific achievement in 2003. Other awards granted to him included the Walter Dixon Memorial Award from the British Medical Association, the Herrick Award for Outstanding Achievement in Clinical Cardiology from the American Heart Association, and the Maimonides Award from the state of Israel. He was also presented with an honorary doctorate from Trinity College in Dublin in 1996.

Swan retired in 1994 and moved to Pasadena, California. He suffered a stroke in 2001 and although his speech and cognition remained intact, he was left with significant disability. On 7 February 2005, at the age of 82, Dr Swan died following complications from a myocardial infarction. He is survived by his wife, six children, eleven grandchildren, and one great-granddaughter.

Development of right heart catheterization

The history of cardiac catheterization dates back to 1929 when Dr Werner Forssmann performed the first right heart catheterization on himself by passing a urethral catheter through his own elbow vein.[1] Following the publication of Forssmann's findings, numerous investigators described catheterization to delineate right-sided cardiac anatomy with the use of contrast.[2] However, it was quickly realized that the value of pulmonary catheterization extended beyond anatomical studies. In 1944, Cournand and Lauson published a paper describing the use of cardiac catheterization for recording right heart pressures.[3] In 1954, Connolly and colleagues demonstrated that pulmonary capillary wedge pressure (PCWP) correlated very closely with left atrial pressures, making it a valuable tool for measuring left heart pressures.[4] In 1956, Forssmann, Cournand, and their colleague Richards received the Nobel Prize in medicine for groundbreaking work using the pulmonary artery catheter (PAC). Over the following decade, right heart catheterization became a valuable tool for measuring hemodynamics (Table 1), gas exchange, and heart-lung interaction,[5] with the hemodynamic data obtained being used to classify patients presenting with acute myocardial infarction according to one of four categories (Table 2).[6]

Because traditional pulmonary catheterization required fluoroscopic assistance and marked technical skill in catheter manipulation for correct placement, it was for the most part limited to the catheterization laboratory. However, this was all to change with the invention of Swan's flow-directed catheter. It was said that he came up with the idea after watching sailboats in Santa Monica Bay during an outing with his children. He postulated that a small balloon attached to the end of the catheter would act as a sail or parachute by catching blood flowing out the pulmonary outflow tract, thereby increasing the ease and frequency of passage into the pulmonary artery. With the help of his friend and colleague Dr William Ganz, he constructed a small prototype consisting of a flexible single lumen catheter with an inflatable balloon at the tip. After obtaining encouraging results with animal studies, Swan and Ganz began using the device in human subjects.

In 1970, Swan, Ganz, and collegues published a case series describing 100 consecutive pulmonary catheterizations with the flow-directed catheter.[7] Sixty of these patients had successful catheter placement without the aid of fluoroscopy. The average time for catheterization was 35 seconds, far shorter than the time needed for placing a traditional catheter. However, one of the catheter's greatest strengths was its ability to remain in situ for days at a time. Recording PCWP traditionally required wedging the tip of a rigid catheter into the distal pulmonary artery, consequently obstructing

Table 1. Hemodynamic monitoring with a pulmonary artery catheter: Normal pressures and resistance values.[27]

	Mean	Range
Right atrium	3 mm Hg	1–5 mm Hg
Right ventricle		
Peak-systolic	25 mm Hg	15–30 mm Hg
End-diastolic	9 mm Hg	4–12 mm Hg
Pulmonary capillary wedge pressure	9 mm Hg	4–12 mm Hg
Systemic vascular resistance	1100 dyne-sec·cm^{-5}	700–1600 dyne-sec·cm^{-5}
Pulmonary vascular resistance	70 dyne-sec·cm^{-5}	20–130 dyne-sec·cm^{-5}

Table 2. Diagnosing and classifying cardiogenic shock: The Forrester classification.[6]

	Pulmonary cardiac wedge pressure < 18	Pulmonary cardiac wedge pressure > 18
Cardiac index > 2.2	Class I Physical exam: Clear lungs Normotensive, warm extremities Treatment: Supportive Hospital mortality: 3%	Class II Physical exam: Pulmonary congestion, elevated JVP Normotensive, warm extremities Treatment: Diuresis Hospital mortality: 9%
Cardiac index < 2.2	Class III Physical exam: Clear lungs, JVP normal Hypotensive, cool extremities Treatment: Volume Hospital mortality: 23%	Class IV Physical exam: Pulmonary congestion Hypotensive Treatment: Intra-aortic balloon pump Pressors Revascularization Hospital mortality: 51%

blood flow. By simply deflating the balloon at the tip of the flow-directed catheter, pulmonary blood flow could be quickly restored, making it unnecessary to remove it after taking hemodynamic measurements. This feature made it an appealing tool for hemodynamic monitoring, and thus the Swan-Ganz catheter allowed right heart catheterization to move from the catheterization laboratory to the critical care setting.

The Swan-Ganz catheter was quickly embraced by the medical community, and its use grew exponentially. Although it was found to have a wide range of applications, its largest impact was in the field of critical care medicine. It was a relatively easy device to use and permitted the physician to tailor therapy to quantitative hemodynamic measurements made from the bedside. In just a few years, the Swan-Ganz catheter became a routine piece of equipment in the intensive care unit, and knowing how to use it was an essential skill for the critical care physician.

The growing enthusiasm for the PAC was almost derailed in 1976 when safety concerns emerged about another medical device, the intrauterine device. The US Congress made an amendment to the Federal Food, Drug, and Cosmetic Act that delegated the responsibility for ensuring the safety and effectiveness of medical devices to the US Food and Drug Administration (FDA). However, under a grandfather clause, the pulmonary catheter was not required to undergo the rigorous testing that was mandated for new devices. Thus, over the next 10 to 15 years, PACs continued to be used with very little scrutiny, and by the mid-1980s they were being used in up to 43% of all critically ill patients.[8]

Emerging criticism

Beginning in the 1980s, a number of reports questioning the safety of the PAC began to emerge. Fein and colleagues published a retrospective study of 70 critically ill patients managed with a PAC during hospitalization. Although the catheter permitted better delineation of cardiogenic and noncardiogenic pulmonary edema, it was also associated with a 33% incidence of major complications and a 4% risk of mortality.[9] In a separate study, the incidence of internal jugular vein thrombosis with pulmonary catheterization was demonstrated to be 67%.[10] In a postmortem study by Rowley and colleagues, pulmonary catheterization was associated with a 7% incidence of infective endocarditis.[11] Other reported complications included pulmonary artery thrombosis, knotting of the catheter, rupture of the pulmonary artery, pulmonary hemorrhage, atrial thrombosis, sepsis, atrial and ventricular arrhythmias, and electrical-mechanical dissociation. However, although these findings were alarming, they were mostly reported in small retrospective studies, making it difficult to draw any firm conclusions.

In 1985, Robin published a landmark editorial in the *Annals of Internal Medicine* calling into question the

Table 3. Excerpt from 2006 Heart Failure Society of America guidelines.

The routine use of invasive hemodynamic monitoring in patients with acute decompensated heart failure is not recommended (strength of evidence: A)

Invasive hemodynamic monitoring should be considered in a patient:
- Who is refractory to initial therapy
- Whose volume status and cardiac filling pressures are unclear
- Who has clinically significant hypotension (typically systolic blood pressure < 80 mm Hg) or worsening renal failure
- Or in whom documentation of an adequate hemodynamic response to the inotropic agent is necessary when chronic outpatient infusion is being considered (strength of evidence: C)

To date, no study has been able to demonstrate that routine pulmonary artery catheterization improves mortality or morbidity outcomes.

need for and safety of routine pulmonary catheterization.[12] In his editorial he highlighted reports of complications and criticized the liberal use of this device despite the lack of any evidence regarding its impact on clinical outcomes. A subsequent retrospective study published by Gore and colleagues in 1987 cast further doubt on the benefit of the PAC.[8] Gore compared the outcome of patients admitted with a complicated myocardial infarction and managed with a PAC to reasonably matched controls. There was no difference in 5-year survival between these two groups. Furthermore, patients in the PAC group had higher in-hospital mortality and longer hospital stays. Supporters of the PAC maintained that despite these results, pulmonary catheterization provided valuable information to guide therapy in critically ill patients, thereby improving decision making and clinical outcomes.[13-15] Despite growing concerns, the pulmonary artery catheter continued to be a frequently used device in the critical care setting over the next 10 years.

The SUPPORT trial published in 1996 was the first prospective study to examine the impact of pulmonary catheterization.[16] This cohort study included 5735 critically ill adult patients admitted to five US teaching hospitals between 1989 and 1994. The results of this trial demonstrated a concerning increase in 30-day mortality (OR 1.24), mean ICU stay (1.8 days), and an extra cost of $13 600 per patient treated. In response to the study and the ongoing debate surrounding the use of pulmonary catheters, the National Heart, Lung, and Blood Institute (NHLBI) and the FDA held a workshop in Alexandria, Virginia, in August 1997.[17] Over 2 days, 85 experts reviewed the available literature and identified several key areas as high priority for clinical trials. These included the use of PAC in persistent or refractory congestive heart failure, acute respiratory distress syndrome, septic shock, and low-risk coronary artery bypass surgery.

Since the NHLBI workshop, several large randomized controlled trials have investigated the role of PAC in some of the patient populations identified at the conference.[18-23] To date, no study has been able to demonstrate that routine pulmonary artery catheterization improves mortality or morbidity outcomes. In fact, some studies have suggested that patients managed with a PAC may have significantly more adverse events. However, these findings should be interpreted with caution as many of them excluded the sickest patients because of ethical concerns in withholding pulmonary catheterization from the control arm. Consequently, those who may have derived the greatest benefit from the PAC were not included in these trials. The 2006 Heart Failure Society of America guidelines do not recommend routine use of invasive hemodynamic monitoring in patients with acute decompensated heart failure (Table 3), although they do mention several situations where the use of a PAC may be considered.[24]

Legacy

The Swan-Ganz catheter was truly revolutionary and is the quintessential technology of the intensive care unit.[25] Although questions surrounding the risk-benefit ratio of the Swan-Ganz catheter continue to be debated, there is no question that it has laid the foundation for the ongoing development of newer and less invasive hemodynamic monitoring technologies. While complete review of these technologies extends far beyond the scope of this article, we would like to touch on some highlights.

Although thermodilution has been one of the most established methods for determining cardiac output, concerns over the PAC have caused a renewed interest in the Fick method,[26] which allows cardiac output to be

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calculated from measurements of oxygen consumption and venous and arterial oxygen content. The calculation can be done at the bedside and is not affected by the shape of the temperature curve used in thermodilution. The Fick method has also proven to be one of the most accurate ways to assess patients with low cardiac output.[27] However, it too has its limitations. Firstly, the Fick method assumes steady state conditions, which may not apply in the hemodynamically unstable patient. It also assumes blood is flowing in and out of a closed system and thus becomes inaccurate in the presence of a shunt. Finally, as measuring actual oxygen consumption can be cumbersome, oxygen consumption is often assumed using a consumption index, which can lead to inaccurate calculations.

Transpulmonary thermodilution is another less invasive technique to calculate cardiac output, and has been gaining acceptance.[28] Similar to the pulmonary artery thermodilution, a cold bolus of saline is injected into the central venous circulation. A thermodilution curve is created from changes in blood temperature detected by a thermistor-tipped catheter placed in the aorta through the femoral artery. In addition to measuring cardiac output, transpulmonary thermodilution can also be used to estimate global end-diastolic volume and intrathoracic blood volume, which can serve as an indicator of cardiac preload.[28] Several clinical validation studies have suggested a good correlation between values obtained with this method and those obtained with traditional pulmonary thermodilution.[29]

Pulse contour analysis is another modality that has received significant attention. This technique uses an algorithm to analyze the contour of an arterial tracing and is based on the principle that the contour of the arterial pulse is proportional to stroke volume. Contour analysis has been well validated and has been demonstrated to correlate closely with values obtained by thermodilution.[29] Frequent calibration is often required, as rapid changes in systemic vascular resistance can affect the accuracy of the measurements. Furthermore, probes typically need central placement (axillary or femoral artery) as measurement from the radial position has yet to be validated.[29] However, pulse contour analysis holds significant promise as a monitoring device in the critical care setting.

Summary

Dr Jeremy Swan's immense contributions to the field of cardiovascular medicine will forever make him one of the true cardiology giants. As well as being a brilliant physiologist and research scientist, Swan was an inspiring leader and served as a mentor to numerous trainees over his career. Although the debate over his flow-directed catheter continues, there is no question that his work has paved the way for much of our current understanding of cardiovascular physiology and hemodynamics in shock states. He leaves behind a legacy of innovation and excellence and will forever be missed.

Competing interests

None declared.

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