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History of Right Heart Catheterization: 100 Years of Experimentation and Methodology Development

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Abstract

The development of right heart catheterization has provided the clinician the ability to diagnose patients with congenital and acquired right heart disease, and to monitor patients in the ICU with significant cardiovascular illnesses. The development of bedside pulmonary artery catheterization has become a standard of care for the critically ill patient since its introduction into the ICU almost 40 years ago. However, adoption of this procedure into the mainstream of clinical practice occurred without prior evaluation or demonstration of its clinical or cost-effectiveness. Moreover, current randomized, controlled trials provide little evidence in support of the clinical utility of pulmonary artery catheterization in the management of critically ill patients. Nevertheless, the right heart catheter is an important diagnostic tool to assist the clinician in the diagnosis of congenital heart disease and acquired right heart disease, and moreover, when catheter placement is proximal to the right auricle (atria), this catheter provides an important and safe route for administration of fluids, medications, and parenteral nutrition. The purpose of this manuscript is to review the development of right heart catheterization that led to the ability to conduct physiologic studies in cardiovascular dynamics in normal individuals and in patients with cardiovascular diseases, and to review current controversies of the extension of the right heart catheter, the pulmonary artery catheter.

Keywords

Right heart catheterization; pulmonary artery catheterization; cardiovascular hemodynamics; cardiovascular diseases; systemic circulation; pulmonary circulation

Right heart catheterization continues to serve as a useful tool in modern day medicine as a result of its ability to accurately and conveniently measure cardiac events in normal and disease states [1-4] and over 1 million cardiac catheterizations are performed annually in the United States [5]. Direct injection of drugs, pressure measurements, and angiographic visualization with contrast media are among the current applications facilitated by this technique [6-8]. The development of this procedure has been an ongoing journey starting in the 1700s with Stephen Hale's cannualization of an equine artery to measure systemic

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arterial pressure, the catheterization of both ventricles in a horse by Claude Bernard in 1844; to the self-catheterization of his own heart by Werner Forssmann in 1929, followed by the development of sophisticated clinical and physiologic procedures by Cournand and Richards in 1944 [7,9-12]. The catheterization of the right heart has improved the accuracy of cardiac pressure, blood volume, and cardiac output measurements by providing a more accurate method for obtaining mixed venous blood samples [7,13-16]. An understanding of the early history of right heart catheterization provides the reader a greater appreciation of current clinical applications and the limitations of this important technique in the field of cardiology.

ANIMAL EXPERIMENTATION FOR CARDIAC CATHETERIZATION DEVELOPMENT

In 1711, the Reverend Stephen Hales is reported to have made the first measurement of blood pressure and cardiac output with the use of brass pipes inserted into the venous and arterial systems of a horse [12,17-19]. Additional studies were conducted by Auguste Chauveau and É tienne-Jules Marey who made graphic records of the auricular and ventricular pressures in a horse using a double cardiac catheter technique [11,12,20].

During the late 1700's, there were two hypotheses concerning the production of heat in animals: the Pulmonary Combustion Hypothesis and the Tissue Combustion Hypothesis [21,22]. Antoine-Laurent de Lavoisier, the father of nutrition, proposed the former hypothesis based on his ideas that heat is produced when respiratory gas exchange occurs during blood flow through the lungs [4,21,22]. These ideas were challenged in 1837 when Gustav Magnus, a chemist and physicist, proposed that tissues serve as the site of heat production [4]. Claude Bernard emphasized the importance of physiologic understanding of disease throughout his career as a physiologist, and thus sought to test these two opposing hypotheses by directly correlating the physics of the circulation with thermodynamic principles [4,21]. Bernard proposed that the pulmonary combustion model would result in blood being warmer in the left side of the heart after passing through the pulmonary system. In order to experimentally study these concepts, the limited resources and techniques at that time required an open chest of an animal [4,21]. This technique, although commonly performed, would provide inaccurate results for temperature readings, and led Bernard in 1844 to perform cardiac catheterization to circumvent this problem, as suggested by André Cournand [4,6,23]. This catheterization procedure involved exposing a horse's jugular vein and carotid artery in order to insert a glass tube into the right and left ventricles by a retrograde approach. Bernard ultimately used this technique to insert a mercury thermometer to obtain the respective temperatures of the two sides of the heart [4,23]. These accurate measurements allowed Bernard to verify the validity of the tissue combustion hypothesis [11]. Although subsequently challenged as the first documentation of intracardiac catheterization, these studies certainly showed that right heart catheterization could be used for monitoring potential cardiac events. Animal catheterization procedures became a common technique in the late 1800s; in particular, Claude Bernard and two other French physiologists, Jean-Baptiste Chauveau and Etienne Marey, continued to use cardiac catheterization in the horse as a means to measure intracardiac pressures [4,20].

HUMAN EXPERIMENTATION FOR CARDIAC PRESSURE MEASUREMENT

Further studies of cardiac catheterization were carried out in the early 1900s by Fritz Bleichroder, Ernst Unger, and W. Loeb who were attempting to inject drugs into the vicinity of diseased areas of the body by passing catheters into the central veins and arteries initially in dogs [4]. However, Bleichroder decided to become a human subject having Unger perform three procedures on him by passing catheters through the basilic vein and into the

axillary, and on separate occasions through the femoral vein and into the inferior vena cava [4]. During one of these experiments, Bleichroder experienced severe chest pain leading the researchers to believe that they may had performed the first human heart catheterization, but they failed to confirm the catheter position by either by x-ray or pressure recording.

Although unaware of the human experiments of Bleichroder and Unger, Dr. Werner Forssmann demonstrated the efficacy and safety of the first recorded human cardiac catheterization in 1922 [24,25].

At age 25, Werner Forssmann was intrigued that cardiac catheterization may improve the administration and efficacy of cardiac medications and advance our understanding of circulatory and metabolic mechanisms [11,24,26]. A recent graduate of Friedrich-Wilhelms University in Berlin, Forssmann was aware of Bernard's safe cardiac catheterization experiments in animals and he believed that they could be used in humans [24]. However, during this period of experimental medicine, the manipulation of a living human heart was not recommended [24], as the simple act of touching the living human heart and exposing it frequently ended in patient death [27]. Nevertheless, Forssmann inserted in himself a ureteral catheter and passed the catheter into the right auricle and documented this self-catheterization on x-ray film [25]. Fortunately this procedure resulted in no major complications and demonstrated that cardiac catheterization of humans could provide the ability to access the heart's interior while remaining safe and painless; a procedure used in animals for decades [4,11,21]. Forssmann also repeated this cardiac catheterization in a septic patient in the belief that the therapeutic advantage of directly injecting the cardiac medications suprarenin (adrenalin) and strophantin (a digitalis preparation) into the central circulation underscored the therapeutic value of the procedure. However, the publication of this seminal article [25] created havoc in the Berlin press and resulted in the suspension of his clinical privileges [12,24,26].

The use of right heart catheterization in humans became a popular method in the 1930's. Klein in Prague used cardiac catheterization to obtain mixed venous blood and studied cardiac output in 30 patients [28]. The physiologist, Thomas, used right heart catheterization to study glucose metabolism in animals [29]. However, it was not until 1941 that Drs. Cournand, Ranges, and Richards further developed the right heart catheterization techniques that could be used for hemodynamic measurements [7,13,30].

RIGHT HEART CATHETERIZATION AND THE DIRECT FICK PRINCIPLE

The pulmonary physiologist and physician, André Cournand, shared a common interest in gas exchange and oxygen movement with Dickinson Richards, an expert in cardiovascular medicine [31-35]. This research team worked at Bellevue Hospital in New York City to redesign the catheter used in Forssmann's experiments [30]. Alterations in the catheter included changes in the design and fabrication of tubing materials with subsequent findings of *in situ* placement for over 48 hours in some patients without a causing significant complications [13]. This technique allowed for the collection of true mixed venous blood, and for the first time the use of the direct Fick principle [36,37] became a reasonable means of measuring cardiac output [13,38,39]. By using the Fick Principle, blood flow to an organ in the body can be calculated using any dissolved indicator in the blood, if the following information is known about the indicator: the amount of indicator taken up by the organ per unit of time is constant, the initial concentration of the indicator supplying the organ is known, and the concentration of the indicator leaving the organ, then cardiac output can be calculated by dividing the uptake of the indicator by the content difference of indicator measured in arterial blood and mixed venous blood samples. In Fick's original description, oxygen consumption was the indicator measured in the body, however this method was

rarely used due to the difficulty of obtaining a mixed venous blood sample before the development of right heart catheterization, unless direct cardiac puncture was used [40].

RIGHT HEART CATHETERIZATION AS A VERSATILE TOOL FOR HEMODYNAMIC STUDY

Right heart catheterization eliminated the difficulty of obtaining a mixed venous blood sample and thus made cardiac output determination a safe technique without causing undue discomfort to the patient [13,26]. Cournand and Richards reported in 1945 detailed information about the placement and management of the right heart catheterization procedure [13]. In more than 260 catheterizations, the catheter could be left in the patient for up to 24 hours with no adverse events other than the development of thrombi near the insertion site in the brachial vein. The authors stressed that catheter placement should proceed with strict aseptic precautions. Moreover, catheters were left *in situ* for over 48 hours in two patients with severe burns, and at autopsy both patients were found to have small thrombi in the central veins and the right atrial and ventricular walls revealed no evidence of valve leaflet damage. However, in one case, a small pulmonary infarction was seen. In 13 healthy males, cardiac indices were calculated with the use of this technique and when compared to other groups of comparable subjects, the average cardiac index was found to be ~27% higher than when measured by the ethyl iodide or acetylene methods. Finally, the measurement of cardiac output with simultaneous samples of the respiratory gases in both the arterial and intra-cardiac venous systems was recorded in 34 normal and 'hospital-normal' subjects [13]. In the following year, Cournand and Richards presented additional observations in 70 patients of pressure measurement comparisons of both the right atrial and right ventricle in normal patients, and in patients with chronic pulmonary disease or cardiac disease [41]. Right heart catheterization was performed without undue discomfort or complications, with the original descriptions of pressure tracings that were obtained and the reported range of variations. Right atrial pressures ranged from −2 to +2 mm Hg when compared to atmospheric pressure. Normal right ventricular systolic pressure ranged from 18 to 30 mm Hg with an average of 25 mm Hg. The difference between the systolic pressure and the pressure at the end of diastole, termed ventricular pulse pressure, ranged from 17 to 26.5 mm Hg with an average of 22.5 mm Hg. These authors observed that both right ventricular systolic and pulse pressures were increased in most patients with chronic pulmonary disease, but were normal in some cases of advanced pulmonary emphysema, and that pressure patterns measured in right ventricular failure due to various causes were described and partially interpreted [41]. Based upon early studies [7,13,30,38,41], Cournand described the dynamics of the pulmonary circulation stating that 1) although an equal amount of blood flows through the lungs and the systemic circulation, momentary differences were observed due to rhythmic changes from breathing; 2) although pulmonary flow equals systemic flow, the pulmonary vascular bed is a low pressure system resulting from the great distensibility of the main pulmonary artery and distal branches, but more importantly due to the very large capacity and deformability of the arteriolar, precapillary, and capillary beds. This low vascular resistance is an essential attribute of the pulmonary circulation in man as well as in mammals; and 3) that the distribution of blood in the pulmonary circulation depends upon local mechanical mechanisms rather than control by the nervous system [42,43].

In an interesting study by Richards and colleagues, cardiac outputs were simultaneously measured by right heart catheterization (the direct Fick method) and by the ballistocardiograph method in paired controls in normal and in hospitalized patients [44]. The authors observed that the ballistocardiographic measurement of cardiac output produced erratic results in both resting and purposeful alterations in respiratory ventilation. Moreover, the authors observed that in patients with significant respiratory illness, the

ballistocardiograph records were too distorted and difficult to read. They concluded that the ballistocardiograph should no longer be used to assess cardiac output [44]. Cournand and Richards developed right heart catheterization as a versatile tool for hemodynamic measurements, as well as determining blood volumes, intra-cardiac pressures, blood gases, pH, and respiratory gas exchange in normal patients as well as in patients affected by either chronic pulmonary obstructive disorder or heart failure [4,13,31,38,39,41,44-47]. Thus, Cournand and Richards vastly improved the diagnostic abilities of physicians by better understanding the physiologic aspects of cardiology; these advances in medicine can in part be attributed to the visionary ideas of Claude Bernard and Werner Forssmann. In recognition of these achievements, in 1956 the Nobel Prize in Physiology or Medicine was awarded to Drs. André Cournand, Dickinson Richards, and Werner Forssmann [24,48].

With the introduction of the right heart catheter by Forssmann [25] and improvements by Cournand and Ranges [30], the ability to study congenital heart disease was now realized with the capacity to measure pressure in either the superior and inferior vena cavae, the chambers of the right heart, and the pulmonary artery [49,50]. Moreover, analysis of blood samples obtained from these sites and compared to the values obtained in a systemic artery permitted the calculation of cardiac output by the Fick principle [49]. The accuracy of the direct Fick method for determination of cardiac output under a given set of conditions depends upon the accuracy with which the oxygen consumption and oxygen content of arterial and mixed venous blood values are measured [49]. Although Cournand believed that blood withdrawn from the right atrium was mixed venous blood [13], Holt and Knoefel reported that true mixing did not occur within this chamber [15]. Moreover, additional studies by Warren and colleagues found significant differences in oxygen saturation of blood samples obtained in the right atrium versus the right ventricle (Fig. 1) [16]. They suggested that these differences were due to different streams of deoxygenated blood from different organs which could exist in the right atrium and that may persist into the right ventricle. Dexter and colleagues, in their study of right heart catheterization, confirmed the findings and observed that true mixed venous blood oxygen content requires sampling of blood from the pulmonary artery (Figs. 2 & 3) unless significant vascular anomalies exist [49]. In the same year, the use of right heart catheterization by Dexter and colleagues in studying complex congenital heart diseases reported the following observations: 1) in patients with patent ductus arteriosus, that blood in the pulmonary artery is more highly oxygenated than blood in the right ventricle; 2) in patients with interventricular septal defects, that blood in the right ventricle is more highly oxygenated than blood in the right atria; 3) in patients with Tetralogy of Fallot, pulmonary stenosis can be identified by finding a higher systolic pressure in the right ventricle than that measured in the pulmonary artery. In some patients the catheter can be introduced through the ventricular septal defect and into the aorta; and 4) in patients with atrial septal defects, the defect may be recognized by passage of the catheter into the left atria, or by the finding of arterial oxygenated blood in the right atria in patients with a left to right shunt [51]. In an interesting study, two laboratories cooperated to conduct a clinical study to measure cardiac output by two methods (direct Fick and dye injection methods) both in normal individuals at rest and during light and heavy exercise and in patients with various cardiorespiratory diseases [37]. Data were compared in 48 almost simultaneous determinations on 31 different subjects. In one laboratory, venous blood samples were obtained from the pulmonary artery; in the other laboratory from the right ventricle or the right atrial chamber. The results agreed within 25% in all but 6 determinations. Moreover, the authors stated that the distribution of their results was symmetrical and the resultant scatter was no greater than expected with the known inaccuracies in both methods. It is interesting to postulate that the venous blood samples obtained from the right heart chambers from one laboratory may have confounded the results of this study, as the true mixing sample site, as found in later studies, is distal to the right ventricle [15,16] or the error may have been due to the method of sampling [52].

The ability to study pulmonary circulatory dynamics was further advanced when Hellems and colleagues first described and measured pulmonary capillary wedge pressure in humans [53]. In their initial report, the passage of a cardiac catheter with a hole in the tip could be introduced into a small branch of the pulmonary artery and obstruct the arterial vessel lumen to allow measurement of downstream pressure [53]. The authors suggested that the pressure transmitted to the obstructing catheter was from the pulmonary capillary bed of the lung, as the blood sample was fully saturated with oxygen. Moreover, the pressures recorded with the catheter in a wedged position were in agreement with measured pulmonary venous pressure. In normal individuals, the measured pulmonary capillary pressure varies from 7 to 17 mm Hg with a mean value of 10 mm Hg. In patients with emphysema, pulmonary vascular disease, or with Eisenmenger's complex with elevated pulmonary artery pressure, the pulmonary capillary pressure is within normal limits, suggesting that the resistance to blood flow is in the pulmonary arterioles and not in the capillary bed. In patients with mitral stenosis or other cardiac abnormalities that can produce left heart failure, the pulmonary capillary pressure was elevated both at rest and during exercise [53]. Following experiments in animals [54], Hellems, Dexter and colleagues were able to use the right heart catheter and advance the distal end of the catheter under fluoroscopic guidance into the wedge position of a distal branch of the pulmonary artery [53]. In these 13 patients, mean occlusion pressures averaged 10 mm Hg with a variation from 7 to 15 mm Hg. Systolic pulmonary artery pressures varied between 19 and 30 mm Hg and diastolic pulmonary artery pressures measured between 6 and 17 mm Hg with an average pressure of 24/10 mm Hg. The authors were able to withdraw fully oxygen saturated blood samples from the occluded venous catheter. Moreover, the absence of valves in the pulmonary artery, vein or capillaries were confirmed as free retrograde flow and transmission of pressure was observed from the pulmonary capillaries when the catheter was wedged in the pulmonary artery [53,54]. Finally, the authors also observed the absence of significant pre-capillary admixture from bronchial arterial with pulmonary arterial blood (venous saturated blood) [53,55]. Subsequent studies by Dexter et al in normal patients at rest found that the average mean pulmonary artery pressure was 15 mm Hg, and the average mean pulmonary "capillary" pressure was 9 mm Hg, with an average arteriolar resistance of 67 dynes/seconds/m^{-5} [56]. The average work of the right ventricle was 0.89 kg/m/min/$BSAm^2$. In patients with uncomplicated patent ductus arteriosus and atrial septal defects, the development of large pulmonary blood flows with increased pulmonary artery to pulmonary capillary gradient would exist, especially when blood flow exceeded approximately 10 L/min/$BSAm^2$. (←**AQ should approve edit of this sentence)** In three patients with Eisenmenger's complex both pulmonary artery pressure and resistance measurements were found to be similar to values observed in the systemic circulation. In patients with mitral stenosis and left ventricular failure, these authors frequently observed elevated pulmonary capillary pressures often exceeding 25 mm Hg, with significantly increased pulmonary arteriolar resistance [56].

Finally, an interesting study in the modification of the right heart catheter by Lategola and Rahn in 1953 reported two years experience with a "self-guiding" pulmonary artery catheter with a balloon fixed on the tip that could consistently and easily advance into the pulmonary artery and would wedge in a distal pulmonary artery [57]. Moreover, the authors stated that this modified catheter, "acting like a sail", would consistently be swept by the flow of blood into the pulmonary artery without the need of fluoroscopic guidance. The authors repeatedly verified the ease of catheter placement by asking medical students and other staff members to place this catheter into the pulmonary artery by merely watching pressure changes in the manometer. The authors also discussed a potential disadvantage of this catheter, in that clots would develop along the folds of the balloon. These clots were minimal in size and did not interfere with experimental procedures [57].

TULANE UNIVERSITY'S CONTRIBUTION TO CATHETERIZATION ADVANCEMENT

Dr. Albert L. Hyman, a cardiologist and professor, joined the Tulane community in 1956, practicing medicine and performing research at Tulane University School of Medicine until 2005. Among his first studies was the analysis of responses to bradykinin in the pulmonary circulation of the dog utilizing a transseptal technique that provided simultaneous measurement of right and left atrial pressures and small intrapulmonary vein pressures under constant flow conditions in the intact chest animal [58]. One of the most important contributions Dr. Hyman made was the development of the procedure for the measurement of small intrapulmonary vein pressures in the intact chest animal [59-66]. With the measurement of pulmonary artery, small vein and left atrial pressures under constant flow conditions, Dr. Hyman's studies were able to define the actions of a number of vasoactive substances and the role of the sympathetic nervous system on the resistance to blood flow in the arterial segments and small veins [67-74]. As the 1986 recipient of the Dickinson W. Richards Memorial Award, Dr. Hyman's significant contributions to the field of cardiac catheterization and the study of pulmonary physiology and pharmacology throughout his career were recognized. With similar research interests, Dr. André Cournand has cited Dr. Hyman's work on pulmonary hypertension in mitral stenosis [75]. Dr. Hyman had great interest in pulmonary diseases as he used catheterization techniques both in his surgical cardiopulmonary laboratory at Tulane University School of Medicine and at the Cardiac Catheterization Laboratory at Touro Infirmary [58,76,77]. Dr. Hyman, as a cardiopulmonary physiologist and pharmacologist, trained Dr. Philip J. Kadowitz and together have collaborated for more than 30 years. Dr. Kadowitz currently investigates pulmonary hypertension through the *in vivo* cardiovascular studies of mice and rats [76-85]. These collaborative efforts have led to the development right heart catheterization techniques for large and small animals to allow the study of pulmonary vascular pressures and responses to investigating the actions of drugs without opening the chest in spontaneously breathing animals [76,77].

BEDSIDE USE OF THE PULMONARY ARTERY CATHETER

The pulmonary artery catheter has been used in the clinical management of the critically ill patient since 1970 [86]. These balloon floatation catheters, known as "Swan-Ganz" catheters were developed for immediate bedside monitoring of right heart chamber and pulmonary artery pressures in critically ill patients with subsequent revisions of the catheter to include measuring cardiac output by the thermodilution technique, calculation of oxygen consumption for nutrition studies and for right atrial and right ventricular pacing [2,87-105]. Initially introduced into clinical practice without substantial supporting studies, recent retrospective and randomized controlled trials have not shown positive benefit with the use of this catheter [87,106-112]. Ramsey et al examined the role of the pulmonary artery catheter in a retrospective cohort study from 56 community-based hospitals from 26 states [111]. A total of 13,907 patients undergoing non-emergent coronary artery bypass surgery in 1997 were reviewed and discharge abstracts were examined to assess the impact of pulmonary artery catheters on in-hospital mortality, length of stay in the ICU, total length of stay, and hospital costs. Outcomes were adjusted for patient demographic factors, hospital characteristics, and hospital volume of pulmonary artery catheters use in the year of analysis. Fifty-eight percent of the patients received a pulmonary artery catheter. After adjustment of the above factors, the relative risk of in-hospital mortality was 2.10 for the pulmonary artery catheter group compared with the patients who did not receive a pulmonary artery catheter (95% confidence interval [CI], 1.40 to 3.14; $p < 0.001$). Although length of stay in the ICU was similar between the two groups, total length of hospital stay was 0.26 days longer in the pulmonary artery catheter group ($p < 0.001$), with hospital costs

$1,402 higher. The authors stated that the use of pulmonary artery catheterization for patients undergoing non-emergent coronary artery bypass surgery was associated with an increased risk of in-hospital mortality, a greater hospital length of stay, and higher total costs [111]. However, a prospective, randomized, controlled trial on survival outcomes was conducted in critically ill patients [108]. It was observed that there was no significant difference in mortality between patients managed with a pulmonary artery catheter [46/95 (47.9%)] when compared to those patients managed without a pulmonary artery catheter [50/106 (47.6)]. In a supporting study, the effects of outcomes with the early use of a pulmonary artery catheter in patients with shock, acute respiratory distress syndrome or both were reported [107]. In this multicenter, randomized, controlled study where treatment was left to the discretion of the patient's physician, there were no significant differences in mortality with or without the pulmonary artery catheter at day 14. In an observational cohort study, no increased risk of death in the population as a whole was associated with use of the pulmonary artery catheter [112]. However, the authors suggested that the use of the pulmonary artery catheter may decrease mortality rate in the most severely ill patient (APACHE Score >31) while increasing mortality rates in a population with a lower severity of illness (APACHE Score <18).

Two large multicenter, international, randomized clinical trials were analyzed and adjusted for differences in baseline risk [106]. In these studies, pulmonary artery catheterization was associated with an increased mortality, except for patients in cardiogenic shock.

Harvey et al conducted a randomized, controlled trial in 1,041 patients from 65 UK intensive care units to ascertain whether hospital mortality is reduced in critically ill patients when they are managed with a pulmonary artery catheter [109]. The authors found no difference in hospital mortality between patients managed with or without a pulmonary artery catheter. They also observed that although no fatal complications were associated with insertion of a pulmonary artery catheter, no clear evidence of benefit or harm in managing critically ill patients with a pulmonary artery catheter were observed. Wheeler et al evaluated the benefits and risk of hemodynamic management guided by either pulmonary artery catheterization versus central venous catheterization in the management of patients diagnosed with acute lung injury [110]. Therapy guided by the pulmonary artery catheter did not improve these measures for patients in shock at the time of enrollment. There were no significant differences between groups in lung or kidney function, rates of hypotension, ventilator settings, or use of dialysis or vasopressors. These authors suggested that the pulmonary artery catheter should not be routinely used in the management of acute lung injury.

These clinical studies have generated recent editorials to call for the reevaluation or elimination of this catheter [113-121]. Leibowitz, in his editorial states cardiac filling pressures do not correlate with accepted standards of intravascular volume determination and left ventricular filling when compared to echocardiographic findings, leaving the intensivist in "an intellectual bind" [121]. Benjamin et al found in ICU patients that when echocardiographic and pulmonary artery catheter measurements were compared, the echocardiographic data disagreed with pulmonary artery catheter data in 55% of comparative examinations [122]. Further studies demonstrating a lack of support for pulmonary artery or central venous pressure monitoring guiding appropriate volume resuscitation were performed in an interesting, but retrospective study in septic patients in a single ICU setting [123]. De Wolf in his editorial states that the use of transesophageal echocardiography (TEE) as an alternative in assessing cardiovascular hemodynamics is limited in its use **compared to???** intermittent assessments in single patients and one needs to be skilled in the use of this technology [113]. Vender agrees that prudence should be taken for any novel technology used by any untrained personnel, as they must demonstrate a

reasonable understanding of any new diagnostic or therapeutic approach or should not be credentialed in the use [117]. The biggest problem continues to be the inappropriate measurement and interpretation of the data, leading to inappropriate and potentially harmful interventions [117]. Certainly, central venous catheterization is still required as it is necessary to facilitate administration of fluids, drugs, and parenteral nutrition [91,113,124-132].

Although the several prospective and randomized clinical trials using the pulmonary artery catheter did not influence outcomes [107-110], these studies may be difficult to interpret due to a multitude of confounding factors, such that the hemodynamic information that is obtained should be cautiously interpreted or should be used in the development of more effective treatment strategies [1,133,134]. However, pulmonary artery catheterization is necessary for the differential diagnosis of pulmonary artery hypertension [135], as no noninvasive tests exist for the accurate diagnosis of precapillary, postcapillary, or mixed hemodynamic types of pulmonary arterial hypertension [87].

CONCLUSION

Right heart catheterization continues to be the gold standard in diagnosing patients with elevated right heart pressures, although this technique has complications. The development of noninvasive techniques has progressed, however prospective clinical trials are lacking. Right heart catheterization is indicated only in patients with complex medical problems or in those patients in whom important hemodynamic measures are only obtainable from its use. It is important to note that the use of the pulmonary artery catheter is a monitoring procedure and not a treatment. When viewed in this context, the pulmonary artery catheter provides the clinician the advantage of continuous hemodynamic monitoring that could assist the trained health care professional in application of therapeutic treatments before the development of symptomatic decompensation.

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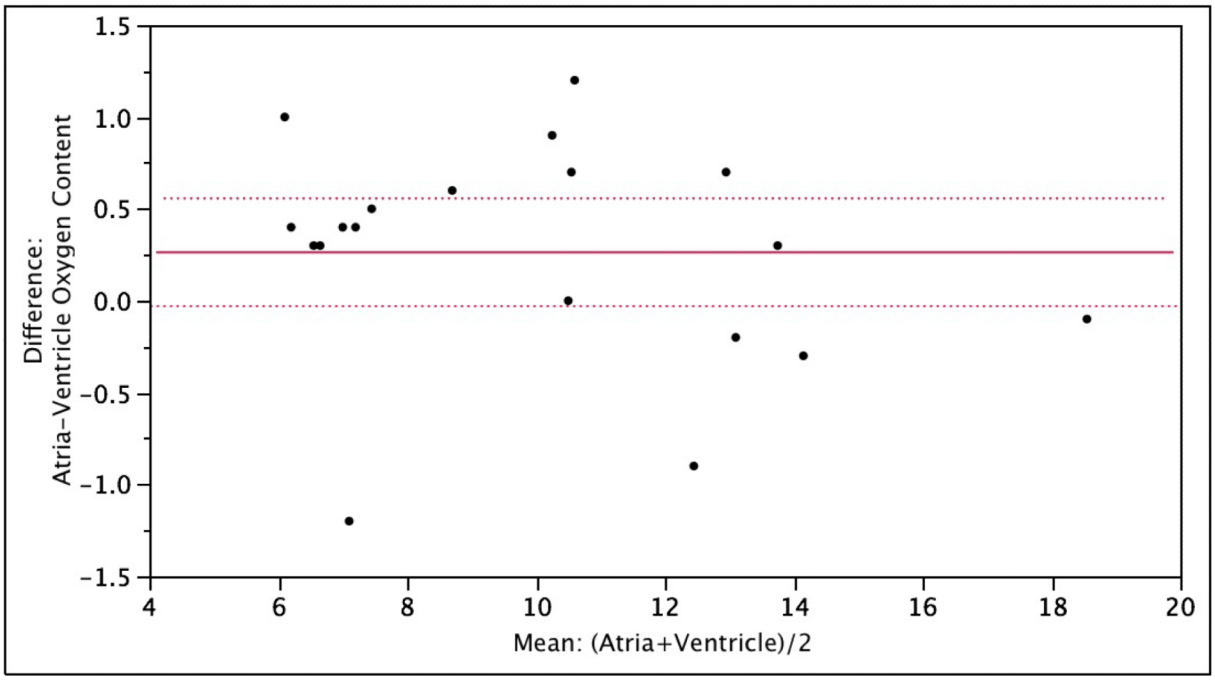

Figure 1.
Graph demonstrating the differences in oxygen content from matched pairs in samples obtained from the right atria and right ventricle in patients undergoing right heart catheterization. Samples above or below the dotted lines are greater than the alpha level of 0.05 for the mean of the paired groups. From Warren, et al. [16]

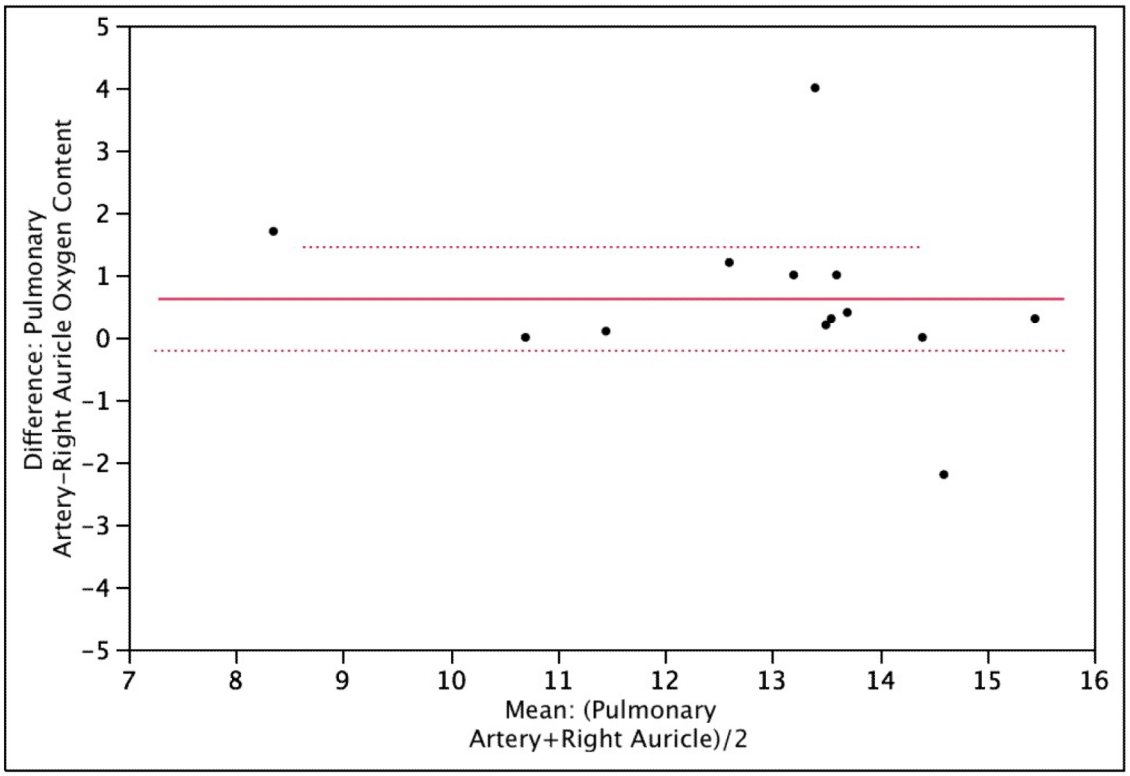

Figure 2.
Simplified graph demonstrating the differences in oxygen content from matched pairs in samples obtained from the pulmonary artery and right auricle (atria) in patients undergoing right heart catheterization. Samples above or below the dotted lines are greater than the alpha level of 0.05 for the mean of the paired groups. From Dexter, et al. [49]

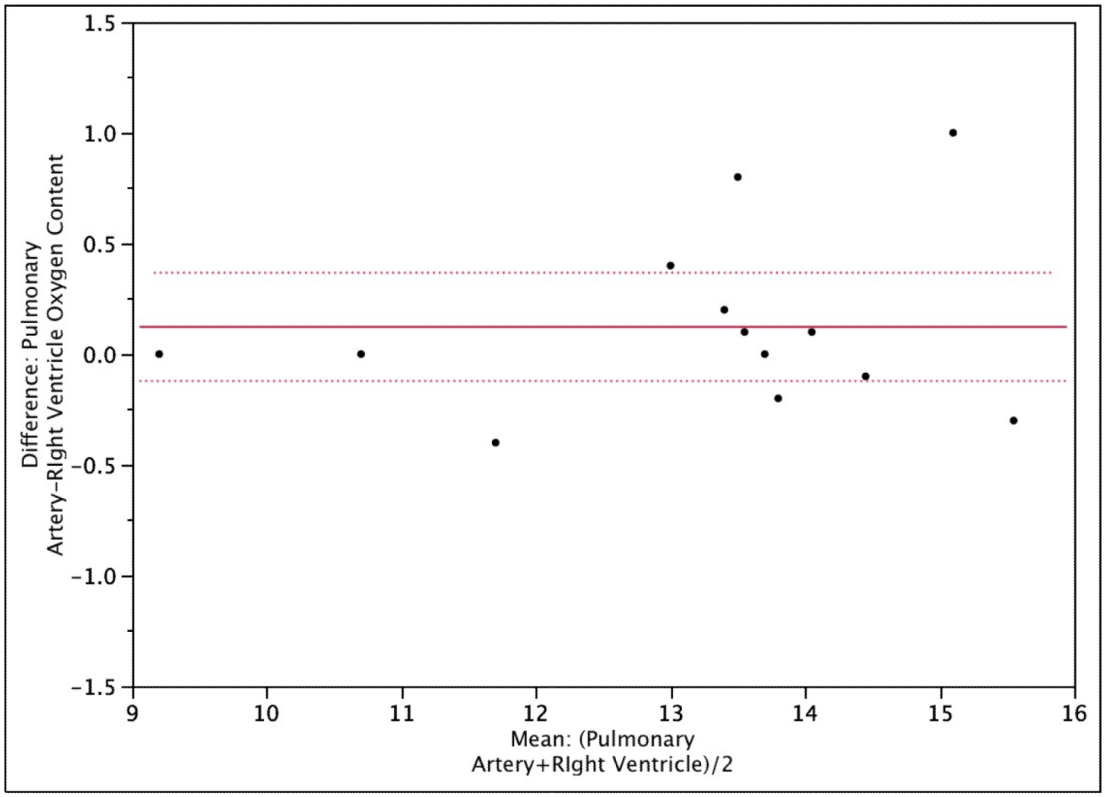

Figure 3.
Simplified graph demonstrating the differences in oxygen content from matched pairs in samples obtained from the pulmonary artery and right ventricle in patients undergoing right heart catheterization. Samples above or below the dotted lines are greater than the alpha level of 0.05 for the mean of the paired groups. From Dexter, et al. [49]