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NONINVASIVE MEASUREMENT OF CENTRAL VENOUS PRESSURE

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to

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by

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ABSTRACT

Central venous pressure is a clinically significant parameter which is frequently monitored in certain acutely ill patients via an indwelling central venous catheter. We are investigating a technique for the noninvasive measurement of CVP in man. The method, first suggested by Rositano at the NASA-Ames Research Center, involves monitoring venous velocity at a point in the periphery with a transcutaneous Doppler ultrasonic velocity meter while the patient performs a forced expiratory maneuver. The idea is that CVP is related to the value of pressure measured at the mouth which just stops the flow in the vein.

We have conceived of two improvements on Rositano's original procedure. First, we have shifted the site of venous velocity measurement from a vein at the antecubital fossa (elbow) to the right external jugular vein in the neck. This allows us to sense more readily events occurring in the central veins. Secondly, and perhaps most significantly, we have developed a procedure for obtaining a curve of relative mean venous velocity vs. mouth pressure. We believe that this type of curve will allow us to predict more precisely the significant cardiovascular parameters.

We have proposed three hypotheses to explain the biophysical mechanisms involved in our measurement technique. These include Webster's original central venous pressure hypothesis, a mean systemic pressure hypothesis extending Guyton's work in dogs, and a peripheral venous pressure hypothesis incorporating a reappraisal of Rositano's ideas. Depending upon the outcome of our further investigation of these and other hypotheses, we may be able to develop our technique to a clinically useful level.

We envision the possibility of circumventing the morbidity associated with the placement and extended use of a CVP catheter by providing the physician

with a simple, noninvasive method of estimating resting central venous pressure. Alternatively, we may be able to measure a cardiovascular parameter potentially more valuable than CVP, that being venous return pressure. We are confident that our work will provide new understanding of the basic physiological relationships between cardiovascular hydrodynamics and respiratory mechanics.

INTRODUCTION

The original objective of our research was to develop a noninvasive technique for measuring central venous pressure (CVP) in man. This cardiovascular parameter is presently being obtained via an indwelling central venous catheter placed through a peripheral vein, a technique which involves some hazards to the patient. In recognizing the clinical value of this measurement, especially during the correction of hypovolemia [1], we were enthusiastic about extending a technique originally suggested by Rositano [2] to provide for the physician a noninvasive, untraumatic method of estimating CVP.

In carrying out Rositano's procedure, the subject forcibly exhales against a pressure-indicating device in order to increase his intrapulmonary pressure. At the same time we monitor blood velocity toward the heart in a peripheral vein (originally an arm vein on the inside of the elbow) using a transcutaneous Doppler ultrasonic velocity meter [3]. Rositano's subjects generated a ramp-type increase in lung pressure over a period of several seconds; however, we have found a rapid increase in pressure to a constant level for a few seconds to be a more reproducible maneuver. During a series of these maneuvers, each to a different level of pressure, there is a characteristic end-point corresponding to the minimum value of peak lung pressure (as measured at the mouth) which causes venous velocity to become zero for at least one heart cycle. Webster has suggested a possible relation between resting CVP and this end-point intrapulmonary pressure [4], [5]. However, before considering extensive clinical trials to attempt to establish this relationship, we believe it necessary to investigate the biophysical mechanisms underlying our technique.

VENOUS VELOCITY-MOUTH PRESSURE CURVES

Rositano's original technique [2] and Webster's later modification [4], [5] simply involve measuring blood velocity in a peripheral vein while the

subject exhales through a high resistance airway so as to elevate the pressure in his lungs and thorax. Only one data point is obtained from each subject: the minimum pressure (measured at the mouth) at which venous velocity becomes zero.

In an effort to understand more fully the biophysical processes involved in this measurement, we expanded upon the Rositano-Webster technique so as to determine a series of data points for each subject. Right jugular venous velocity was monitored with a Parks Doppler Flowmeter (either Model 806 or Model 810). We chose a neck vein as the flow monitoring point in an attempt to get as close as possible to the central veins without having to contend with ultrasonic transmission through the air spaces in the lungs. Mouth pressure was recorded from a Statham P23BB pressure transducer, and a visual indication of mouth pressure was provided to the subject via a Marshalltown pressure gauge reading ± 40 cm H_2O full scale. Three traces were recorded on a Beckman R-411 Dynograph recorder: Instantaneous venous velocity (v), Mean venous velocity-v filtered by a low-pass filter with an RC time constant of 0.53 sec. ($\bar{v}$), and mouth pressure (P_M).

The subject was instructed to exhale into the pressure-measuring system until the pressure gauge indicated a predetermined value. To prevent glottal closure during the maneuver, which would invalidate the correspondence between intrapulmonary pressure and indicated mouth pressure, a small leak was included in the system consisting of a 1/2 in. 27 ga hypodermic needle. The value of mouth pressure was held for a few seconds until the investigator told the subject to relax and breathe normally for approximately one minute. Following this the investigator would instruct the subject to repeat the maneuver to a different level of mouth pressure. This procedure was followed for peak values of P_M from zero to approximately 30 cm H_2O, usually in steps of 2 cm H_2O. All

subjects were instructed to begin all maneuvers from the end of a normal expiration (lung volume at its functional residual capacity or FRC). This is the most reproducible point in the respiratory cycle because at FRC the recoil forces of the lung and the chest wall are exactly balanced [6, p. 427]. By maintaining the volume the same at the beginning of each maneuver and by minimizing the flow in the airways during the maneuver, we may assume that the lung volume and, therefore, the transpulmonary pressure (mouth pressure minus intrathoracic pressure) is constant (approximately 5 cm H_2O) <u>during</u> the maneuver [7, pp. 373-374], [6, p. 429]. Following this line of reasoning we may expect that the quantity (P_M - 5 cm H_2O) accurately predicts the true value of introthoracic pressure (P_{ITh}) during the maneuver. The effect of these increases in P_{ITh} on right atrial pressure and venous return will be discussed in later sections.

Using the procedure outlined above we have generated sets of data on seven male volunteers in the following manner. From the strip chart records of $\bar{v}$ and P_M we have determined the ratio of the minimum value of $\bar{v}$ during the forced expiratory maneuver ($\bar{v}_m$) to the value of $\bar{v}$ just prior to the maneuver ($\bar{v}_o$). This ratio ($\bar{v}_m/\bar{v}_o = \bar{v}_R$) is the minimum value of the relative mean venous velocity at the point of measurement corresponding to the peak value of P_M during that maneuver (see typical record in Fig. 1). Fig. 2 shows a typical plot of $\bar{v}_R$ <u>vs</u>. P_M. We calculated a linear regression curve for each set of data for five of our subjects. (During one trial we were uncertain of the $\bar{v}$ baseline because of amplifier drift, and one subject did not perform all of his maneuvers from FRC.). The values of the mouth pressure intercept of the regression curve (P_{M_I}) and the r^2 (the square of the correlation coefficient r) of the data are given for the five subjects in Table 1. The value of r^2 represents the fraction of the total variation in the data which is accounted

for by the regression line [8, pp. 332-333]. The residual fraction of the variation ($1-r^2$) is not explained by the regression line and may be due to measurement errors, nonlinearities in the underlying process, etc.

Subject	Age	P_{M_I} (cm H_2O)	r^2
S.W.F.	26	27.4	.904
J.A.C.	23	30.8	.863
D.K.S.	24	33.2	.873
K.M.M.	26	16.9	.872
K.J.M.	23	22.7	.663

We will discuss possible physiological interpretations of the $\bar{v}_R - P_M$ curve in the following sections. Of course, a linear least squares analysis of the data may not be the best method of estimating the underlying process, but further refinement of our data analysis techniques must await the results of the physiological investigations to be outlined below.

CENTRAL VENOUS PRESSURE HYPOTHESIS

In Rositano's original work on erect subjects [2] there was a considerable time delay from the onset of the increase in intrapulmonary pressure to the cessation of peripheral venous velocity measured at the antecubital fossa. Webster [4], [5] reasoned that if the intrathoracic pressure were quickly raised to a level above the resting central venous pressure (CVP) that the central veins would collapse (at least transiently) because the extraluminal pressure would be greater than the intraluminal pressure, thus causing a cessation of flow in the central veins. If this transient cessation of central venous flow (venous return) could be detected in the periphery, the intrathoracic pressure at which the flow first stopped should be equal to the resting CVP.

Webster further argued that the problem with Rositano's original technique was that there was not a continuous column of blood from the right atrium to the veins in the arm. With the subject erect the veins in the arm and shoulder above heart level would be partially collapsed. Therefore, even though blood was prevented from entering the right atrium following an increase in intrathoracic pressure, blood would continue to flow in the periphery until the collapsed segment of vein was filled. Webster's solution to this problem was to place the subject in the recumbent supine position with the forearm slightly below heart level. In normal subjects this caused the veins between the elbow and the right atrium to become somewhat filled as evidenced by venous velocity in the arm becoming pulsatile due to the communication of cardiac events into the periphery. Under these conditions, Webster reasoned, the arm vein should act very much as a nondistensible fluid-filled tube so that any cessation of flow in the central veins would be immediately detected in the arm vein. In this way he hoped to measure resting CVP noninvasively by claiming that the value of mouth pressure which just stopped venous flow would be equal to CVP minus a 4 mm Hg correction factor for the difference between lung pressure and intrathoracic pressure [4].

We have recently called into question Webster's original assumption that central venous collapse is the mechanism causing cessation of venous return during the initial phase of a forced expiratory maneuver. This assumption is based on an analogy between our technique and sphygmomanometry. However, there is an important difference between the two methods which may render the analogy invalid. After occlusion of the artery by the application of external pressure, the pressure in the vessel upstream from the point of occlusion is not significantly changed because only a small percentage of the total cardiac output is diverted by the procedure. Any obstruction to flow in the central

veins, however, affects practically all of the cardiac output (except for the coronary and bronchial circulations) and causes blood to begin to pool immediately in the veins in the periphery. This results in an increase in pressure in essentially all venous segments causing venous return to commence again.

Several other considerations cause us to question the central venous pressure hypothesis. First, it is doubtful that all of the central veins will collapse at the instant intrathoracic pressure exceeds resting CVP. This would require the translocation of several hundred ml of blood, which would take a minimum of two seconds (200 ml at 100 ml/sec). Therefore, if only a small segment of the central veins collapses instantaneously (say, at or near the right atrium), the essential question is this: Is the observed transient cessation of peripheral venous flow during a forced expiratory maneuver due to this possible central venous segment collapse, or is it due to some other mechanism? We will discuss alternate explanations of the observed phenomena below.

MEAN SYSTEMIC PRESSURE HYPOTHESIS

During a Valsalva maneuver (forced expiration against a closed glottis) the mean value of right atrial pressure rises above its resting value for the duration of the maneuver [9, p. 305]. Since the maneuvers performed by our subjects in obtaining the data for the relative mean venous velocity - mouth pressure curves are essentially graded Valsalva maneuvers, we may be perturbing RAP away from its resting value in an amount predictable by the value of the change in mouth pressure during the maneuver. Because of this possibility, we are led to consider the relationship between our $\bar{v}_R - P_M$ curves and Guyton's venous return curves [10], [11, pp. 177-208].

Guyton's work in open-chest dogs involved replacing the right ventricle with an external perfusion system which allowed him to manipulate the dog's

right atrial pressure (RAP) at will and at the same time measure the mean volumetric flow rate in the external circuit with a rotameter. At equilibrium the flow rate measured in this manner was equated with venous return. By measuring venous return at various values of RAP under conditions which allowed him to maintain a constant, normal vasomotor tone in the experimental animal, Guyton was able to generate a venous return curve for each of 26 open-chest dogs. These curves were averaged by weighting each point on these plots of venous return vs. RAP in proportion to the weight of the animal. The result was an average normal venous return curve for the open-chest dog. Using a not altogether convincing argument, he then extrapolated this result to obtain a predicted venous return curve for the intact dog. Finally, using even less convincing reasoning, Guyton presented his predicted venous return curve for the intact human (see Fig. 3) [10], [11, p. 186]. The merits of Guyton's extended series of extrapolations will not be considered in detail here, but it appears that the general shape of his predicted human venous return curve is not so much in question as is the value of the intercept of the curve on the RAP axis.

Since the shape of Guyton's venous return curve for positive RAP's is similar to our $\bar{v}_R - P_M$ curves and since there appears to be some correspondence between the techniques used to obtain these two types of curves (manipulation of the RAP and measurement of venous flow), we are led to compare the RAP intercept of Guyton's curve with the P_M intercept of our curve. Guyton claims that the end-point of the curve at zero venous return corresponds to the point at which RAP equals mean systemic pressure (MSP), which he defines as "the pressure in all parts of the systemic circulation when all blood flow ceases" [11, pp.

187-188]. This claim is based upon both a simplified algebraic analysis of the circulatory system [11, pp. 257-266] and direct measurement of MSP in dogs after cessation of heart pumping [12]. Even though there appears to be a numerical correspondence between the directly measured average MSP in the dog and the RAP intercept of the average open-chest canine venous return curve, (approximately 7 mm Hg in each case), we have some doubts as to both the theoretical basis for this correspondence and the practical correspondence between the two values if measured in the same animal under the same conditions.

At this point if we do accept Guyton's hypothesis that the RAP intercept of the venous return curve is equal to MSP, what then is the relationship between MSP and the P_M intercept (P_{M_I}) of our $\bar{v}_R$-P_M curves? If there is a one-to-one correspondence between the stepwise change in mouth pressure and the initial change in RAP during a forced expiratory maneuver, then the value of mouth pressure when venous return is zero may equal the difference between MSP and the resting value of RAP. This results from the fact that the zero value of P_M by definition occurs when RAP is at its resting value. If any change in P_M away from zero results in a change of identical magnitude in RAP away from its resting value, then when RAP is brought up to the value of MSP and venous return is zero, P_M at this point will be equal to P_{M_I}. Since RAP has undergone a change equal to the difference between its resting value and the value of MSP and P_M has undergone an identical change from zero to P_{M_I}, we can equate P_{M_I} to the quantity (MSP - resting RAP). Guyton has termed this difference the "pressure gradient for venous return" [11, p. 200], which we have shortened to venous return pressure (VRP) (see Fig. 3). If P_{M_I} as determined by our technique is equal to or is a reliable estimator of VRP,

then it may be of some significance to the clinician in assessing cardiovascular function.

PERIPHERAL VENOUS PRESSURE HYPOTHESIS

Guyton claims that the normal resting RAP in the human is 0 mm Hg [11, p. 146] and that the normal MSP in man is 7 mm Hg [11, p. 186]. Therefore, Guyton's data would indicate that the normal VRP for man should be 7 mm Hg or approximately 9.5 cm H_2O. Our measurements from the $\bar{v}_R - P_M$ curves for five normal subjects give a range of P_{M_I} from 16.9 cm H_2O to 33.2 cm H_2O with a mean value of 26.2 cm H_2O. Although this sample size is too small to make a statistically meaningful comparison, it appears that unless Guyton's prediction of the normal value of MSP is grossly in error, P_{M_I} as measured by our technique may not be an accurate estimator of VRP. A re-examination of Rositano's original work [2] and an analog computer circulatory model study [13] have led us to another possible explanation for the $\bar{v}_R - P_M$ curve.

Rositano originally stated, "If the lung pressure is increased, blood flow toward the heart in a vein, say at the arm, will cease when the arm-heart level differential [venous] pressure is zero" [2]. If Rositano's assumption is taken at face value and if we again may assume that $\Delta RAP/\Delta P_M$ is unity, then P_{M_I} may actually be the difference between the mean value of the peripheral venous pressure at the point where the velocity is being measured and resting RAP. This interpretation requires the further assumption that the vein is not appreciably collapsed between the position of velocity measurement and the right atrium. Under these conditions we may hypothesize that flow at a particular point in the periphery will become zero only when the pressure gradient between that point and the right atrium is zero. Since our velocity measurements are made very rapidly after the beginning of the forced expiratory maneuver (presumably before the peripheral venous pressure at the point of measurement

is altered), then we may be able to interpret P_{M_I} as the value of the pressure gradient from that point in the periphery to the right atrium under resting conditions.

FURTHER INVESTIGATIONS AND POSSIBLE CLINICAL APPLICATIONS

During the next report period we plan to conduct investigations which will allow us to formulate with some certainty the biophysical mechanisms involved in a Valsalva-type maneuver in man. We will then be able to judge the clinical significance of our technique.

We are presently in the process of further studies with the analog computer model developed by one of us [13]. We hope that these investigations will give us some further insights as to the merits of and the relationships among the three hypotheses discussed above. Our initial results from this model have given credence to the peripheral venous pressure hypothesis and have caused us to have serious doubts about much of Guyton's ideas concerning mean systemic pressure.

We are investigating the usefulness of constructing a hydraulic model similar to that used by Holt to study collapsible tube flow [14]. This type of apparatus would allow us to investigate the central venous pressure hypothesis without invoking as many of the simplifying assumptions as required for our analog computer model. Simultaneously we could measure pressure and flow at various points along the tube and obtain data much the same as one would from a catheterized human subject [9], but without the hazards involved.

We have also given some consideration to radiographic studies in either dogs or humans to observe the dimensional alterations in the central veins during a forced expiration. This procedure may not be necessary if we are able to judge the central venous pressure hypothesis in an indirect manner, and in any event we may not be able to visualize the central veins with suf-

ficient resolution using this technique to make a conclusive decision concerning central venous collapse during a Valsalva-type maneuver.

Two of our hypotheses depend upon knowledge of the relationship between mouth pressure and RAP during a Valsalva-type maneuver. Wells [15] has investigated the effect on RAP of sinusoidal variations in airway pressure in dogs. However, since the linearity of the system in question is highly doubtful, it would be unwise to attempt to transform his results from the frequency domain into the time domain. Therefore, one of our highest priorities is to measure the changes in RAP directly in man during a forced expiratory maneuver. We are making arrangements with the cardiac catheterization lab at the University of Wisconsin Medical Center to perform these measurements on consenting patients who are undergoing cardiac catheterization for other purposes. We plan to obtain $\bar{v}_R - P_M$ curves on several of these patients and at the same time record RAP at each value of mouth pressure. The results from these trials should provide us with enough information to understand the mechanisms underlying our technique.

It may be premature to speculate at this time concerning the applicability of our technique to clinical medicine. However, we can mention possible applications of the three pressure measurements hypothesized above. Certainly, if we are able to measure the resting value of CVP noninvasively, the clinician will be provided with a nontraumatic alternative to central venous catheterization when he deems this measurement necessary [16], [1]. Although mean systemic pressure and the related venous return pressure are parameters not commonly recognized by the clinician, Guyton's work indicates that VRP may be a more valuable index than CVP when attempting to assess the adequacy of systemic tissue perfusion [11, pp. 200-201]. If, in the final analysis, the peripheral venous pressure hypothesis proves to be correct, then the noninvasive measure-

ment of a venous pressure gradient from a point in the periphery to the right atrium may be only as valuable as its ability to estimate venous return pressure.

We believe that during the next six months our tests will enable us to answer many of the questions posed above.

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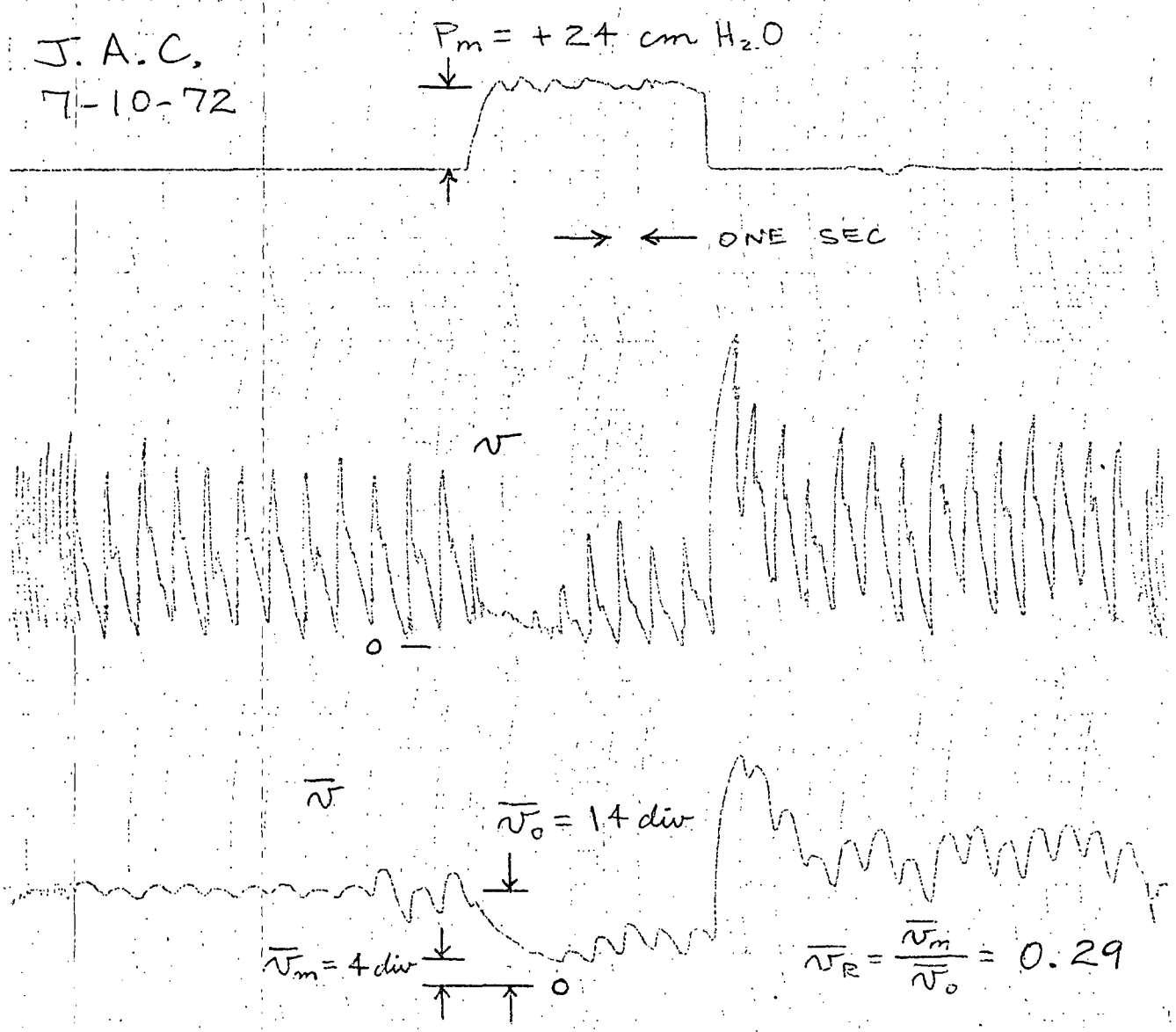
FIGURE CAPTIONS

Figure 1. Typical record of mouth pressure (P_M), instantaneous jugular venous velocity (v), and mean jugular venous velocity ($\bar{v}$) during a Valsalva-type maneuver in man. $\bar{v}$ is a low-pass version of v (RC time constant = 0.53 sec). $\bar{v}_o$ is the value of $\bar{v}$ just before initiation of the maneuver, and $\bar{v}_m$ is the minimum value of $\bar{v}$ during the maneuver. The minimum relative value of $\bar{v}$ ($\bar{v}_R$) is computed from the ratio $\bar{v}_m/\bar{v}_o$.

Figure 2. Typical plot of the minimum value of the relative mean venous velocity ($\bar{v}_R$) vs. the peak value of mouth pressure (P_M) during a forced expiratory maneuver in man. The subject was a 23-year old male (same subject as used for data in Fig. 1). Venous velocity was monitored at the right external jugular vein. The regression curve was calculated from a least squares analysis of the data points.

Figure 3. Guyton's predicted venous return curve for the intact human [11, p. 186]. Guyton argues that the intercept of the curve on the RAP axis is both empirically and theoretically identical to mean systemic pressure. The scale below the abscissa shows how the mouth pressure scale would align with the RAP scale if $\Delta RAP/\Delta P_M$ were unity and resting RAP were zero. For a different value of resting RAP the zero of the P_M scale would line up with that value, but under all conditions venous return pressure (the difference between MSP and resting RAP) would be numerically equal to P_{M_I}.


J. A. C.
7-10-72
P_m = +24 cm H_2O
ONE SEC
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0
$\bar{v}$
$\bar{v}_0$ = 14 div
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0
$\bar{v}_R = \frac{\bar{v}_m}{\bar{v}_0} = 0.29$

Fig. 1

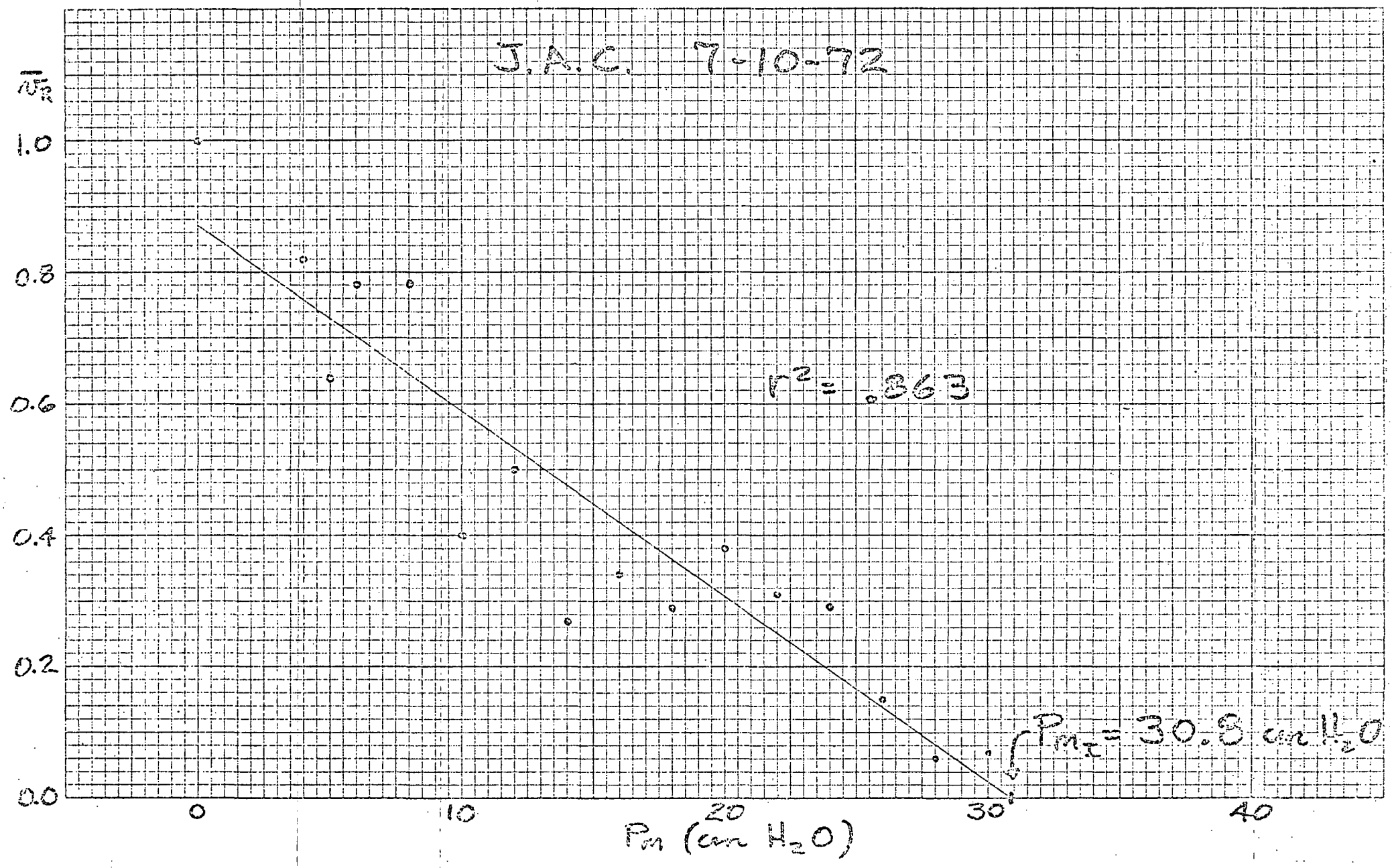
J.A.C. 7-10-72
$\bar{v}_R$
1.0
0.8
0.6
0.4
0.2
0.0
$r^2 = .863$
$P_{m_T} = 30.8$ cm H_2O
0
10
20
30
40
P_m (cm H_2O)

Fig. 2

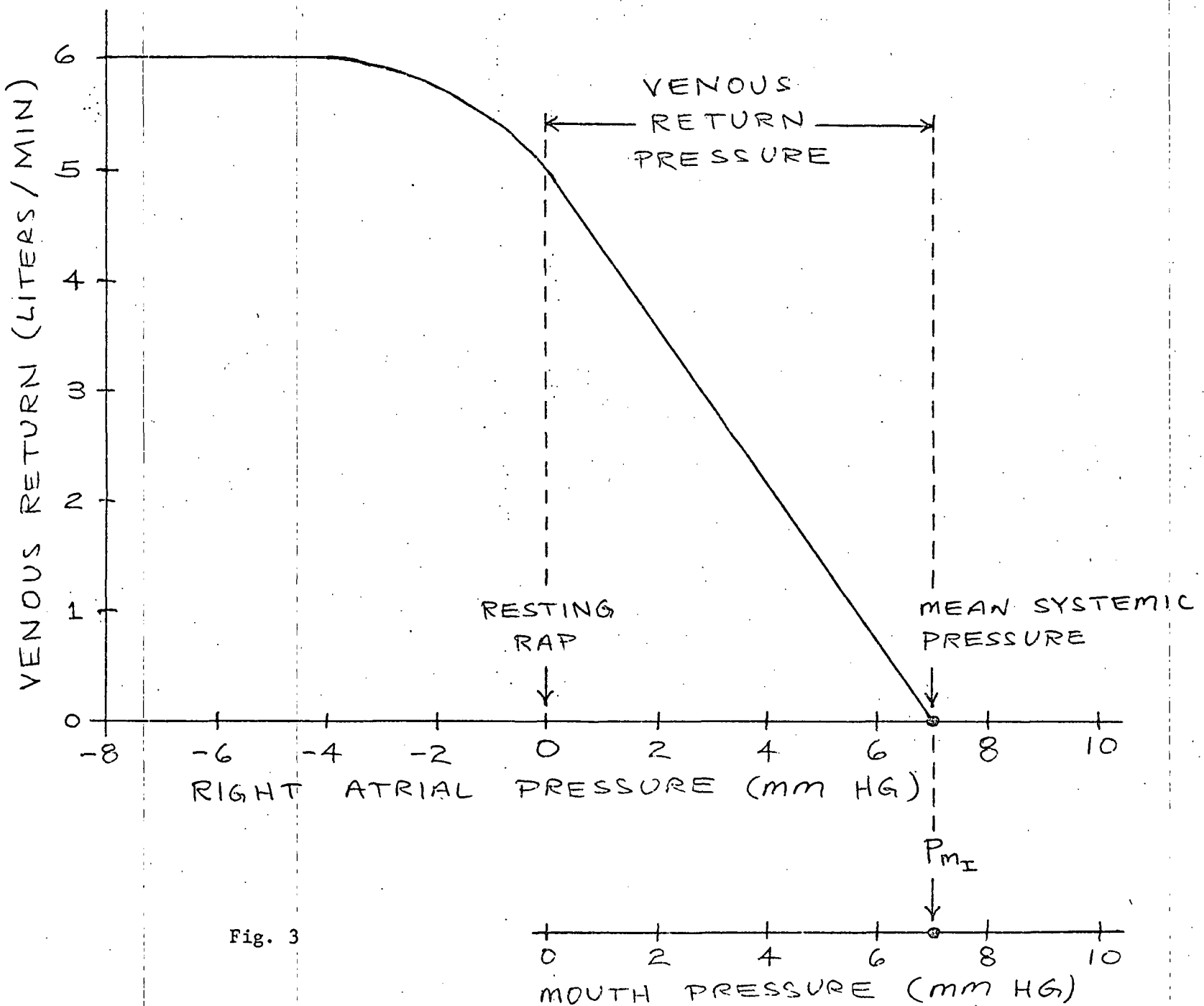
VENOUS RETURN (LITERS / MIN)
6
5
4
3
2
1
0
VENOUS
RETURN
PRESSURE
RESTING
RAP
MEAN SYSTEMIC
PRESSURE
-8
-6
-4
-2
0
2
4
6
8
10
RIGHT ATRIAL PRESSURE (mm HG)
P_{m_I}
0
2
4
6
8
10
MOUTH PRESSURE (mm HG)

Fig. 3