Clinical Significance of Mean Circulatory Filling Pressure and Cardiac Preload under Anesthesia

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The circulatory effects of a rapid infusion of plasma substitute with intravenous administration of nitroglycerine (TNG) were investigated in low pressure systems of anesthetized patients by measuring various hemodynamic parameters. Measurements were made when the systolic blood pressure reached 70–80% of the control value after intravenous administration of TNG at 1~2μg/kg/min and a 3.5% modified gelatin solution (Haemaccel®) at a rate of 0.5 ml/kg/min. After the TNG was administered, the mean circulatory filling pressure (Pms) decreased, and the venous to arterial capacitance ratio (C_V/C_A) increased; however, they returned to control values after a rapid Haemaccel® infusion. Changes in the pressure gradient between the X and Y valley of the right atrial pressure wave decreased to 70 ± 14% of the control value when TNG was given and recovered to 106 ± 22% by infusion. Pulmonary vascular resistance (PVR) decreased to 70 ± 24% of the control value when TNG was administered and was restored to 96 ± 40% by a rapid infusion. In the left ventricle, the mean velocity of myocardial circumferential fiber shortening (V_{CF}) decreased in all cases when TNG was given and it recovered by a rapid infusion. In the right ventricle, V_{CF} did not always decrease, and in a few case increased, but all cases recovered by a Haemaccel® rapid infusion. We conclude that the augmentation of the right ventricular preload reserve is achieved by administration of TNG and infusion of a plasma substitute.

(Key words: right atrial pressure wave, mean circulatory filling pressure, preload reserve, rapid infusion, nitroglycerine)

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As in the left ventricle of the heart (LV), the right ventricle (RV), stroke volume (SV) is governed by preload, afterload, contractility and heart rate. An increase in preload or contractility, or a decrease in an abnormally elevated RV afterload, all mediate improved RV ejection and SV[1]. Cardiac output best correlates with the preload of the ventricle. Cardiac pumping capability and the magnitude of the venous return determine the equilibrium level of the cardiac output[2].

This study was designed to assess the theory and method of circulatory management which does not cause overload on the right side of the heart in rapid infusion with augmentation of the right cardiac preload reserve[2] to counteract a sudden hypotension in the induction of anesthesia, and to evaluate the efficacy of maintaining RV preload and ejection due to volume loading with a colloidal solution, 3.5%

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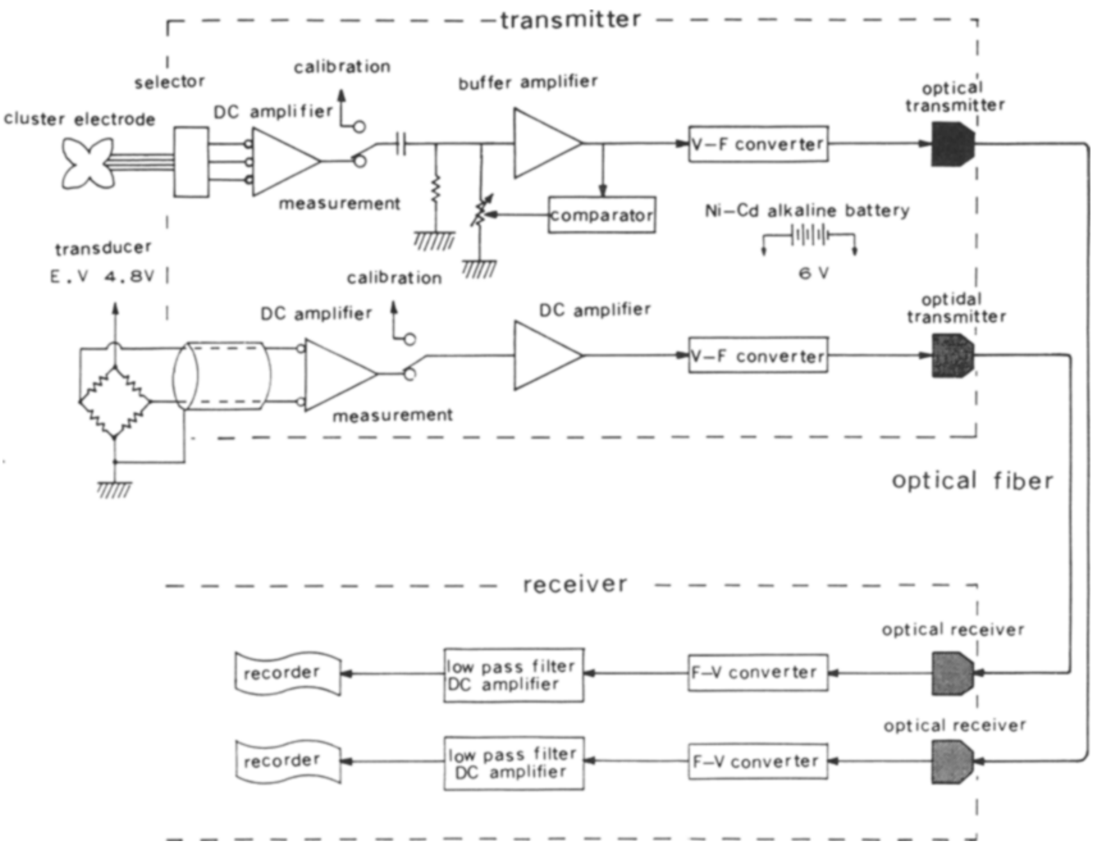


Fig. 1. Block pattern of the fiber optic electrocardiography and blood pressure measuring system

modified gelatin solution (Haemaccel®), under continuous nitroglycerine (TNG) infusion for prevention of increases in PVR and hypotensive response to hemodynamically unstable patients under anesthesia.

Materials and Methods

28 ASA I to ASA II class surgical patients, ranging in age from 39 to 86 years undergoing major surgeries, except thoracotomies and craniotomies in which direct pressure measurement is required, were studied. The instruments for measurements were specially designed using optical fibers to isolate the recorder and the amplifiers for Millar's micromanometer and an ECG completely from the ground. These modifications reduced common-mode noise, prevented non-linearity or rectification effects at skin-electrode points, offered accurate measurement of the right atrial pressure waves and excellent electrical safety[3] (fig. 1).

In order to determine the pre-ejection period and ejection time of the LV and RV, an intraesophageal electrocardiogram was also used to electromechanically analyze the pressure waves. A microcomputer, ATAC-450 (Nihon Koden), was used to determine the mean circulatory filling pressure (Pms)[4] and to calculate the effective circulating blood volume (Q)[5].

Right hemodynamic monitoring was performed in every patient by inserting a Swan-Ganz thermodilution catheter into the pulmonary artery through the right antecubital vein. Pulmonary artery and pulmonary capillary wedge pressures were recorded using a Data Recorder (SONY FE-30A) and a Polygraph system (HP 7758). Whenever possible, the right ventricular pressure was also measured on withdrawal of the catheter.

Cardiac output was determined by thermodilution, using an Edwards 9500 computer.

In every case, at least three successive measurements were made, and the average value was calculated.

The following measurements were made when the systolic blood pressure reached 70–80% of the control value after intravenous administration of TNG at 1–2μg/kg/min and it recovered by a following infusion of 3.5% modified gelatin solution at 0.5 ml/kg/min.

1) right atrial pressure (RaP) and its waves
2) pulmonary arterial pressure (PA)
3) pulmonary capillary wedge pressure (PCWP)
4) mean circulatory filling pressure (Pms)
5) venous to arterial capacitance ratio (C_V/C_A)
6) venous volume elasticity coefficient (Ev') dyne·cm^{-5}
7) pressure gradient between X and Y valley pressure values of the right atrium as a cardiodynamic index of the right atrium as a conduit[6]
8) pulmonary vascular resistance (PVR)
9) left ventricular ejection time (LVET)
10) right ventricular ejection time (RVET)[7]
11) pre-ejection period (PEP_L, PEP_R)
12) LVET/PEP_L, RVET/PEP_R (an index of myocardial contraction velocity of the ventricle.)

The effective circulating blood volume (Q) was then calculated from the venous pressure and its wave forms[5].

$$Q = Q_A + Q_V \quad (1)$$

$$C = C_A + C_V \quad (2)$$

$$\frac{Q_A}{C_A} = Q_A \cdot E'_A \quad (3)$$

$$\frac{Q_V}{C_V} = Q_V \cdot E'_V \quad (4)$$

Rearranging equation (1) ~ (4)

$$Pms = \frac{Q}{C} = \frac{Q_A + Q_V}{C_A + C_V} \quad (5)$$

$$\therefore Q = \frac{Pms}{E'_V}\left(1 + \frac{C_A}{Q_V}\right) \quad (6)$$

Q: Total blood volume (hemodynamically effective circulating)

Q_A, Q_V: Arterial and venous Q

C: Capacitance

C_A, C_V; Arterial and venous capacitance

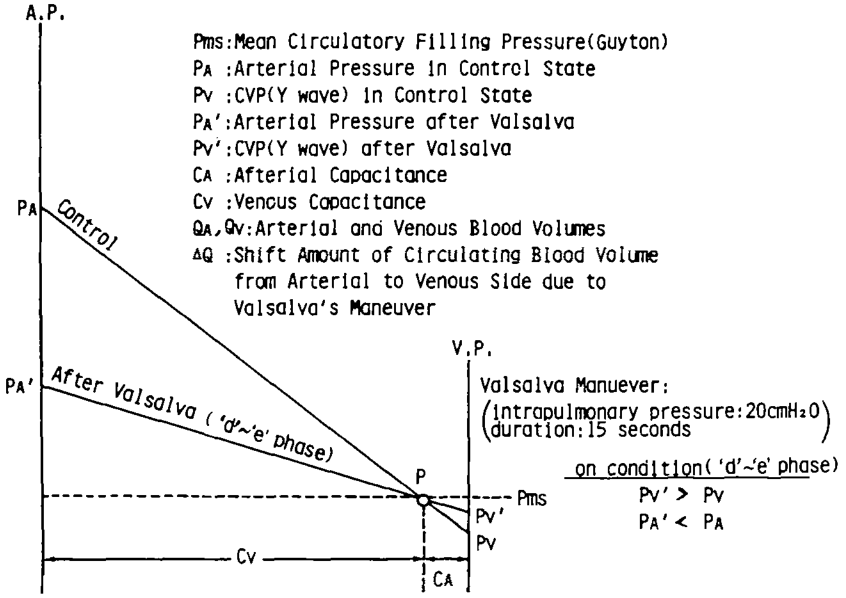
E'_A, E'_V: Volume elasticity coefficient of arteries and veins

Pms: Mean circulatory filling pressure

The venous volume elasticity coefficient (E_V')[5] was calculated from the change in the right atrial pressure Y valley wave after 5 ml/kg of the modified gelatin solution was administered. The effects of TNG on preload and afterload change, particularly during rapid infusion of a plasma substitute, were studied in relation to the concepts of afterload matching and preload reserve[2] in both the right and left cardiac systems.

Mean circulatory filling pressure (Pms) is regarded as the pressure energy source of venous return. Guyton[8] defined Pms as the value obtained at the moment when the intravascular pressure has equalized everywhere under cardiac arrest. Clinically however, it is necessary to measure Pms when the heart is functioning, thus the development of methods for clinical measurement of Pms was necessiated. The method we devised is based on Hori's theory: graphic estimation of Pms by measurement of the systolic blood pressure and the right atrial pressure Y wave at two points[9]. These points become the control state and circulatory equilibrium after transitorily disturbing the equilibrium of the cardiovascular system by Valsalva's maneuver. Valsalva's maneuver was applied with 20cmH_2O of endotracheal pressure for 15 seconds under endotracheal anaesthesia. Under halothane anaesthesia, this does not change sympathetic activity but may impede the outflow from the right ventricle by decreased RV filling[10-14].

In fig. 2, the systolic blood pressure and the right atrial pressure Y wave, before Valsalva's maneuver, are plotted on the left and right ordinates, respectively. The same procedure is repeated at the new circulation equilibrium which is attained at the 'd' → 'e' phase (Scott DB, 1969)[10], immediately after Valsalva's maneuver is released. Hori[9], and Muteki[4,6,15] demonstrated theoretically that Pms can be estimated by drawing a line parallel to the abscissa from the intersecting point to the ordinate of venous pressure. Furthermore, the venous-arterial capacitance (C_V/C_A) ratio can be estimated by drawing vertical line from the intersecting point the abscissa.



$$\frac{P_A - P_A'}{P_A' - P} = \frac{P_V' - P_V}{P - P_V'} \qquad \therefore P = \frac{P_A' P_V - P_A P_V'}{P_A' - P_A + P_V - P_V'} \quad (1)$$

where,

$$\left.\begin{aligned} P_A &= \frac{Q_A}{C_A} \\ P_V &= \frac{Q_V}{C_V} \end{aligned}\right\} (2) \qquad \left.\begin{aligned} P_A' &= \frac{Q_A - \Delta Q}{C_A} \\ P_V' &= \frac{Q_V + \Delta Q}{C_V} \end{aligned}\right\} (3)$$

substitute (2) and (3) equations to (1), and rearrange

$$P = \frac{Q_A + Q_V}{C_A + C_V} = P_{ms}$$

Fig. 2. Clinical measurement of mean circulatory filling pressure (Pms) and capacitance ratio of venous to arterial vessel (C_V/C_A)
Hori's theory to estimate Pms by measuring systolic blood pressure and the right atrial pressure Y wave at two points. (Reproduced by Hori M:Venous return. Respiration and Circulation 20:644 656, 1972)

Statistics

The significance of the differences between the control, TNG and the rapid infusion groups (i.e. Pms, PVR, Q, C_V/C_A and |Y-X|) were determined by analysis of variance using Willcoxon's method or Student's t-test, assuming $P<0.05$ to be statistically significant.

Results

Pms decreased when TNG was administered, and recovered to the control level when a modified gelatin solution was adequately infused. C_V/C_A increased remarkably to 368 ± 37% of the control value when TNG was administered and recovered to 140 ± 31% of the control value when a modified gelatin solution was rapidly infused (fig. 3).

The effective circulating blood volume (Q) was 50.7 ± 16.0 ml/kg when calculated by cardiodynamic analysis of the changes in the central venous pressure (Y valley) and pressure waves when a fixed volume of solution (5 ml/kg) was infused. Changes in the pressure gradient between the X and Y valleys of the right atrial pressure waves were found to be linked with the conduit function of the right atrium. They decreased to 79 ± 14% of the control value when

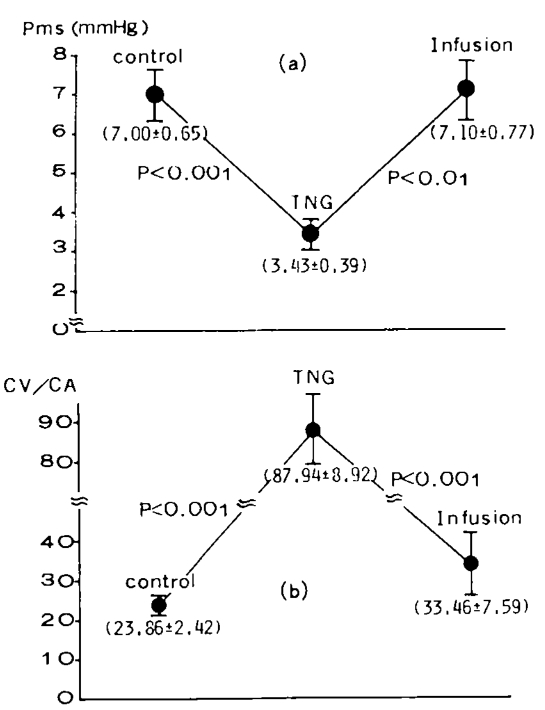


Fig. 3. Change of Pms and C_V/C_A due to a rapid infusion of plasma substitute with nitroglycerine

(a) Mean circulatory filling pressure (Pms) decreased significantly when TNG was administered and increased significantly by infusion.

(b) Capacitance ration of venous to arterial vessel (C_V/C_A) increased significantly when TNG was administered and recovered to the control level by infusion.

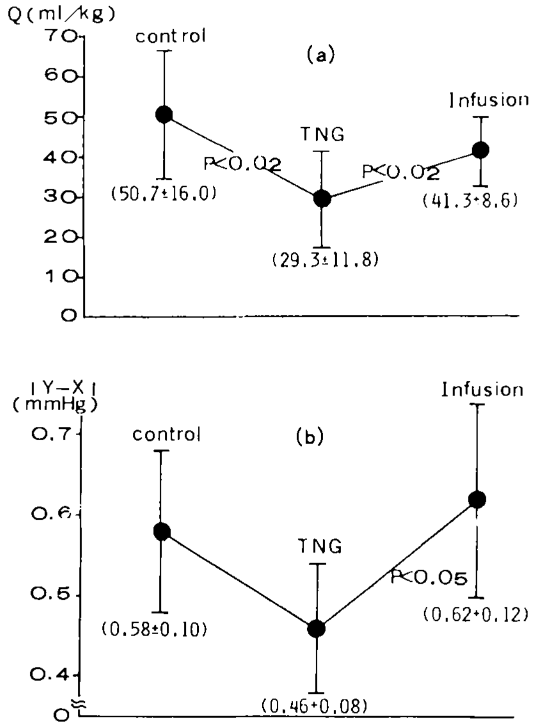


Fig. 4. Change of circulating blood volume (Q) and |Y-X| due to a rapid infusion of plasma substitute with nitroglycerine

(a) Circulating blood volume (Q) decreased when TNG was administered, and increased by infusion.

(b) Pressure gradient between the right atrium X and Y valley pressure values of the |Y-X| decreased when TNG was administered and recovered by infusion.

TNG was administered, but recovered to 106 ± 22% when a modified gelatin solution was infused (fig. 4).

PVR decreased to 70 ± 24% of the control value when TNG was given, and increased thereafter to 96 ± 40% of the control value by rapid infusion of modified gelatin solution. The ejection fraction of the left ventricle also decreased when TNG was given, but almost recovered to the control level by infusion (fig. 5).

Changes in the cardiodynamics caused by rapid infusion of a modified gelatin solution were determined by afterload and myocardial circumferential fiber shortening velocity (V_{CF}) after TNG was administered. V_{CF} was substituted by LVET/PEP[16]. The relevant coordinates in the right side of the heart were also studied, to compare the relationship between both sides of the heart. Afterload in the right side of the heart was studied in relation to the pulmonary arterial pressure. As a result, a decline in the mean V_{CF} which denotes afterload mismatch in an rapid infusion was minimized by the administration of TNG (fig. 6).

In order to schematize the relationship between preload and afterload in the heart, stroke volume (SV) was expressed by:

$$SV = \text{Preload} - \frac{\text{Afterload}^{17}}{\text{Emax}}$$

Thus, the proper ventricular pump function to counteract anestheticaly induced circulatory

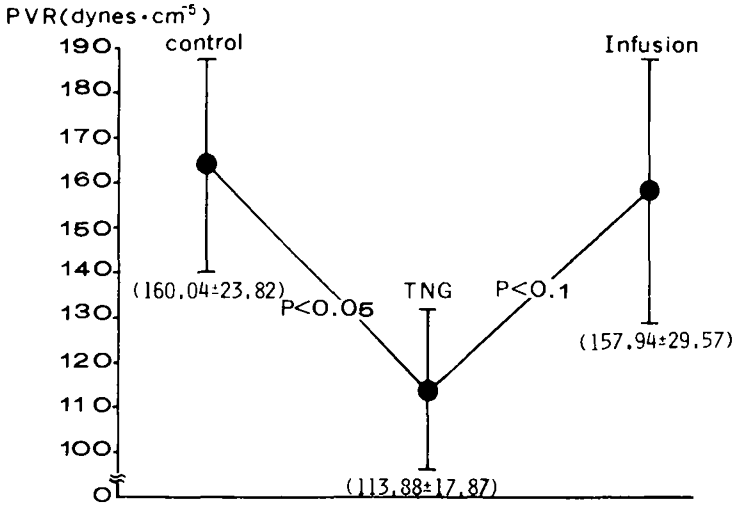


Fig. 5. Change of pulmonary vascular resistance due to a rapid infusion of plasma substitute with nitroglycerine
PVR decreased significantly when TNG was administered and recovered to the control level by infusion.

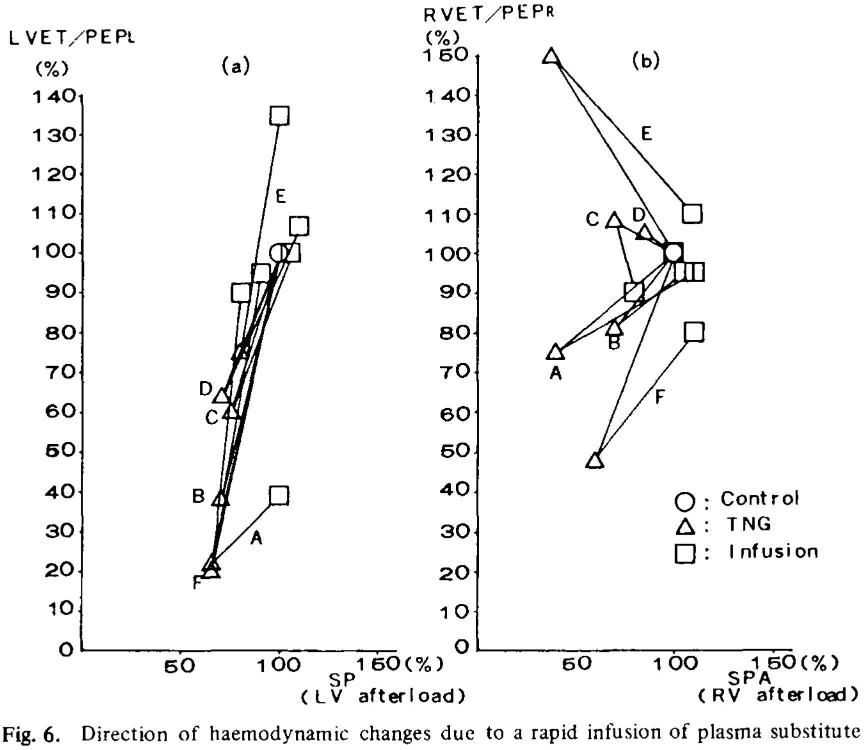


Fig. 6. Direction of haemodynamic changes due to a rapid infusion of plasma substitute with nitroglycerine on the force and velocity diagram during ejection in the left and right ventricles

(a) Left ventricle: LVET/PEP (V_{CF}) decreased in all cases when TNG was administered and almost recovered with rapid infusion.

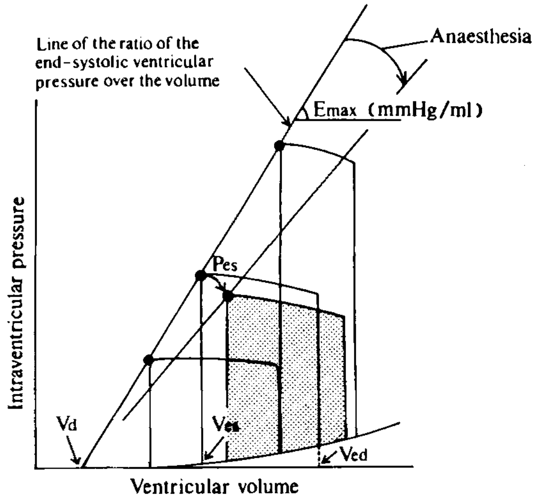
(b) Right ventricle: RVET/PEP (V_{CF}) indicated various change in the co-ordinate with decreased pulmonary artery pressure due to administration of TNG, but all recovered to the control with rapid infusion.

disequilibrium is maintained by the retained Emax (myocardial contractility when preload is increased by transfusion and PVR (afterload) is lowered by TNG administration) (fig. 7).

Discussion

There is still very little clinical information available concerning the hemodynamics of the venous system in patients during surgery, and accurate clinical evaluation is also lacking. In order to obtain accurate information on central venous pressure (CVP) during surgery, specially designed instruments were used. Millar's micromanometer, which has the highest fidelity for measuring pressure waves, was used to measure the right atrial pressure (CVP). An amplifier, with an optical fiber was devised, with excellent antinoise characteristics, especially against high frequency range noises. This equipment allowed accurate and safe measurements during surgery[4,6,15].

From viewpoint of the circulatory equilibrium[18], the clinical significance of the mean circulatory filling pressure (Pms) particularly in case of circulatory management during an operation has not yet been fully studied. Pms was originally defined as the pressure that would be measured at all points in the entire circulatory system if the heart were stopped suddenly and the blood were redistributed instantaneously in such a manner that all pressure were equal[8]. In cases of intraoperative circulatory management, Pms must be measured under the heart beat[4,6,15]. Therefore, a micro-computer (ATAC-450) was used for graphic analysis measurements of the circulatory disequilibrium during recovery from rapid changes in the arterial systolic pressure, CVP and Y valley pressure (Y_{Ra}) after the passive Valsalva's maneuver under endotracheal anesthesia with an endotracheal pressure increase ($20 cmH_2O$ for 15 seconds) had been performed. We called the Pms, obtained under the heart beat, the dynamic mean pressure of the systemic circulation (dynamic Pms)[6,19] Thus, we measured dynamic Pms during operations to evaluate cardiovascular functions with concept of circulatory equilibrium between high and low pressure systems under anesthesia and investigated its changes, depending on the hemodynamic changes under the influence of various anesthetic factors. We recognized with the previous study that it decreases under spinal anesthesia, recovers by rapid fluid infusion, increases with catecholamine preparations, and diminishes with TNG[6,15].



$$\mathrm{Emax} = \frac{\mathrm{Pes}}{\mathrm{Ves} - \mathrm{Vd}} \quad \cdots\cdots ①$$

$$\text{Stroke Volume (SV)} = \mathrm{Ved} - \mathrm{Ves} \quad \cdots\cdots ②$$

From ① and ② equations,

$$\mathrm{SV} = \mathrm{Ved} - \mathrm{Vd} - (\mathrm{Pes} / \mathrm{Emax}) \quad \cdots\cdots ③$$

Rearrange the expression,

$$\boxed{\mathrm{SV} = \text{Preload} - \text{Afterload} / \mathrm{Emax}}$$

Pes : End-systolic ventricular pressure
Ves : End-systolic ventricular volume
Ved : End-diastolic ventricular volume
Vd : Ventricular volume at the point of intersection of the Emax line

Fig. 7. Effects of anaesthesia on Emax
Emax is depressed by anestheisa which diminishes myocardial contractility and reduces ventricular stroke work. Rapid infusion with TNG under anesthesia may augment preload reserve.

Considering jointly the conservation of the right atrial function, right cardiac function (force-velocity relation coordinates) and dynamic Pms it is thought that the infusion solution stabilized the dynamic Pms under the administration of TNG and extends the limit of the preload reserve, which can prevent a rapid change in the blood pressure at the time of inducing anesthesia and the like. Therefore, the measurement of new hemodynamic indices, obtained by the analysis of the CVP wave form, in addition to the blood pressure, pulse, etc., in case of intraoperative circulatory management, seems very useful for a more precise and versatile evaluation of hemodynamics form the viewpoint of circulatory equilibrium.

In circulatory management under anesthesia, it was theoretically ideal when preload was maintained at a fixed level in order to maintain SV and recover the decline in Emax (Suga H)[17] due to anesthesia, thus reducing afterload. It is, therefore, desirable to administer TNG (0.5–2.0 μg/kg/min) to augment preload and prevent excessive volume load due to rapid infusion of a solution beyond the limits of preload reserve[20].

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