ADVANCED LUNG-VENTILATOR SYSTEM (ALVS) FOR CONTROLLED BREATHING OPTIMIZATION

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Abstract: An advanced lung-ventilator system (ALVS) properly designed for the optimization of conventional dual-controlled ventilation (DCV) and of new airways pressure waveforms with more physiological shape has been tested on simulators of respiratory system in order to evaluate its clinical application.

A compensation procedure making the chosen airways pressure waveform independent of patient airways resistance and lung compliance variations along with a complete real-time monitoring of respiratory system parameters are the innovative functional features implemented.

The preliminary experimental results show that ALVS performance is useful for the research activity concerning with the improvement of both diagnostic evaluation and therapeutic outcome relative to mechanical ventilation treatments.

Introduction

Since the introduction of artificial respiration, the design and the functional features of lung ventilators have been undergone a continuous evolution and improvement till today [1]. The recent developments of technology have yielded electro-mechanical devices able to perform the automatic control of artificial ventilation through microprocessor feedback acting between preset and actual measured values of the basic physical parameters [2,3]. Nevertheless the crucial still unsolved question is the optimal choice of ventilation modality and parameters setting to be apply to the specific patient and pathology [4-6]. The present paper deals with the design of an advanced lung-ventilator system (ALVS) conceived for analysis and control of improved artificial ventilation.

The ventilators currently used in the clinical practice for controlled breathing provide for two different ventilation modality: volume-controlled ventilation (VCV) and pressure-controlled ventilation (PCV), which are implemented with constant inspiratory flow and airways pressure, respectively [3,7-11]. Moreover, the waveform of the physical parameter (flow or pressure) controlled by the ventilator are fixed on account of simplified hardware and software design. For this reason the ventilator performance and its possible versatility are drastically reduced.

The aim of the present work consists in developing a system (ALVS) which implements the dual-controlled ventilation (DCV), i.e. the pressure-controlled ventilation with ensured tidal or minute volume, including the waveform optimization procedure [12-14].

Materials and Methods

The main functional units making up the ALVS, shown in the Fig. 1 along with their physical connection, are represented by the implementation of the following three devices: a) stationary and transient flow generator stabilizer (STFGS); b) time-varying airways pressure stabilizer (TVAPS); c) dynamic respiratory system simulator (DRSS).

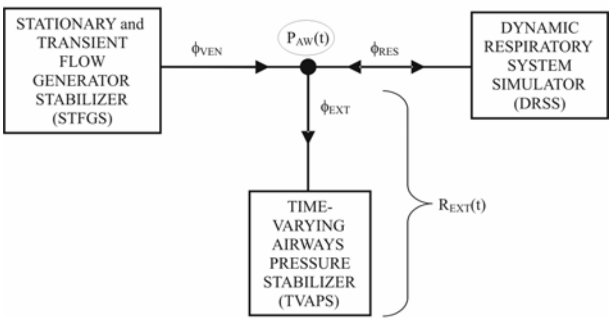

Figure 1: The advanced lung-ventilator system (ALVS). The STFGS, TVAPS and DRSS units along with significant ventilation parameters considered in the text (ϕ_{VEN}; ϕ_{EXT}; ϕ_{RES}; $P_{AW}(t)$; $R_{EXT}(t)$) are pointed out.

The ALVS design has been carried out in order to put in practice the DCV ventilation including the following functional performances: 1) capability of applying to the patient airways any pressure waveform of clinical interest during both the inspiration and the expiration time; 2) insensitivity of such waveform in shape and intensity to the load (respiratory parameters of patient) fluctuations or variations; 3) capability of monitoring the waveform of pressure (airways and endoalveolar), flow and lung volume as a function of

ISSN: 1727-1983

time together with the loop of pressure (airways and endoalveolar) and flow as a function of lung volume, as well as power of calculating the current value of inspiratory and expiratory airways resistance, static and dynamic lung compliance and respiratory work; 4) compatibility of spontaneous breathing activity of patient by flow or pressure support ventilation with assisted/controlled breathing or/and triggered ventilation [15,16].

As it is clear observing the Fig. 1, the points 1) and 2), i.e. the application of the pre-established airways pressure waveform ($P_{AW}(t)$) and its keeping irrespective of the current value assumed by any other pre-set parameter as well as of load (airways resistance and lung compliance) fluctuations or variations, can be achieved by means of a steady flow (ϕ_{EXT}) crossing a time-varying fluidodynamic resistance ($R_{EXT}(t)$). The regulation and the control of the steady flow and of the fluidodynamic resistance is implemented inside the STFGS and the TVAPS, respectively.

The Fig. 2 shows the coupling between the STFGS, the TVAPS and the DRSS and their internal configurations including the monitoring system and two on-off flow switches (S1, S2).

The monitoring system, required for meeting the above mentioned point 3), consists of two sensors for forward or ventilation (ϕ_{VEN}) and backward or external (ϕ_{EXT}) flow measurement together with two sensors for airways (P_{AW}) and endoalveolar (P_{EA}) pressure measurement [17].

The measurement of lung volume (V_P) as well as the detection of tidal or minute volume are performed by the ALVS monitoring system through the time integration of the difference between ϕ_{VEN} and ϕ_{EST}. Such difference equals the respiratory (ϕ_{RES}) i.e. the flow crossing the airways resistance.

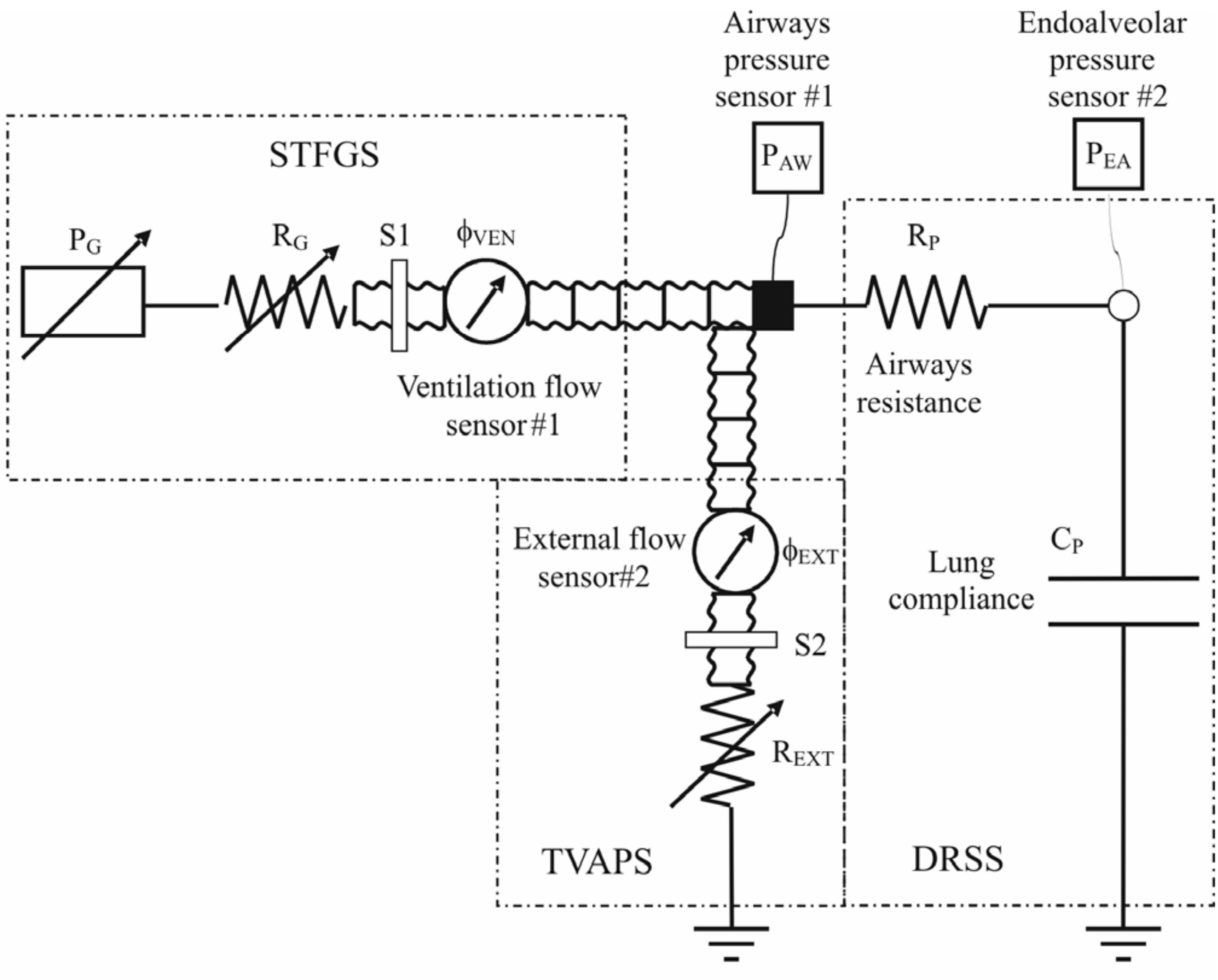

Figure 2: Internal configuration of the STFGS, TVAPS and DRSS units including the monitoring system of the ALVS. The components crossed with folded arrows are devices whose characteristic parameter output can be varied according to input setting control.

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The STFGS consists of the series between a variable pressure generator (P_G) and its time-varying resistance (R_G).

The TVAPS implements a time-varying resistance ($R_{EXT}(t)$) placed between airways and ground (atmospheric) level.

The DRSS includes a variable resistance (R_P) connected in series with a variable elastic compliance (C_P) simulating, respectively, the airways resistance and the lung compliance of a wide variety of patients and pathologies. The simulator device adopted is extremely simple but it is adequate for treating all the cases of patients with homogeneous respiratory features [16].

The STFGS has been specially designed for independent stabilization of the flow crossing the TVAPS (ϕ_{EXT}) both in stationary and in transient conditions. The stationary and the transient conditions occur when ϕ_{RES} is zero or not, respectively, on account of zero or non zero difference between P_{AW} and P_{EA}, respectively.

During stationary conditions the STFGS delivers to the TVAPS the steady flow required for the control and the stabilization of pre-established positive end expiratory airways pressure ($PEEP_{EXT}$) on account of each previous monitored expiration. $PEEP_{EXT}$ control and stabilization irrespective of load fluctuations or variations is actually carried out through the regulation of P_G, R_G and R_{EXT} equilibrium values.

The transient conditions are correlated to the presence of non zero ϕ_{RES} during both inspiration (ϕ_{INS}) and expiration (ϕ_{EXP}), occurring when P_{AW} is increased from $PEEP_{EXT}$ up to its maximum value and soon after decreased down to the same $PEEP_{EXT}$ value, respectively.

Thus, the presence of non zero ϕ_{RES}, if not compensated, would brings about a fluctuation of ϕ_{EXT} around its equilibrium value and in turn a $P_{AW}(t)$ distortion if compared to that resulting from the product of ϕ_{EXT} equilibrium value with selected R_{EXT} waveform ($R_{EXT}(t)$).

In summary, ϕ_{EXT} fluctuation alters significantly $P_{AW}(t)$ which is intended to apply and makes it dependent on the respiratory characteristics of patient (R_P; C_P).

In order to maintain across the TVAPS the same level of steady flow during transient conditions also, the STFGS puts into practice a compensation procedure as follows.

The ϕ_{EXT} is kept steady on controlled ϕ_{EXT} equilibrium value by modelling the ϕ_{VEN} waveform around ϕ_{VEN} equilibrium value on account of the instantaneous ϕ_{RES}, and P_{EA} values as well as R_{EXT}/R_P ratio. The modeling of ϕ_{VEN} waveform intensity and shape during breathing is performed through the regulation around R_G equilibrium value.

The compensation procedure just described acts during the controlled breathing itself and it is based on feedback process minimizing the difference between current monitored and desidered $P_{AW}(t)$. The compensation procedure, providing for steady and stabilized ϕ_{EXT} level during all the time of ventilation, makes possible the desidered shape of $P_{AW}(t)$ excitation during both inspiration and expiration through an identical shape of $R_{EXT}(t)$.

The intensity of $R_{EXT}(t)$ is controlled via feedback process minimizing the difference between desidered and measured tidal or minute volume delivered to the patient (dual control). The above mentioned point 4) can be easily met with the implementation of particular $R_{EXT}(t)$. For instance, the patient can be treated with the conventional CPAP (Continuous Positive Airways Pressure) or BILEVEL/BIPAP (two levels of Continuous Positive Airways Pressure) ventilation setting R_{EXT} on a single constant value for all the time or on two different constant values for two consecutive time intervals, respectively.

If required, the compensation procedure can be apply in these cases also.

If useful, as for the measurement of both inspiratory and expiratory airways resistance, static lung compliance and intrinsic or auto positive end expiratory pressure, the STFGS and the TVAPS can be disconnected at any time from the DRSS (patient) by means of the on-off flow switches S1 and S2, respectively.

The theory of the problem is based on analytical treatment of the physical model implemented by the ALVS design [15-18].

The electrical-equivalent network of the ALVS used for analyzing and solving the theoretical problem is shown in the Fig. 3.

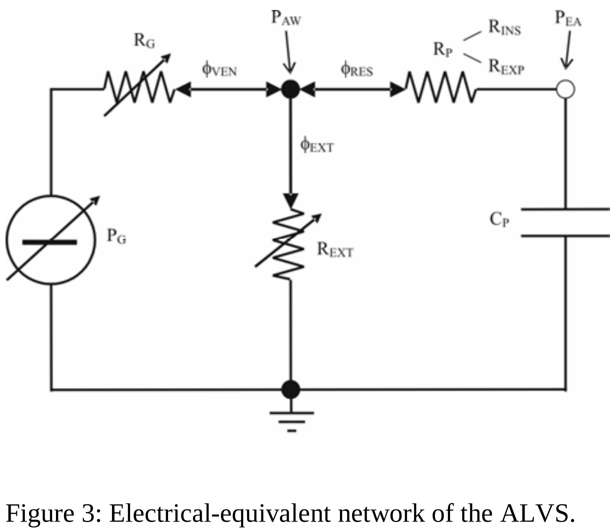

Figure 3: Electrical-equivalent network of the ALVS.

The rightness of the adoption of such model comes from the equivalent behaviour exhibited by fluidic and electrical circuits inside the conditions and hypothesis defining the present work [16]. Thus, the electrical potential, current, charge, resistance and capacity of electrical circuits can be replaced by pressure, flow, volume, resistance and compliance of fluidic circuits, respectively.

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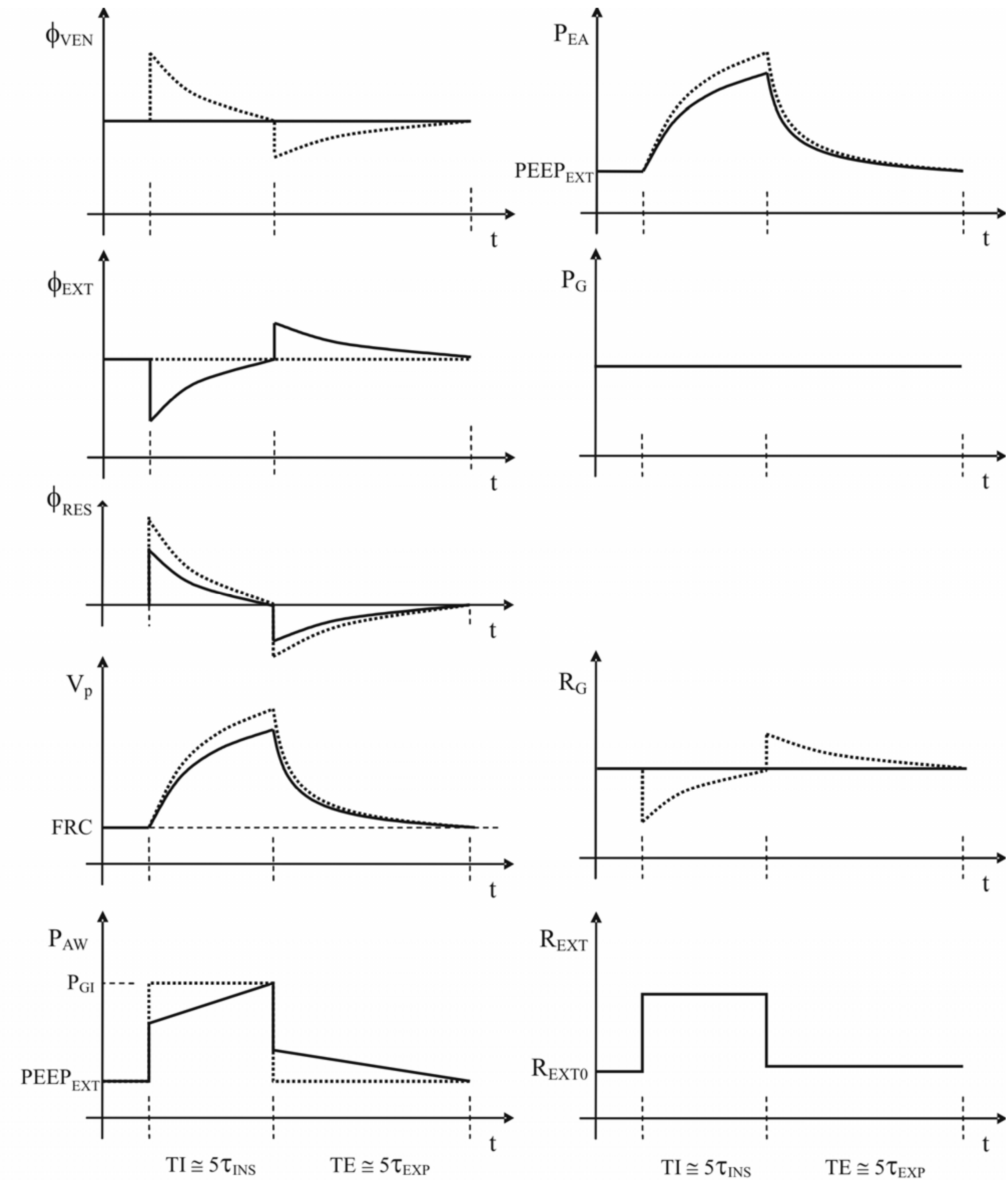

Figure 4: Time-waveform of ventilation parameters (ϕ_{VEN}; ϕ_{EXT}; ϕ_{RES}; V_P; P_{AW}; P_{EA}) and of ALVS components output (P_G; R_G; R_{EXT}) in advanced dual-controlled ventilation with square waveform as airways pressure (P_{AW}) excitation occurring with (dotted lines) or without (continuous lines) the application of the compensation procedure. See text.

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Moreover, theorems and methods usually employed for solving electrical network problems are available and in particular, Kirchhoff's laws give a powerfull theoretical instrument to the purpose.

Observing the DRSS configuration it appears as an integration circuit leading to the well known relationship between P_{AW} excitation and P_{EA} or ϕ_{RES} reaction.

Results

In order to check the theoretical results consisting in the analytical expression of both inspiratory and expiratory waveforms relative to airways and endoalveolar pressure, flow and lung volume, a great number of laboratory tests have been performed with ALVS.

The first group of experimental tests demonstrates that ALVS provides successfully the compensation procedure for advanced DCV ventilation with square waveform as P_{AW} excitation if the frequency of breathing does not exceed the value of about 20 acts/min. This result is consisted with controlled breathing of adult or child patient. This result is reported clearly in the Fig. 4.

The second group of experimental tests show that the optimization of breathing control in DCV ventilation with square waveform as P_{AW} excitation, i.e. conventional PCVTMV, is carried out setting the time of inspiration and expiration at about five times the inspiratory and expiratory time constant, respectively.

In this case, concerning the lung volume control, the according experimental and theoretical results point out that the tidal or minute volume are independent on R_P or C_P, respectively.

The last results are very interesting for clinical application because an increase of R_P (obstructive process) or a reduction of C_P (restrictive process) does not affect the control of tidal or minute volume, respectively.

The setting of the optimal time of both inspiration and expiration are implemented through a diagnostic procedure performed real-time by the ALVS monitoring system of providing also the waveform of pressure (airways and endoalveolar), respiratory flow and lung volume as a function of time together with the lung volume-airways (endoalveolar) pressure and respiratory flow-lung volume loops, as well as the current value of inspiratory and expiratory airways resistance, static and dynamic lung compliance and respiratory work.

The third group of experimental tests was devoted to study the application of non conventional waveforms as P_{AW} excitation to lung simulator with different parameters setting. To the purpose, three inspiratory waveform shapes have been considered and applied by the ALVS: square, triangle and trapezoidal.

The preliminary experimental results, obtained with different simulated patient characteristics and clinical requirements, are in good agreement with theoretical ones, validating the model and the analysis adopted. In particular, the trapezoidal waveform exhibits the best functional features in terms of breathing control as well as physiological approximation.

Conclusions

The chance of reaching an improved dual-controlled ventilation available in the clinical practice has been the goal of the present work. With the term "improved" we mean as far as possible similar to physiological breathing pattern together with extremely flexible in adapting to individual patient requirements, pathologies and their evolution.

In such context two relevant results have been obtained. First, through the implementation of a compensation procedure which stabilizes the flow across the resistance controlling the airways pressure applied to the patient, ALVS behaves like an ideal pressure generator. This makes possible any airways pressure waveform of clinical interest during both inspiration and expiration through an identical shape of such resistance waveform, eliminating the dependence of respiratory system parameters fluctuations or variations.

Second, the according theoretical and experimental results obtained show that moving from square to triangle to trapezoidal airways pressure waveforms as inspiratory excitation for controlled breathing, the patient reaction approaches more and more the physiological breathing characteristics, adapting very well to current clinical requirement during the ventilation treatment.

The favorable results of the present work establish the rationale for clinical test employing advanced dual-controlled ventilation with square waveform as airways pressure excitation and suggest new theoretical, experimental and clinical studies in the field of assisted/controlled ventilation with more physiological waveforms as airways pressure excitation.

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