An improved pneumatic control system inflates and deflates an inflatable CPR vest (10) in a controlled manner. The control system (18) adapts to the non-linear vest pressure time curve during deflation of the vest (10) caused by the nonlinear behavior of the chest, especially toward the end of the deflation cycle. The computer controlled system governs the inflation and deflation of the vest (10) within a preset range of vest operating conditions using a deflation algorithm to predict vest pressure, including vest bias pressure (Pb). The control system (18) also provides alarms and automatic system shutoff when certain parameters in the inflation/deflation cycle are not met. Integrated as part of the pneumatic control system is a pneumatic system that includes a reservoir (64) recharged during the deflation cycle. The pneumatic system is disclosed including alternatively a motorized pump (32) to recharge a reservoir (64) and a high-pressure air tank (22) to recharge the reservoir.
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IMPROVED PNEUMATIC CONTROL SYSTEM DESIGN FOR A CARDIOPULMONARY RESUSCITATION SYSTEM

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to cardiopulmonary resuscitation (CPR) and circulatory assist systems and in particular to an improved pneumatic control system providing both increased safety and reduced energy consumption.

2. Description of the Prior Art

Cardiac arrest is generally due to ventricular fibrillation, which causes the heart to stop pumping blood. The treatment of ventricular fibrillation is defibrillation. If, however, more then a few minutes have lapsed since the onset of ventricular fibrillation, the heart will be sufficiently deprived of oxygen and nutrients such that defibrillation will generally be unsuccessful. At that point it is necessary to restore flow of oxygenated blood to the heart muscle by cardiopulmonary resuscitation in order for defibrillation to be successful.

U.S. patent 4,928,674 issued to Halperin et al. teaches a method of cardiopulmonary resuscitation that generates high levels of intrathoracic pressure. Halperin et al. teaches the use of an inflatable vest operating under a pneumatic control system to apply circumferential pressure around a patient's chest. Halperin et al. teaches the fundamental basis of a pneumatic control system to inflate and deflate the vest in a controlled manner. The present inventors have improved the basic CPR vest control system design to enhance safety, reliability and reduce energy consumption.
SUMMARY OF THE INVENTION

The present invention is an improved pneumatic control system to inflate and deflate an inflatble CPR vest in a controlled manner. The control system is specifically designed to adapt to changing physical properties of the human chest during resuscitation. In particular the control system must adapt to the non-linear vest pressure-time curve during deflation of the vest caused by the non-linear behavior of the chest, especially toward the end of the deflation cycle. The control system also provides alarms and automatic system shut-off when certain parameters in the inflation/deflation cycle are not met.

Integrated as part of the pneumatic control system is an energy efficient scheme to provide the compressed air needed to inflate the CPR vest. The pneumatic system must recharge a reservoir during the deflation cycle. Two embodiments are taught: one with a motorized pump to recharge a reservoir; the other with a pressure tank containing air under high pressure to recharge the reservoir. In either embodiment, the volume and pressure of air in the reservoir pump output, and other design features are optimized to increase energy efficiency.

A first object of the present invention is a computer-controlled system capable of inflating and deflating the vest within a preset range of operating conditions even though the physical properties of the chest and vest application conditions vary among patients and during chest compression.

A second object of the present invention is a deflation algorithm that will accurately predict when the vest pressure is reduced to a bias pressure (Pb). This is critical since, if the bias pressure (Pb) is too high, the blood return from the peripheral vessels to the right atrium will be obstructed. As a result, the generation of blood flow during subsequent compressions will be inefficient and perfusion of the heart and brain will be insufficient. If
the bias pressure is too low, air consumption for vest inflation in the next compression cycle will be excessive. The algorithm controlling the deflation of the vest must also take into account the nonlinearity of the vest pressure as a function of time (i.e. pressure-time curve) during the interval when pressure in the vest decreases and the patient's chest recoils.

A third object of the present invention is a method for measuring vest pressure in the control console remote from the vest. Incorporating the pressure transducer as part of the disposable vest would be undesirable; so, pressure measurement must occur at the console end of the pneumatic hose connecting the vest to the pneumatic control system. To correlate actual vest pressure with measured pressure, a novel signal processing scheme is necessary to compensate for any damping and/or delay caused by air moving through the pneumatic hose.

A fourth object of the present invention is a pneumatic system optimized to produce a sufficiently large pressure gradient to move air rapidly into the vest at a minimum energy cost. To achieve this object, the invention teaches optimization of motorized pump output, the volume and pressure characteristics of the storage reservoir, and the flow characteristics of the valve and hose.

A fifth objective of the present invention is the use of a high pressure tank of compressed air as the energy source for the CPR vest. This energy source makes a portable CPR vest system practical. Other energy sources, such as engines fueled by gasoline, hydrogen, alcohol, or other fuels are also within the scope of this invention.

A sixth objective of the present invention is the overall optimization of the control system and pneumatic system to produce an energy efficient system.

A seventh objective of the present invention is a computer system capable of monitoring the function of the CPR vest inflation/deflation cycle and providing indications and alarms if certain key parameters are not met
BRIEF DESCRIPTION OF DRAWINGS

Figure 1 is a schematic drawing of the CPR vest system showing the inflatable CPR vest component and the pneumatic control system component.

Figure 2 shows the pressure in the CPR vest during a series of inflation/deflation cycles as a function of time (i.e. the vest pressure-time curve).

Figure 3 is a block diagram for the pneumatic control system.

Figure 4 shows the pressure-time curve for a single inflation/deflation cycle with the valve closure delay illustrated.

Figure 5 is a flow chart showing the deflation control algorithm.

Figure 6 is a block diagram showing the invented technique to simulate CPR vest pressure at the control console using remote sensing and signal processing.

Figure 7 is a schematic drawing of a pneumatic filter used to match the measured dynamic pressure with the actual CPR vest dynamic pressure.

Figure 8 shows the recharging pressure cycle of the reservoir as compared to the CPR vest inflation/deflation cycle.

Figure 9 is a block diagram showing a pneumatic system using a high pressure tank filled with compressed air as a power source.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The overall cardiopulmonary resuscitation (CPR) system incorporating the disclosed invention is shown in Figure 1. An inflatable CPR vest 10 is placed around the patient using handle 12 to pull the vest under the patient's back. The vest is then secured around the patient by connecting Velcro™ strips (not shown). The vest 10 comprises a belt 11, a handle 12, a radially expandable bladder 13, and a safety valve 20. A female connector 14 on the vest 10 connects it by a hose 16 to a pneumatic control system contained in a console 18. The pneumatic control system 18
inflates and deflates the bladder 13 to achieve a particular cycle of chest compression and release.

As shown in Figure 2, the vest bladder 13 is first inflated to a certain pressure (Pc) to apply circumferential pressure to the chest. The vest bladder is then deflated in a controlled manner to a second lower bias pressure (Pb). This cycle is repeated a number of times; at a set number of cycles (e.g., the fifth cycle in Figure 2) the bladder pressure is decreased further to ambient pressure (Pa) to allow the expiration of air from the patient's lungs.

For successful performance of vest CPR it is critical to maintain certain parameters of the vest pressure cycle as shown in Figure 2. Peak compression pressure (Pc) must be achieved in the vest by the end of the inflation within specified safety limits. The system must adapt to changing physical properties of the human chest during resuscitation, to varying properties of the chest from patient to patient, and be independent of whether the vest was tightly or loosely applied. Computer controls are necessary to assure that set operational parameters are met for different patients under different conditions. Applicants have, through experimentation, established that the following operational parameters should be maintained. The ranges are described in Table 1 in terms of normal operation and safety limits.
<table>
<thead>
<tr>
<th>Target</th>
<th>Low Limit</th>
<th>High Limit</th>
<th>Low Limit</th>
<th>High Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Cycle Length (ms)</td>
<td>1000</td>
<td>995</td>
<td>1005</td>
<td>667</td>
</tr>
<tr>
<td>Ventilation Cycle Length (ms)</td>
<td>1250</td>
<td>1245</td>
<td>1255</td>
<td>667</td>
</tr>
<tr>
<td>Inflation Time (ms)</td>
<td>175</td>
<td>100</td>
<td>250</td>
<td>60</td>
</tr>
<tr>
<td>Deflation Time (ms)</td>
<td>150</td>
<td>N/A</td>
<td>200</td>
<td>N/A</td>
</tr>
<tr>
<td>Duty Cycle (ms)</td>
<td>400</td>
<td>300</td>
<td>500</td>
<td>200</td>
</tr>
<tr>
<td>Peak Vest Pressure (Torr)</td>
<td>235</td>
<td>220</td>
<td>250</td>
<td>180</td>
</tr>
<tr>
<td>Bias Vest Pressure (Torr)</td>
<td>15</td>
<td>5</td>
<td>25</td>
<td>N/A</td>
</tr>
<tr>
<td>Bias Pressure During Ventilation</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>N/A</td>
</tr>
</tbody>
</table>

The following definitions of operational cycle parameters were used in Table 1:

**Total Cycle Length** - Time interval between the start of a compression and the start of the following compression, when patient ventilation does not take place.

**Ventilation Cycle Length** - Total cycle length when patient ventilation takes place.

**Peak Vest Pressure** - Highest pressure relative to atmospheric registered in the single-use vest bladder during the vest cycle.

**Bias Vest Pressure** - Vest pressure at the beginning of vest inflation.

**Deflation Time** - Time interval between the beginning of pressure drop and time when vest pressure reaches the bias vest pressure target.

**Duty Cycle** - Time interval between the time the vest pressure reaches 50% of peak pressure during vest inflation and time the vest pressure drops to 50% of peak vest pressure during deflation.

**Inflation Time** - Time interval between the beginning of vest pressure rise and the time when vest pressure reaches 95% of the peak vest pressure.
Controlling the deflation of the vest bladder is a key feature of the present invention. The bias pressure (Pb) must be accurately controlled; too high and it will prevent effective generation of blood flow in the patient; and, too low and it will result in an increased use of compressed air with a correspondingly high energy consumption during the next compression cycle - making practical application of a vest difficult. The vest pressure cycle shown in Figure 2 is repeated as long as treatment is applied.

Figure 3 is a schematic drawing showing the control system 18, connected by pneumatic hose 16 to vest bladder. A pressure relief valve 20 is incorporated into the vest design and would release air from the vest if pressure exceeds some set amount above the designed compression pressure (Pc). The system 18 comprises: air tank 22 (for storing pressurized air); control valve 24 (consisting of two independent valves 24a and 24b); vest pressure transducers 26 (for monitoring pressure in the vest); computer 28; motor 30; main air pump 32 (for pumping compressed air into tank 22); pilot air pump 34 (for generating compressed air to operate control valve 24); power supply 36, batteries 38, pilot pressure manifold 40 (distributes air to control valves 24 for operation as directed by the computer 28). The control valves 24a and 24b may alternatively be positioned at the vest end of the pneumatic hose 16, or as part of the vest 10, or within the control console 18 as shown in Figures 1 and 3. In operation, valve 24a will be open allowing air from tank 22 to flow through pneumatic hose 16 to inflate bladder 13. When pressure transducer 26 detects pressure approaching compression pressure (Pc) the valve 24a is closed. At the appropriate time interval, valve 24b is opened allowing compressed air in the vest bladder 13 to escape. When sensor 26 detects pressure in the vest approaching the bias pressure (Pb), computer 28 using an innovative deflation routine closes valve 24b. (Note: during the ventilation cycle, which in a preferred embodiment is the fifth cycle, the valve 24 is not
closed allowing the pressure to approach ambient pressure (Pa)). Computer 28 utilizes an algorithm, to be discussed later, to operate valves 24a and 24b in advance of the pressure reaching the preset levels to anticipate the time delay between valve actuation and actual closure.

Figure 4 shows the vest pressure-time curve for a typical compression cycle. Algorithms are used to control the vest bladder inflation and deflation such that the appropriate valve is actuated in anticipation of the desired pressure being reached. This feature provides increased safety and reduced air and energy consumption. As shown in Figure 4, the command to stop inflation is given in advance because of the intrinsic delay in closing the inflation valve (the valve closure delay). To achieve the desired compression pressure (Pc), the algorithm calculates the inflation rate and sends the command to close the valve at a set time (the valve closure delay time) in advance of when the desired pressure will be achieved. The algorithm is relatively simple since the rate of inflation is essentially constant and the vest pressure-time curve during inflation will, therefore, be linear. However, the deflation control algorithm is more complex and also very critical. The deflation algorithm must adapt to changing physical properties of the human chest during resuscitation, variance in application of the vest and disturbances introduced by patient ventilation. In specific, the deflation rate is not constant (see, Figure 4) because, among other things, the behavior of the chest during recoil is non-linear, especially toward the end of the deflation cycle. The algorithm must accurately deflate the vest until the bias pressure (Pb) is achieved. If the algorithm misses the mark and the bias pressure is too high, blood flow generation will be hindered. Similarly, if the bias pressure overshots and is too low, the amount of air and energy consumed to reach the desired compression pressure (Pc) is the next compression cycle will be too large and will decrease the efficiency of the system. Such decreased efficiency would require a larger energy source and reduce the portability of the
system. In the preferred embodiment, the Applicants suggest a predetermined bias pressure (Pb) of 15 Torr ±5 Torr based on their experimentation.

The flow chart in Figure 5 outlines the deflation control algorithm. The vest deflation algorithm is executed during the deflation part of the compression/decompression cycle. During each digitizing interval, which in the preferred embodiment is 4 ms, the sensors (which will be described in detail later) measure the vest pressure, increment the deflation counter (i.e. stack index) and add the latest pressure reading to the first-in-first-out (fifo) stack. The algorithm then calculates the pressure changes for the eight (8) previous intervals from the pressure measurements stored in the fifo stack. Then, it calculates the total sum of the pressure differences and divides by the number of the total pressure readings to determine the rate of pressure descent. This gives the average pressure change or "average delta" for the 8 previous intervals. (Note: This rate will change as one enters the nonlinear portion of the deflation cycle.) The algorithm next calculates the "extended pressure" which is the product of the "average delta" and the valve closure delay plus the current pressure (i.e. the last pressure reading in the fifo stack):

\[
\text{Extended Pressure} = (\text{Average Delta} \times \text{Valve Closure Delay}) + \text{Current Pressure}
\]

If the Extended Pressure is less than the low pressure target (Pb) and if: 1) this cycle is not a ventilation cycle and 2) the elapsed deflation time is greater than a minimum allowed deflation time, then the command is issued to close the deflation valve. If it is a ventilation cycle (which occurs on the 5th compression cycle in the preferred embodiment) the vest pressure is allowed to decrease to ambient pressure (Pa). Testing the minimum time for deflation is added in the above decision tree to prevent the apparatus from stopping deflation too early, which is dangerous. The
algorithm also provides the following alarms: 1) if the elapsed time to reach bias pressure is greater than a certain maximum allowed deflation time, and 2) if the minimum pressure reading did not drop below 5 Torr in the ventilation cycle. These conditions could indicate valve or hose obstruction which could present a hazard.

Alternatives to the above deflation algorithm are envisioned by the Applicants which would still accomplish the essential features of:
1) calculating the deflation rate that varies in a non-linear manner, and
2) anticipating the Extended Pressure (i.e., the anticipated vest pressure if the valve closure command were issued) in such a nonlinear environment, so as to achieve the desired bias pressure (P_b). An example of a possible alternative would be the use of non-linear curve fitting to project vest pressure.

In order to achieve the compression pressure (P_c) and bias pressure (P_b), the pressure in the vest must be accurately measured. However, measuring vest pressure can prove to be difficult since the vest is separated from the inflation system by a length of pneumatic hose. Two configurations for the placement of the sensors are possible; each with its own advantages and disadvantages. The pressure sensor can be placed on or in the vest. However, the vest may be disposable and pressure sensors are too expensive to be included in a disposable vest. Alternatively, the pressure sensors could be kept in the controller console and pressure would be measured at the control valve and not at the vest end of the hose. This alternative configuration is shown in Figures 6 and 7. The advantage of this configuration is that: 1) no control lines or signal lines lead to the vest from the controller and 2) the sensor is not disposed of with the vest, thereby reducing the cost of the disposable vest. The disadvantage, however, is that a direct measurement of the vest pressure is not available. Therefore, the pressure measured in this way must undergo special conditioning. As shown in Figure 6, pressure (A) is measured by pressure sensors 42.
However, pneumatic and/or electronic and/or software filters (44,46) are necessary to process the actual pressure reading (A) so that it corresponds to the vest pressure (B). These filters simulate the damping and delay caused by the pneumatic hose 48. Generally the filters (44,46) must damp frequencies above 4kHz.

Figure 7 shows a combined pneumatic/electronic filtering system. Pneumatic filter 50 consists of a needle valve and is used to damp the high frequency components of the measured pressure which are unimportant for vest control. A second RC electronic filter 52 also smooths out the pressure signal detected by the pressure sensor 42 before the signal is digitalized by the A/D converter 56. During the final stages of system assembly, the needle valve is adjusted to make the pressure signal monitored remotely at the controller console identical to the pressure in the vest.

It is to be understood that various combinations of pneumatic and/or electronic and/or software filters are within the contemplation of the inventors to match the remotely measured pressure to the vest pressure and simulate the delay and damping caused by the pneumatic hose. Since the most important components of vest pressure are low frequency (< 10 Hz), the filter must remove the high frequency components. Applicants have found that removing the frequency components above 4kHz achieves satisfactory results. Such filtering would not, however, mask or remove the changes in vest pressure that might occur under failure conditions.

For the successful performance of CPR it is also critical that the system maintain certain parameters of the vest pressure cycle as consistently as possible. One such critical parameter is the rate at which the vest is inflated. To achieve this a large pressure gradient is needed to move air rapidly into the vest. The rate at which the vest will be inflated is determined by: the tank volume, tank pressure, and the flow factor of the control valve. Using an air storage tank of less than optimal volume will lead to the need for higher tank pressure. Higher tank pressure will lead to
higher pump motor power requirements and lower pump efficiency, which are undesirable. Using a tank of higher than optimal volume will slow the rate of initial charging of the tank by the air pump, delaying the start of resuscitation and resulting in higher time-averaged pressure in the tank, increasing power requirements and reducing efficiency. It also increases the size of the console. Applicants have experimentally found that using a tank volume of approximately 17.51, control valve with Cv factor of approximately 11 and pump air delivery of approximately 15 scfm at 413 Torr gives optimal system performance.

Figure 8 shows optimized reservoir pressure during the inflation/deflation cycle. As shown, the reservoir pressure 58 will drop as the vest pressure 60 increases. The reservoir pressure 58 must then recharge during the time period between closure of the inflation, valve and opening of the inflation valve on the next inflation cycle. The pump flow rate and reservoir size must be optimized in order to achieve the reservoir pressure profile shown in Figure 8. If the resulting reservoir pressure and/or volume is too low the system will not have enough air to inflate the vest, if too high, too much energy will be used to recharge the reservoir.

In an alternative embodiment, shown in Figure 9, a pressure tank 62 can substituted for the pump. This design would be most fitting for a portable unit carried by ambulance and/or emergency medical personnel. Flow from the high pressure tank 62 would be discharged into a reservoir 64. The pressure in the tank 62 may be 4,000 psi and the pressure in the reservoir would be reduced to 30-40psi, as controlled by inlet valve 66.

Expanding the high pressure air into the reservoir is necessary for safety, to prevent air from becoming extremely cool due to rapid expansion, and for rapid replacement of air supply tanks. The control system, which may use either a pneumatic controller or a microprocessor controller, would activate inflation and deflation valves 68 in a manner similar to that described earlier in this specification.
In addition to the features described above, which enhance the overall energy efficiency of the CPR vest system, various safety enhancements have also been made. One such safety feature monitors peak vest pressure. The microprocessor processes an algorithm that monitors vest pressure and activates an alarm if certain conditions are met. An alarm is activated if vest pressure in excess of 280 Torr occurs for longer than 10ms or vest pressure in excess of 45 Torr occurs for longer than 1.0 second. A second independent pressure transducer and separate analog processor back up the first system. This back up system will continue to operate in the event of microcontroller failure. This back up system will activate an alarm if a vest pressure is in excess of 300 Torr is detected or vest pressure in excess of 50 Torr is detected for a period longer than 1.25 seconds. If either system activates an alarm, the following will occur: a) Interruption of the main power line to the normally-open control deflation valve, causing pressurized air in the vest to vent into the atmosphere; b) Interruption of the power line to the normally open tank pressure dump valve, causing pressurized air in the tank to be exhausted into the atmosphere; and, c) Interruption of the signal line to the air pump motor power supply, causing the pump motor to stop.

The following additional safety features are also designed into the vest CPR system: 1) A diagnostic circuit to test the function of the back up vest pressure monitoring safety circuit every time the device power switch is activated. 2) The vest is equipped with a pressure relief valve factory preset to open at approximately 310 Torr to prevent overpressurization of the patient's chest. The valve makes a distinct noise to warn the operator when it is activated. 3) An alternative power source (battery) is engaged when: (a) main power switch is "on" and AC line plug is not connected, (b) when the AC power supply circuit failed, (c) during power interruptions, or (d) when the AC line voltage is too low for normal operation. Switching to the battery will not interrupt or slow down the operation of the device.
The CPR vest system design also incorporates the following alarm, display and indication features:

1. **High Vest Pressure Indicator.** An alarm is activated when the vest pressure detected by the back up safety circuit is in excess of 300 Torr instantly or greater than 50 Torr for longer than 1.25 second.

2. **System Failure Indicator.** An alarm is activated if: a) vest pressure is in excess of 280 Torr for longer than 10 ms or in excess of 45 Torr for more than 1.0 second; b) Slow vest deflation detected by computer; c) Failure to reduce vest pressure for ventilation detected by computer; or d) Vest pressure sensor(s) failure detected by computer.

3. **Low Vest Pressure Indicator.** An alarm is activated if the peak vest pressure detected by computer is lower than 180 Torr for more than two consecutive vest inflation cycles.

4. **Vest Pressure Indicator.** Vest pressure indicator is a three-zone LED bar graph. The indicator in the central green zone indicates that air pressure in the vest during the compression phase of the cycle is normal and CPR is safe. Indicator in the low yellow zone indicates that chest compressions may be ineffective. Indicator in the high yellow zone shall indicate that air pressure in the vest may be approaching the high danger limit.
In the preferred embodiment, the following pressures are associated with each zone:

<table>
<thead>
<tr>
<th>LED#</th>
<th>Legend</th>
<th>Color Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1</td>
<td>yellow</td>
</tr>
<tr>
<td></td>
<td>300 Torr</td>
<td>287</td>
</tr>
<tr>
<td>2</td>
<td>yellow</td>
<td>262</td>
</tr>
<tr>
<td>3</td>
<td>green</td>
<td>237</td>
</tr>
<tr>
<td>4</td>
<td>green</td>
<td>212</td>
</tr>
<tr>
<td>5</td>
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</tr>
<tr>
<td>10</td>
<td>200 Torr</td>
<td>162</td>
</tr>
<tr>
<td>6</td>
<td>yellow</td>
<td>187</td>
</tr>
<tr>
<td>7</td>
<td>yellow</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>150 Torr</td>
<td>162</td>
</tr>
</tbody>
</table>

5. Battery Service Indicator light indicates that the battery can not provide more than a specified period of normal operation after full charge.

6. Power ON indicator indicates that the power switch on the console is in the ON position. Indicator is located on the POWER OFF/CHARGE-ON switch.

7. CPR ON Indicator indicates that the vest CPR system is performing chest compressions. Indicator is located on the CPR button.

8. Battery Operating Indicator shows that the system is operating from the internal battery. Indicator is turned off automatically when the system is plugged into AC line.

9. Battery Charge Indicator goes on when the vest CPR system is connected to the AC wall power socket and internal battery is being charged (Power switch is in OFF position.)

25 In addition to the alarm and indicator features, the applicants realized that for the CPR vest system to be used in the chaos of an emergency situation, the controls must be simple and straightforward. Therefore the CPR vest system has been designed with the following controls:
1. **POWER OFF/CHARGE - ON** is a two-position switch. To operate the vest CPR system the switch needs to be in ON position. When not in operation, the vest CPR system power cord is plugged into the wall outlet for charging. During storage the power switch is in OFF/CHARGE position.

2. CPR button is used to activate compressions.

3. STOP button is used to stop CPR.

4. Silence Alarms button is used to silence audio alarms.

A CPR vest utilizing efficient control algorithms, an energy efficient pneumatic inflation system, and alarm and control and safety features has been outlined. Obviously, many modifications and variations of the present CPR vest system and the features described therein are possible in light of the above teachings. It is therefore to be understood that within the scope of the appendable claims, the invention may be practiced otherwise then as specifically described.
WHAT IS CLAIMED IS:

1. A pneumatic control system selectively inflating and deflating a CPR vest that is placed circumferentially around a patient's chest for performing cardiopulmonary resuscitation, said pneumatic control system comprising:
   a. a source of compressed air,
   b. an inflation valve means in fluid communication with said source of compressed air and the CPR vest for controlling flow of compressed air into the CPR vest,
   c. a deflation valve means in fluid communication with the CPR vest for controlling flow of compressed air from the CPR vest,
   d. a pressure sensor means for determining the air pressure in the CPR vest; and,
   e. a computer controller receiving input from the pressure sensor means for selectively activating said inflation valve means and said deflation valve means to achieve certain parameters in the CPR vest's pressure cycle and adapting to changing physical properties of the chest.

2. The pneumatic control system of claim 1, wherein said computer controller comprises:
   a. a first means for determining incremental changes in CPR vest pressure over a plurality of discreet increments during the deflation cycle,
   b. a calculation means for determining the extended vest pressure based on the incremental changes in vest pressure and a constant association with closure delay of the deflation valve means, wherein extended vest pressure is the calculated vest pressure that would occur if the valve were closed immediately; and,
   c. an activation means for closing the deflation valve means when 1) the extended vest pressure is less than a preset bias pressure (Pb), 2) the
time lapse from opening the deflation valve means is more than a set
minimum time, and
3) a ventilation cycle is not designated.

3. The pneumatic control system of claim 1, wherein said
computer controller further comprises:
a means for designating a ventilation cycle for every set number of
inflation deflation cycles of the CPR vest, wherein the activation means
does not close the deflation valve means for the ventilation cycle but allows
the CPR vest to deflate to ambient pressure.

4. The pneumatic control system of claim 1, wherein said
computer controller further comprises:
an alarm means for activating an alarm on the occurrence of at least
one of the following:
a) the extended vest pressure falls below the preset bias
   pressure (Pb) in less than a preset time from opening of the
deflation valve means, and
b) if vest pressure does not fall to ambient pressure during the
   ventilation cycle;

5. The pneumatic control system of claim 1, wherein the bias
pressure (Pb) is set to approximately 15 Torr.

6. The pneumatic control system of claim 1, wherein the
pressure sensor means is located remote from the CPR vest and is coupled
to the CPR vest by a pneumatic hose and wherein the pressure sensor
means contains a filter means for simulating the removal of high frequency
components and damping caused by air flow through the pneumatic hose.
so that the remotely measured pressure substantially equals pressure in the CPR vest.

7. The pneumatic control system of claim 6, wherein the filter means damps frequencies above 10Hz.

8. The pneumatic control system of claim 6, wherein the filter means is a pneumatic filter.

9. The pneumatic control system of claim 1, wherein the source of compressed air further comprises:
   a motorized pump for producing compressed air;
   a reservoir in fluid communication between the motorized pump and the inflation valve means, wherein the reservoir's volume and pressure are optimized for an inflation valve means with a particular flow coefficient, so that the reservoir can be recharged in the time period between the closure of the inflation valve means and the next opening of the inflation valve means, so as to have sufficient pressure and volume to inflate the CPR vest.

10. The pneumatic control system of claim 1, wherein the reservoir tank volume is approximately 171 and the motorized pump delivers approximately 15 scfm at approximately 8psi.

11. The pneumatic control system of claim 1, wherein the source of compressed air comprises:
   a high pressure tank;
   a reservoir, and
a control valve in fluid communication between the high pressure tank and the reservoir, wherein the control valve is activated by the computer controller to maintain a predetermined pressure in the reservoir.

12. The pneumatic control system of claim 11, wherein an engine fueled by one of gasoline, hydrogen, or alcohol provides the power for the pumps.

13. The pneumatic control system of claim 11, wherein the high pressure tank stores compressed air in excess of 4,000 psi.

14. The pneumatic control system of claim 1, wherein said computer controller will interrupt inflation of the CPR vest on the occurrence of at least one of the following:
   i) if vest pressure exceeds a certain preset maximum value, and
   ii) if vest pressure exceeds a second preset valve for a preset time.

15. The pneumatic control system of claim 14, wherein the preset maximum value is approximately 280 Torr and the second preset value is approximately 45 Torr and the preset time is 1 second.

16. The pneumatic control system of claim 1, further comprising an independent safety circuit for activating an alarm on the occurrence of at least one of the following:
   i) if vest pressure exceeds a certain preset maximum value, and
   ii) if vest pressure exceeds a second preset value for a preset time.

17. The pneumatic control system of claim 1, wherein said computer controller further comprises an alarm means for activating an alarm on the occurrence of at least one of the following:
4 i) slow vest deflation,
5 ii) absent release for ventilation,
6 iii) vest pressure in excess of defined limits.
7 iv) failure detected in said pressure sensor means, and
8 v) peak vest pressure for two consecutive vest inflation cycles is
9 below a preset value.

18. The pneumatic control system of claim 1, wherein said
2 computer controller interfaces to a vest pressure indicator for displaying
3 peak vest pressure during compression in three zones: the first zone
4 indicating normal pressure, the second zone indicating ineffective low
5 pressure, the third zone indicating pressure is dangerously high.

19. The pneumatic control system of claim 18, wherein the first
2 zone is indicated by a green light, the second zone is indicated by a yellow
3 light, and the third zone is indicated by a yellow light.

20. The pneumatic control system of claim 18, wherein the first
2 zone is indicated if the vest pressure is greater than 187 Torr but less than
3 262 Torr, the second zone is indicated if the vest pressure is below 187 Torr
4 and the third zone is indicated if the vest pressure is above 262 Torr.
AMENDED CLAIMS

[received by the International Bureau on 16 July 1996 (16.07.96); original claims 1-20 replaced by amended claims 1-19 (5 pages)]

1. A pneumatic control system selectively inflating and deflating a CPR vest circumferentially surrounding a chest of a patient for performing cardiopulmonary resuscitation, said pneumatic control system comprising:

   a source of compressed gas in fluid communication with the CPR vest to cyclicly pressurize the vest;
   a deflation valve in fluid communication with the CPR vest having a first state in which gas is prevented from escaping the vest, and a second state in which gas escapes from the vest;
   a pressure sensor, and,
   a computer controller receiving the dynamic signal from the pressure sensor and operatively connected to the deflation valve for selectively switching said deflation valve between the first and second states, wherein said computer controller executes program instructions to:

   (i) analyze the dynamic signal from the pressure sensor to measure a current pressure and a series of incremental pressure changes in CPR vest pressure over a plurality of discreet increments in time as gas escapes from the vest during the second state of the deflation valve;

   (ii) predict an extended vest pressure equal to the sum of the current pressure and a product of a current of the series of incremental pressure changes in CPR vest pressure and a predetermined constant indicative of a pressure loss occurring in the vest while the deflation valve switches from the second to the first states; and,

   (iii) activate the deflation valve to switch from the second to the first states when the extended vest pressure is the same as or less than a preset bias pressure (Pb).

2. The pneumatic control system of claim 1, wherein said computer controller executes program instructions to:
activate the deflation valve to switch from the second to the first state when the deflation valve is in the second state more than a set minimum time.

3. The pneumatic control system of claim 1, wherein said computer controller executes program instructions to:
   designate a ventilation cycle to periodically occur during which ventilation cycle the deflation valve remains in the second state to allow the CPR vest to deflate to an ambient pressure.

4. The pneumatic control system of claim 1, wherein said computer controller comprises:
   an alarm activated by the computer controller on the occurrence of the following:
   a) the extended vest pressure fails to fall below a preset bias pressure (Pb) in less than a preset time from switching of the deflation valve from the second to the first states when a ventilation cycle is not occurring.

5. The pneumatic control system of claim 1, wherein the bias pressure (Pb) is set to approximately 15 Torr.

6. The pneumatic control system of claim 1, wherein the pressure sensor is located remote from the CPR vest and is coupled to the CPR vest by a pneumatic hose and wherein the pressure sensor contains a pneumatic filter means for simulating the removal of high frequency components and damping caused by air flow through the pneumatic hose, so that the remotely measured pressure substantially equals pressure in the CPR vest.

7. The pneumatic control system of claim 6, wherein the filter means damps frequencies above 10Hz.
8. The pneumatic control system of claim 6, wherein the filter means is a pneumatic filter.

9. The pneumatic control system of claim 1, wherein the source of compressed gas comprises:
   a motorized pump for producing compressed gas;
   a reservoir in fluid communication with the motorized pump and the CPR vest, wherein the motorized pump pressurizes the reservoir and compressed gas from the reservoir cyclicly inflates the CPR vest.

10. The pneumatic control system of claim 1, wherein the source of compressed gas comprises a reservoir tank having a volume of approximately 17 liters and a motorized pump supplying approximately 15 scfm or greater of compressed gas at approximately 8psi or greater.

11. The pneumatic control system of claim 1, wherein the source of compressed gas comprises:
   a high pressure tank;
   a reservoir in fluid communication with the CPR vest; and
   a control valve in fluid communication with and between the high pressure tank and the reservoir, wherein the control valve is activated by the computer controller to maintain a predetermined pressure in the reservoir.

12. The pneumatic control system of claim 11, wherein the high pressure tank stores compressed air in excess of 4,000 psi.

13. The pneumatic control system of claim 1, wherein said computer controller interrupts inflation of the CPR vest on the occurrence of at least one of the following:
   i) if vest pressure exceeds a certain preset maximum value, and
ii) if vest pressure exceeds a second preset value for a preset time.

14. The pneumatic control system of claim 13, wherein the preset maximum value is approximately 280 Torr and the second preset value is approximately 45 Torr and the preset time is 1 second.

15. The pneumatic control system of claim 1, wherein said computer controller comprises an independent safety circuit for activating an alarm on the occurrence of at least one of the following:
   i) if vest pressure exceeds a preset maximum value, and
   ii) if vest pressure exceeds a second preset value for a preset time.

16. The pneumatic control system of claim 1, wherein said computer controller comprises an alarm activated on the occurrence of at least one of the following conditions:
   i) slow vest deflation,
   ii) absent release for ventilation,
   iii) vest pressure in excess of one or more defined limits,
   iv) failure detected in said pressure sensor, and
   v) peak vest pressure for a preset number of consecutive vest inflation cycles is below a preset value.

17. The pneumatic control system of claim 1, wherein said computer controller interfaces to a vest pressure indicator having a peak vest pressure display showing three zones: wherein a first zone indicating normal pressure, a second zone indicating ineffective low pressure, and a third zone indicating pressure is dangerously high.
18. The pneumatic control system of claim 17, wherein the first zone is indicated by a green light, the second zone is indicated by a yellow light, and the third zone is indicated by a yellow light.

19. The pneumatic control system of claim 17, wherein the first zone is indicated if the vest pressure is greater than 187 Torr but less than 262 Torr, the second zone is indicated if the vest pressure is below 187 Torr and the third zone is indicated if the vest pressure is above 262 Torr.
Fig. 3

SUBSTITUTE SHEET (RULE 26)
DEFLATION CONTROL ROUTINE

MEASURE VEST PRESSURE

INCREMENT DEFLATION COUNTER

ADD LATEST VEST PRESSURE READING INTO FIFO STACK

CALCULATE RATE OF PRESSURE DESCENT
AVERAGE DELTA = AVERAGE DELTA OF READINGS IN FIFO STACK

CALCULATE EXTENDED PRESSURE
EXTENDED PRESSURE = (AVERAGE DELTA x VALVE CLOSURE DELAY) + CURRENT PRESSURE

IS LOW PRESSURE TARGET MET?

IS THIS A VENTILATION CYCLE?

IS VEST AT AMBIENT PRESSURE?

CHECK TIME LAPSE LESS THAN MIN ALLOWED DEFLATION DROP?

ISSUE COMMAND TO CLOSE VALVE

CAPTURE LOWEST PRESSURE READING LEFT IN VENT CYCLE

IF VENT CYCLE DID MIN. PRESSURE READING DROP BELOW 5 TORR

NO

ALARM

YES

GO TO INFLATION ROUTINE

Fig. 5
Fig. 6

Fig. 7

SUBSTITUTE SHEET (RULE 26)
Fig. 8  TANK AND VEST PRESSURE CYCLE

Fig. 9

SUBSTITUTE SHEET (RULE 26)
INTERNATIONAL SEARCH REPORT

International application No.
PCT/US96/03497

A. CLASSIFICATION OF SUBJECT MATTER
IPC(6) : A61H 31/00
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED
Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
<thead>
<tr>
<th>Category*</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
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<td>X</td>
<td>US, A, 4,928,674 (HALPERIN ET AL.) 29 May 1990, see column 3 line 35 to column 4 line 15; and column 6 lines 1-10.</td>
<td>1, 14</td>
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<td>Y</td>
<td>US, A, 5,307,791 (SENOUE ET AL.) 03 May 1994, see column 7 line 60 to column 8 line 7.</td>
<td>2-13, 15-20</td>
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<td>Y</td>
<td>US, A, 3,167,067 (H. J. RAND) 26 January 1965, see column 1 lines 40-61.</td>
<td>4, 16, 17, 9, 10, 12</td>
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<td>Y</td>
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<td>Y</td>
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Further documents are listed in the continuation of Box C. [X] See patent family annex.

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<tr>
<td>&quot;Y&quot;</td>
<td>document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combinations being obvious to a person skilled in the art</td>
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<td>document member of the same patent family</td>
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Date of the actual completion of the international search: 24 APRIL 1996

Date of mailing of the international search report: 20 MAY 1996

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Form PCT/ISA/210 (second sheet)(July 1992)
**DOCUMENTS CONSIDERED TO BE RELEVANT**

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<tr>
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<td>A</td>
<td>US, A, 5,370,603 (NEWMAN) 06 December 1994.</td>
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