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# A TIME-CYCLED EXTERNAL CARDIAC COMPRESSOR

December 1968



U.S. ARMY MATERIEL COMMAND
HARRY DIAMOND LABORATORIES
WASHINGTON, D.C. 20438



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ABSTRACT

During cardiac arrest, the flow of oxygenated blood to the brain becomes insufficient to support life. With new methods of cardiopulmonary resuscitation, blood circulation can be maintained, the heart restarted, normal circulation resumed, and the patient's life saved. One method of maintaining circulation during this critical resuscitative period consists of rhythmically depressing the chest, thereby squeezing the heart and forcing blood to circulate. This method is known as external cardiac compression.

A simple pneumatically powered external cardiac compressor has been developed by the Harry Diamond Laboratories in cooperation with the Walter Reed Army Institute of Research. This machine is time cycled and is controlled by a fluid-amplifier-driven oscillator. The device can also be synchronized with an EKG signal. Using the two controls on the machine, the operator may select ram forces up to 0.62 kN (140 lb) and frequencies from 30 to 85 cpm. Chest deflection cannot exceed 7.5 cm (3 in.). The ratio of compression to total period is approximately 0.45 on the present model, but ratios from 0.21 to 0.73 could be obtained by modifying the oscillator. Performance characteristics were obtained from tests in which springs were used as physical models of the chest.

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## 1. INTRODUCTION

When a person suffers a cardiac arrest, it is vital that his blood circulation and oxygenation be maintained until attempts can be made to get the heart beating normally again. If blood circulation and oxygenation are not maintained, irreparable brain damage will occur in 4 to 6 min. Oxygenation can usually be accomplished by some method of artificial respiration. Blood circulation can be maintained by squeezing the heart in a rhythmic manner, and this squeezing may be done internally (requiring an incision in the chest wall) or externally (ref 1). The latter method, known as external cardiac massage, consists of alternately compressing and releasing the sternum of the individual in distress. During compression of the chest, the heart is squeezed between the sternum and the spine, forcing blood out. When the sternum is released, the heart can fill with blood. This resuscitative method may be applied manually (ref 2,3) or mechanically (ref 4,5,6).

This report describes an external cardiac compressor (ECC) designed to perform external cardiac massage mechanically. This ECC is a joint development of the Harry Diamond Laboratories (HDL) and the Walter Reed Army Institute of Research (WRAIR). It is a time-cycled machine, and the cycling frequency and ram force can be independently varied. The basic control unit is a fluid-amplifier-driven oscillator. Other features of the ECC are simplicity of design and operation, and the capability of being synchronized with EKG signals.

## 2. FUNCTIONAL REQUIREMENTS

The main criterion for the effectiveness of an ECC is cardiac output flow. Flow in turn will affect blood pressure. Flow is determined by heart rate and stroke volume of blood delivered by the heart. Stroke volume depends on the size of the heart and the extent of diastolic filling and systolic emptying (ref 7).

When the ECC is in use, heart rate is equal to the number of compressions per minute. The systolic emptying and diastolic filling are functions of the pulse shape of the chest-deflection-versus-time curve. Systolic emptying is also affected by the amount and rate of deflection of the sternum during the compression stroke. Forces required to compress the chest are a function of the elastic properties of the chest.

At present, ECC compression rates of 40 to 120 cpm have been used or suggested by investigators. Average chest deflections of 2.5 to 5 cm (1 to 2 in.) with an upper limit 7.5 cm (3 in.) have also been suggested. The ram forces required depend on the "spring constant" of the chest wall. This constant may vary from 6.5 to 13.1 kN/m (37 to 75 lb/in.), and therefore to insure that deflections of up to 5 cm (2 in.) can be achieved, ram forces of up to 0.67 kN (150 lb) should be available (ref 8).

## 3. OPERATIONAL DESCRIPTION

The time-cycled ECC developed by these laboratories consists of a ram assembly, a column, a base, and a fluid-amplifier-driven oscillator (fig. 1). The oscillator provides the control for ram frequency. The arm can be moved vertically along the column to conform to the chest thickness of the patient under the rubber pad at the end of the ram. Also, the ram may be moved laterally along the arm to aid in positioning it on the patient. Two controls permit independent adjustment of ram force and frequency.

### 3.1 Oscillator

A schematic diagram of the system including the oscillator is shown in figure 2. The oscillator consists of a piston attached to a spool valve and a bistable fluid amplifier. The oscillator operates in the following manner. Opening the frequency control valve allows compressed gas to flow to the power nozzle of the fluid amplifier. As the gas issues from the power nozzle as a jet, it attaches either to the right or left side of the amplifier and flows out the corresponding receiver. Assuming the jet initially attaches to the left, flow issues from the left receiver and into the valve housing where it forces the piston to move from left to right. As the piston moves to the right, some of the air in the right side of the housing is entrained through the right receiver of the fluid amplifier; air also escapes to the ambient surroundings through the bleed. Motion to the right continues until the left striker contacts the left feedback trigger, at which time the amplifier is switched by a pulse of air from the left feedback line. Switching the amplifier output to the right receiver reverses the motion of the piston, and it travels to the left until the right striker hits the right feedback trigger. Switching is accomplished in the same manner as before, and the cycle is complete. Increasing the input pressure to the fluid amplifier (through the frequency control) causes the piston to move faster and increases the frequency of the oscillator.

The spool valve, which is attached to the oscillator piston, controls the flow of gases to the ram assembly. It is designed so that when the groove opens the inlet port to allow gases to flow to the ram assembly, the exhaust port is closed. Similarly, when the groove opens the exhaust port to relieve the pressure inside the ram assembly, the inlet port is blocked.

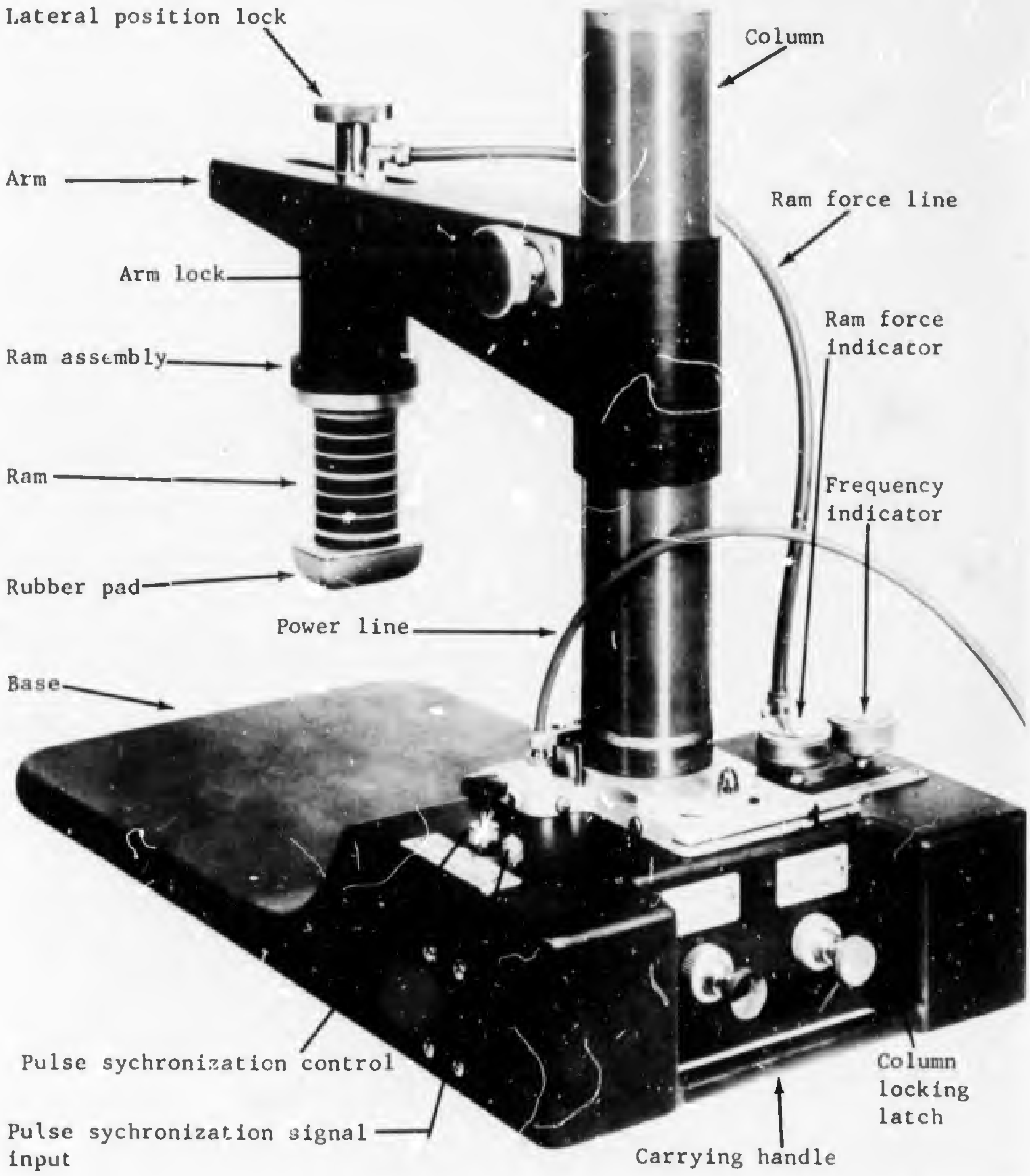


Figure 1. Army external cardiac compressor.

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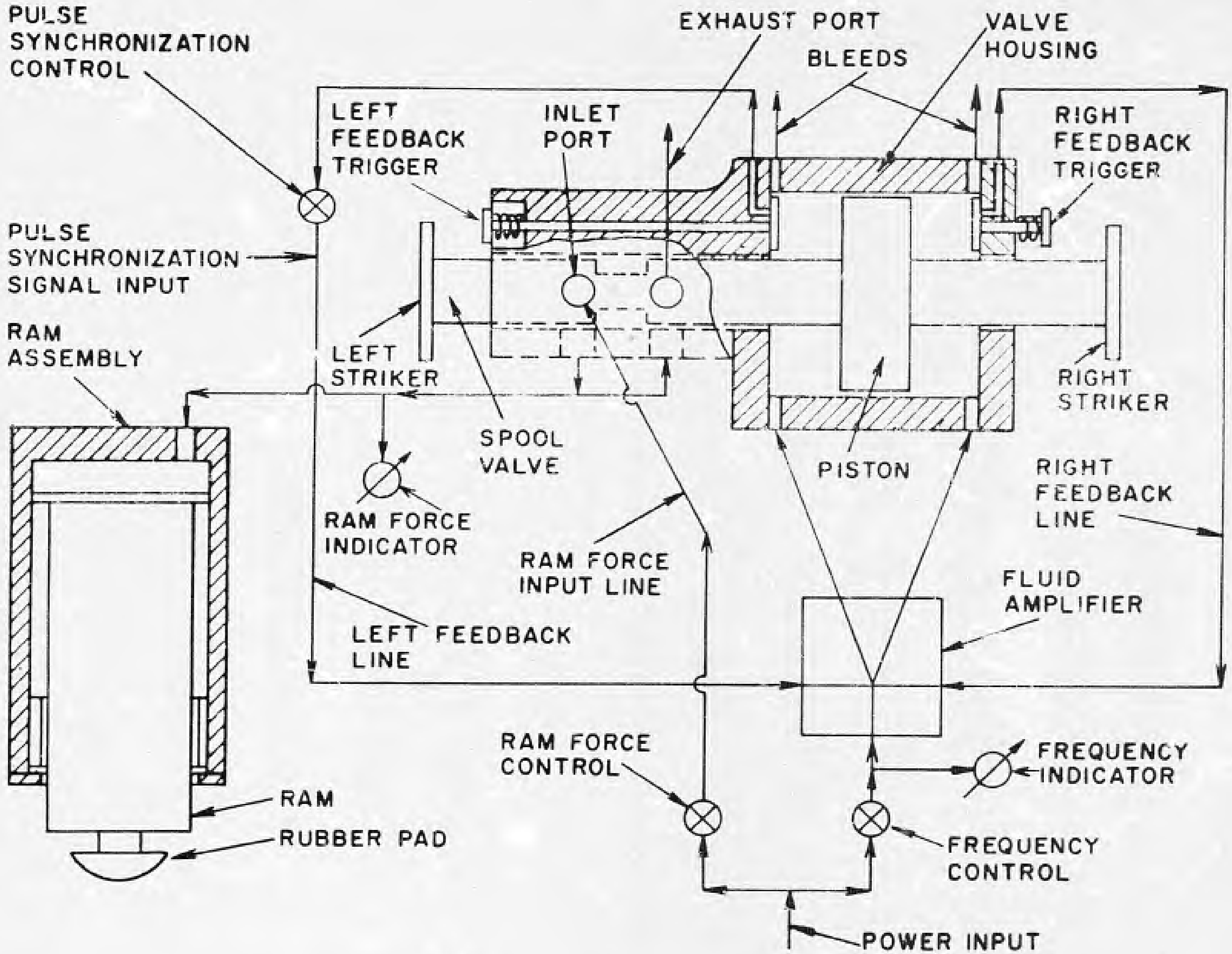


Figure 2. Army ECC schematic diagram.

3.2 Ram Assembly

As previously explained, the spool valve controls the flow of gases to the ram assembly. The force produced by the ram is determined by the adjustment of the ram force control (fig. 2) which regulates the pressure applied to the spool valve. The ram force indicator is a pressure gauge recalibrated to read available force directly in pounds. The downward excursion of the ram will depend on the force applied and the spring constant of the patient's chest. The ram is returned to the reset position by the elastic force of the chest. The ram is constructed to permit a maximum excursion of 7.5 cm (3 in.).

3.3 Pulse Synchronization

This ECC can be synchronized with any phase of the heart's pumping cycle by using a normally closed solenoid valve and a cardiac programmer. The programmer provides the electrical signal (using the EKG signal from the patient) to activate the solenoid valve. The solenoid valve, when triggered, sends a pneumatic signal to the fluid amplifier driving the oscillator. The pulse synchronization control (fig. 2) blocks the signal from the left feedback trigger, so that switching the amplifier from the left to the right receiver can occur only when the signal comes from the solenoid valve. The action of the right feedback trigger is unchanged.

## 4. PERFORMANCE CHARACTERISTICS

To study some of the performance characteristics of the ECC, a series of experimental tests was performed. Two springs, one having a spring constant of 5.4 kN/m (31 lb/in.) and the other 11.2 kN/m (64 lb/in.), were used to simulate the chest. The rubber pad attached to the ram was initially positioned in contact with one of the springs so that the full 7.5 cm (3 in.) ram travel was available, but with no initial deflection of the spring. A pressure transducer monitored pressures in the ram assembly, from which ram forces could be calculated using the ram cross-sectional area; a displacement transducer monitored ram displacement. The outputs of the transducers were displayed on a storage oscilloscope. Input pressure to the oscillator was measured with a pressure gauge.

4.1 Oscillator Frequency

The basic part of the ECC is the oscillator. Figure 3 shows oscillator cycling rates as a function of input pressure for ram forces of 0.18 and 0.62 kN (40 and 140 lb). These results indicate that oscillator frequency increases with increasing input pressure and is

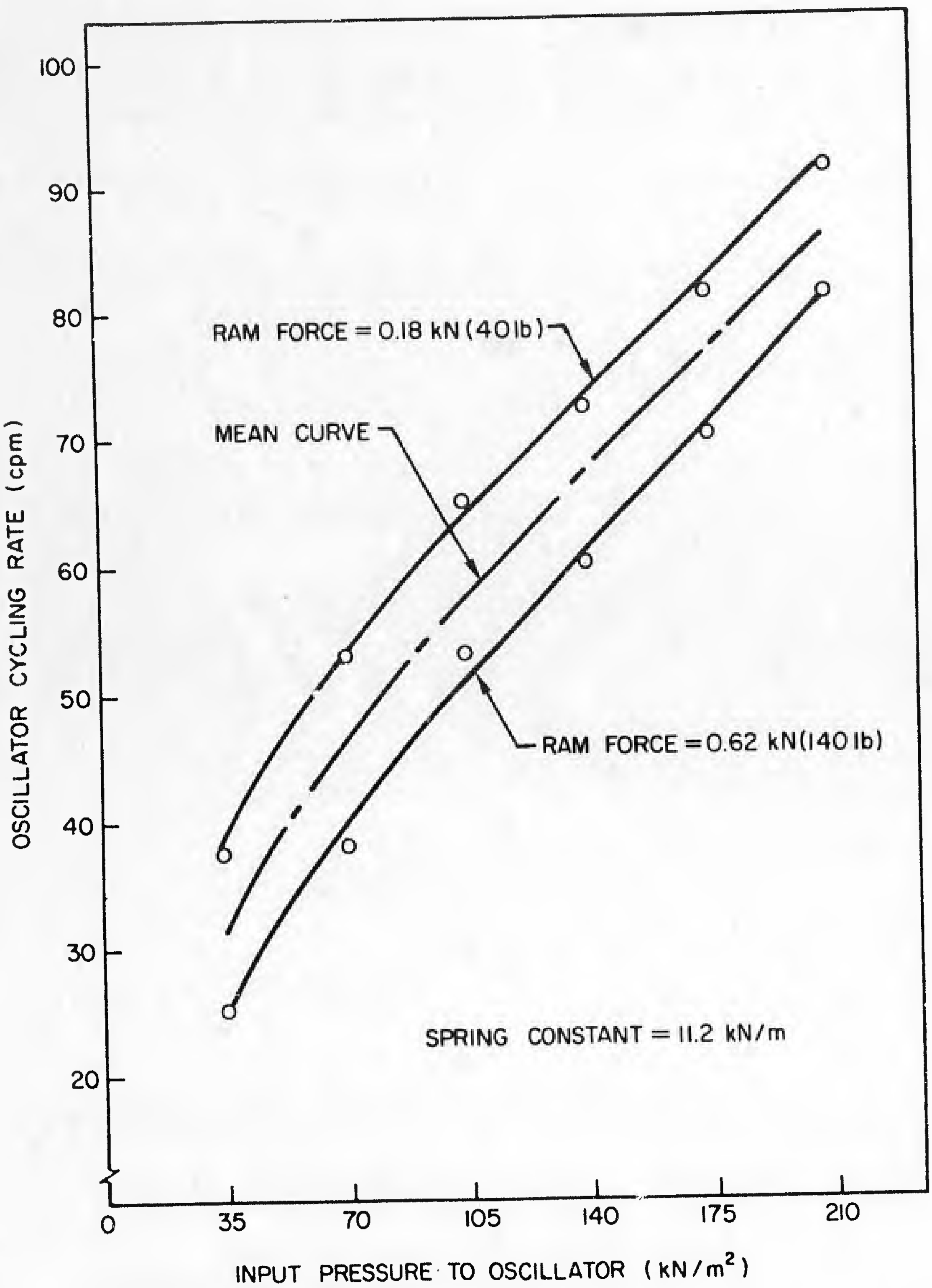


Figure 3. Oscillator frequencies.

affected by ram force so that the higher ram force causes the oscillator to slow down. Frequency increases because as input pressure increases the output pressures and flows from the fluid amplifier also increase and, in so doing, drive the oscillator piston faster.

The mean curve shown in figure 3 is constructed from the midpoints of the data for the two given ram forces. These two ram forces represent realistic extremes that would be encountered in actual use. The frequency values from the mean curve are used to construct the frequency control indicator—a pressure gauge that monitors oscillator input pressure (fig. 2). The dial of this gauge is modified to read frequency instead of pressure, using the relationship determined by the mean curve in figure 3. Using the mean curve frequency values, the error would not exceed 8 cpm, based on the extremes of ram forces tested. The mean frequencies range from 30 to 85 cpm for the oscillator tested. Minor modifications could be made to the oscillator to alter this range if necessary. However, most ECC devices presently in use have cycling rates around 60 cpm, so that the range offered by this oscillator seems adequate.

### 4.2 Ram Displacement

Ram displacement, representing chest deflection, is illustrated in figure 4 as a function of peak ram force for each of the two springs used. The data show that displacements up to 7.5 cm (3 in.) and peak ram forces up to 0.62 kN (140 lb) were achieved. The linearity of the data merely verifies that the springs used have linear force-displacement relationships over the range tested. The data also show some variations produced by different oscillator input pressures (corresponding to different oscillator cycling rates), but these variations are probably due mostly to experimental errors, inasmuch as there is no clear trend of the effect of oscillator cycling rate on the force-displacement curve.

### 4.3 Pulse Shape

The pulse shape of the ECC can be altered to produce different ratios of the compression stroke duration ($t_s$) to the period of a cycle (T). This adjustment is made by moving the right striker along the oscillator shaft, thereby changing the distance between the right striker and the oscillator valve housing (distances measured with the left striker touching the left feedback trigger). Figure 5 shows that for the distances used, $t_s/T$ ratios from 0.21 to 0.45 were obtained. Because the ECC oscillator was designed originally to produce a $t_s/T$ ratio of approximately 0.5, distances greater than those shown in figure 5 could not be tested because of limitations in the hardware. However, tests on an earlier model oscillator showed that $t_s/T$ ratios as high as 0.73 could be achieved. All other tests in this report are for a $t_s/T$ ratio of 0.45.

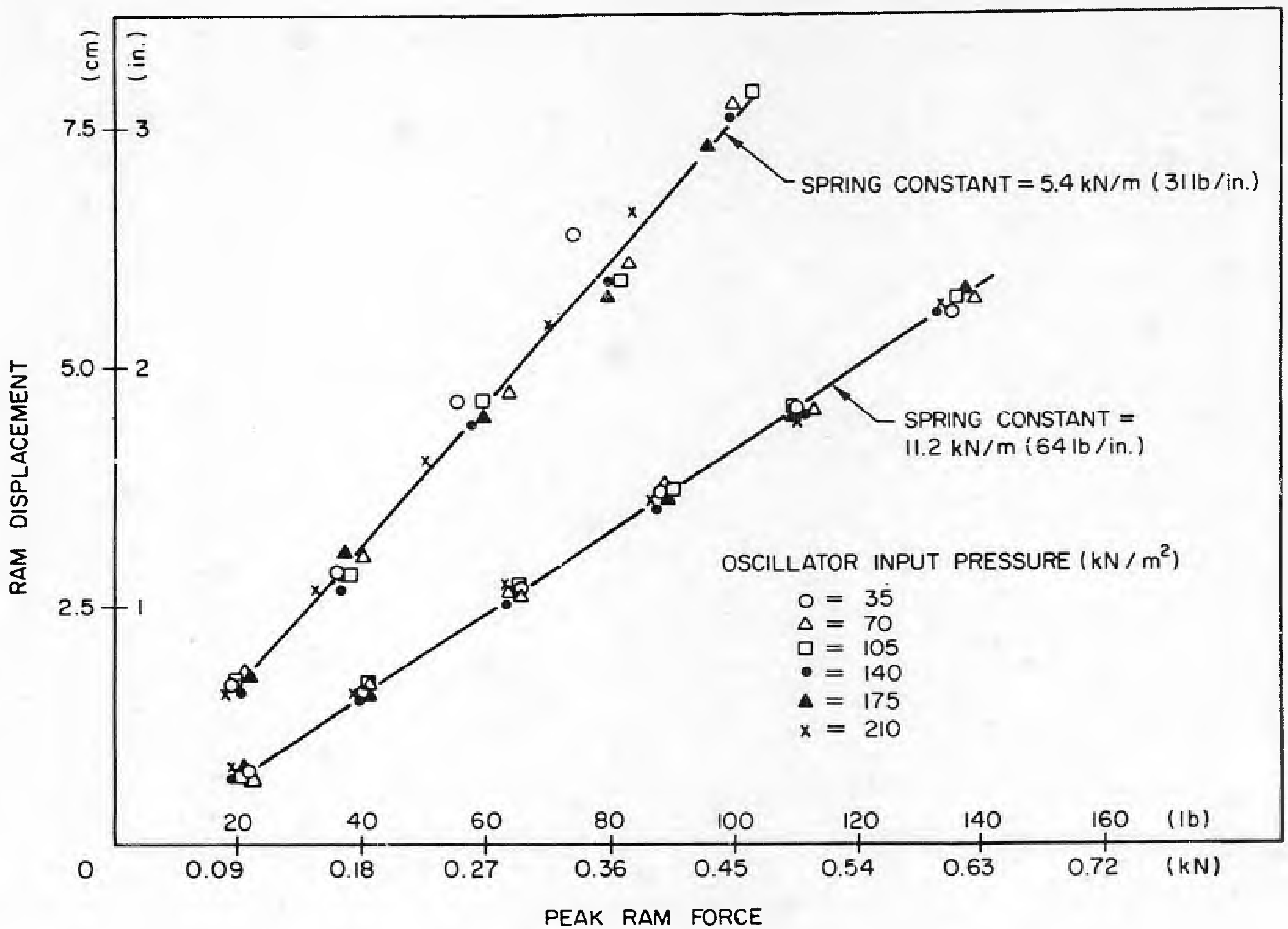


Figure 4. Ram displacement.

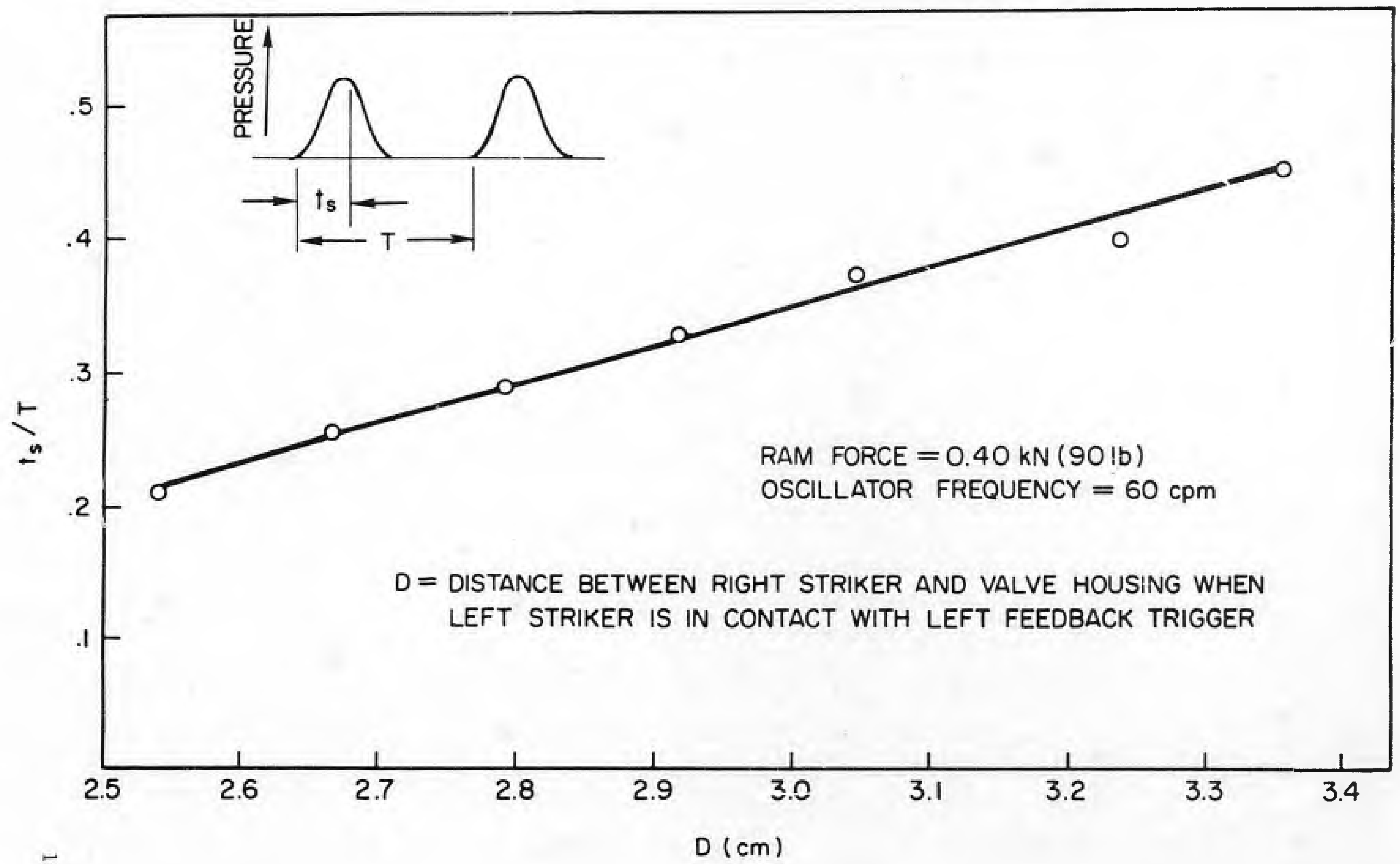


Figure 5. Pulse shapes.

The adjustment of the right striker is not intended to be incorporated into the ECC as an external control but would be set during assembly to produce the desired $t_s/T$ ratio. In the first prototypes of the ECC, this ratio was set for approximately 0.5.

## 5. PRELIMINARY MEDICAL EVALUATION

Two dog tests have been performed at WRAIR using the time-cycled ECC. The general procedure in these tests has been to use electrical shock to produce fibrillation in an anesthetized dog. The ECC is then used to maintain the animal's circulation. Arterial pressures are monitored from the femoral artery using an appropriate transducer and a chart recorder.

In the first animal test, a prototype of an earlier stroke-limited ECC (ref 9) was modified to be driven by the type of oscillator described in this report. The oscillator overrode the stroke-limited mode of operation with time-cycled performance. This modified unit was then applied to a 0.09 kN (20-lb) dog using the procedure outlined above. Arterial pressures were maintained at 65 mm Hg in the dog, and the chest deflection curve (as a function of time) had a steeper slope than those for similar curves obtained previously from the stroke-limited ECC.

The second test was performed with the time-cycled ECC prototype (fig. 1). In this test the Army ECC was alternated with a commercially available ECC in 10-min intervals of operation. During the time that machines were interchanged, hand massage was administered to the animal. The test results are summarized in table I. After the second run with the HDL unit, the ram force was increased from 0.22 kN (50 lb) to 0.44 kN (100 lb), at which time a large increase in arterial pressure was observed and the test was terminated.

Table I. Medical Test Results (Test No. 2)

| Duration (min) | Type | Ram force (kN) | Ram frequency (cpm) | Peak arterial pressure (mm Hg) |
|---|---|---|---|---|
| 10 | HDL | 0.22 | 60 | 45 |
| 10 | Commercial | 0.22 | 60 | 55 |
| 10 | HDL | 0.22 | 60 | 65 |
| 10 | HDL | 0.44 | 60 | 90 |

The results of both animal tests show that the Army ECC was able to maintain adequate circulation in the dog. Further testing is necessary to determine accurately the degree to which this circulation is maintained.

## 6. SUMMARY

A time-cycled ECC has been designed and fabricated for the Army to aid in the resuscitation of patients suffering cardiac arrests. With only two controls—ram force and frequency—this ECC offers extreme simplicity of operation. The performance characteristics of the ECC reveal that it can produce ram forces up to at least 0.62 kN (140 lb) and chest deflections up to 7.5 cm (3 in.). Cycling rate is variable from 30 to 85 cpm and is only slightly affected by changes in ram force. The oscillator in the ECC can be adjusted to produce compression to total period ratios from 0.21 to 0.73, although this adjustment is not in the form of an external control. The ECC is also capable of being synchronized with an EKG or other externally generated signal.

Early medical evaluation indicated that the Army ECC was able to maintain blood circulation within dogs at an adequate level. Further medical testing will be required to determine the overall effectiveness of this ECC as a resuscitative device.

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13. ABSTRACT

During cardiac arrest, the flow of oxygenated blood to the brain becomes insufficient to support life. With new methods of cardiopulmonary resuscitation, blood circulation can be maintained, the heart restarted, normal circulation resumed, and the patient's life saved. One method of maintaining circulation during this critical resuscitative period consists of rhythmically depressing the chest, thereby squeezing the heart and forcing blood to circulate. This method is known as external cardiac compression.

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| Resuscitation | 7 | 3 | | | | |