Optimal Parameters of Electrical Impulses for Defibrillation by Condenser Discharges

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■ Determination of the defibrillation threshold of the heart is important not only for developing the technique of defibrillation per se but also for improving the design of instruments used for that purpose. Previous work[1,2] has shown the necessity of selecting, for the discharge circuit, parameters that will keep voltage as low as possible, but many questions concerning the optimal parameters for d-c condenser discharges still remain unanswered. Gurvič[3] has described a major portion of existing information on this subject, and Mackay and Leeds[4] have studied optimal parameters for condenser discharges up to 15 microfarads (μF). However, none of the work reported thus far has utilized a wide enough range of capacitances; the actual voltage at the electrodes was not measured; and inductive effects in the discharge circuit were not taken into account.

The present paper reports results based on more than 1000 measurements of defibrillation threshold, together with statistical evaluation of effects obtained by means of three different types of condenser discharge. In all experiments we measured the voltage at the condenser, the voltage at the electrodes, and the current and duration of the discharge impulse. In order to exclude the influence of ischemia[5-7] and other technical artefacts, the experiments were done under standard conditions and for this reason the results are valid only for the given technique. Defibrillation thresholds were determined for three types of discharge: 1) pure condenser discharge, as used most frequently in the literature but with very variable results; 2) condenser discharge through an iron core inductance of 0.25 henry, as used in our first apparatus, and 3) discharge through an inductance of 0.29 henry but without a core. The parameters of these discharges were recorded photographically, with triggering from a special synchronizing circuit.

It was found that the third method produced fewer cardiac arrhythmias and that capacitances ranging from 4 to 200 μF were satisfactory.

Methods

EQUIPMENT DESIGN AND USAGE

A diagram of the equipment and its arrangement are shown in figure 1, as follows: (A) electrocardiograph (ECG) with oscilloscope for continuous control and recording of cardiac action (Mingograf 42), (B) condensers, (C) electronic switch for the synchronizing circuit, (D) oscilloscope showing the shape of the discharge, (E) camera for recording from D, and (F) synchronizing circuit, that 1) opened the leads to the electrocardiograph during the discharge and then reconnected them, and 2) connected the discharge circuit to the animal.

Cardiac potentials were recorded on the electrocardiograph through the relay. The oscilloscope lead inputs were connected to the animal through a resistance divider. The entire procedure was started by a contact on the camera. This contact, by means of two synchronizing contacts, set into motion the time base of the oscilloscope and the synchronizing circuit. The latter then disconnected the electrocardiograph and, through the electromagnetic switch, caused a condenser discharge to be delivered to the heart. The electrocardiograph was then reconnected automatically.

PREPARATION OF ANIMALS AND PROCEDURE

Experiments were done on dogs (body wt 20 to 25 kg) under thiopental (Pentothal) anesthesia (20 to 40 mg/kg). The limb lead electrocardiograms were recorded and arterial pressure was measured through a catheter in the femoral artery. On the posterior and anterior walls of the thorax were placed two electrodes, 15 x 17 cm,
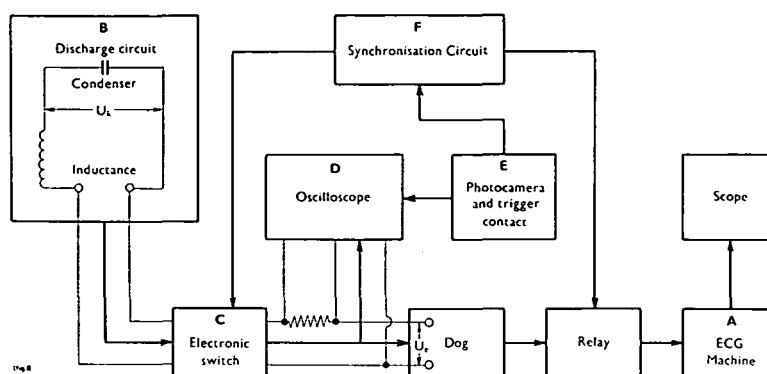
FIGURE 1

Diagram of equipment used to determine the defibrillation threshold of the heart. See text.

made of lead. The sites of application had been shaved and ECG paste applied for good electrical contact.

Ventricular fibrillation was produced by a 40-volt burst of alternating current from the power lines for 0.8 sec through the electrodes on the thorax. After 7 to 10 sec the first defibrillating shocks were administered at selected levels close to the expected threshold voltage. If defibrillation occurred, the procedure was repeated after 30 to 60 sec, with a shocking voltage lower by 100 volts, and so forth. The last 100-volt step that was successful in producing defibrillation was considered to be the threshold value.

If the first shock was not successful, the procedure was repeated with a voltage higher by 100 volts until defibrillation was attained. If this could not be accomplished within 30 sec, a standard 2500-volt shock was used to prevent myocardial ischemia. The finally attained threshold values were then repeated, or corrected.

During these preliminary procedures photographic records were not taken. When the threshold value was determined, shocks were repeated with recordings, including the voltage actually delivered to the electrodes during the first record, and including the delivered current (through a series resistor) in the second repetition. Voltage, current and time constants had been calibrated previously on the oscilloscope, so that absolute measurements could be made from the subsequent films.

In a single animal we were able to record 5 to 10 defibrillation thresholds, i.e., 30 to 40 discharges. If, following several discharges, the ECG or other parameter of cardiac action changed, the animal was no longer used. For each capacitance value selected, about 40 defibrillation thresholds were determined in order to obtain sufficient data for statistical analysis.

Results

Average values for each capacitance were calculated, with 95% confidence limits (table 1). From these data we drew curves of threshold voltage on the condenser, voltage on the electrodes, current, and duration of pulse. In the first group (pure condenser discharge), pulse duration corresponds to the time constant. In the second and third group (discharge with inductance), only the first half-period of the underdamped oscillations was evaluated. Figure 2 presents these data for each group of animals. Figure 3 shows the various wave forms of shocks used. Pulse duration was measured from the voltage curves on the oscillograms. With capacitances of 4 and 8 μF the sensitivity of the oscilloscope (in amplitude) was reduced to 0.5. This explains the lower amplitude of the oscillograms at 4 and 8 μF in figure 3.

A. DEFIBRILLATION THRESHOLD WITH A PURE CONDENSER DISCHARGE

The results obtained by analyzing 343 threshold determinations in this group are shown in table 1A. The graphed results are shown in figure 2A, where the U_k curve indicates the threshold voltage at the condenser, the U_e curve the voltage at the electrodes, I, the maximal current, and T (solid line), the pulse duration. The type of connection in the discharge circuit is shown by the diagram in the upper middle part of figure 2A, just above the curves. Figure 3A shows the shapes of impulses produced by the different capaci-

tances, corresponding to data in figure 2A.

The crosshatched area in figure 2A shows the range of optimal values for this type of impulse. Threshold voltages decrease, along

with current, when capacitance increases. This effect levels off between 66 and 100 μF, and with 200 μF there is a small further decrease but here the increase of energy delivered

TABLE 1

Average Values of Threshold Voltage, Current and Pulse Duration

A: *Defibrillation threshold with a pure condenser discharge*

Capacity, μF	4	8	16	24	32	50	66	100	200
Average voltage on condenser, kV	5.0	3.0	2.3	2.0	1.5	1.5	1.2	1.2	1.0
Average voltage on electrodes, kV,	3.49	2.83	1.97	1.80	1.45	1.23	1.04	1.04	0.89
95% confidence limits	± 0.13	± 0.03	± 0.10	± 0.04	± 0.03	± 0.03	± 0.06	± 0.02	± 0.01
Average current, amp,	89.3	81.1	63.1	51.3	39.3	34.3	27.9	29.9	25.0
95% confidence limits	± 6.5	± 7.2	± 1.6	± 3.4	± 1.02	± 1.1	± 1.2	± 0.8	± 0.6
Average pulse duration, msec,	0.65	1.1	2.1	2.7	3.9	10.0	12.7	16.6	29.6
95% confidence limits	± 0	± 0.2	± 0.1	± 0.2	± 0.4	± 0.6	± 0.8	± 0.7	± 1.8

B: *Condenser discharge modified by an iron core inductance (L = 0.25 henry, R = 20 ohms)*

Capacity, μF	4	8	16	24	32	50	66	100	200
Average voltage on condenser, kV	4.4	2.9	2.2	1.9	1.4	1.4	1.2	1.2	1.0
Average voltage on electrodes, kV,	2.01	1.89	1.33	1.29	0.95	0.90	0.82	0.83	0.77
95% confidence limits	± 0.15	± 0.27	± 0.02	± 0.03	± 0.01	± 0.02	± 0.03	± 0.01	± 0.01
Average current, amp,	59.8	51.7	39.3	35.5	26.5	24.8	22.1	23.8	21.7
95% confidence limits	± 5.0	± 4.3	± 0.4	± 0.8	± 0.5	± 0.7	± 0.6	± 0.4	± 0.5
Average pulse duration, msec,	1.7	2.9	4.7	6.5	8.5	12.8	15.1	18.6	31.6
95% confidence limits	± 0.1	± 0.2	± 0.2	± 0.3	± 0.3	± 0.9	± 0.9	± 0.8	± 1.8

C: *Condenser discharge modified by an inductance without a core (L = 0.29 henry, R = 27 ohms)*

Capacity, μF	4	8	16	24	32	50	66	100	200
Average voltage on condenser, kV	5.0	3.4	2.5	2.3	1.8	1.7	1.5	1.5	1.3
Average voltage on electrodes, kV,	0.76	0.85	0.58	0.51	0.53	0.54	0.52	0.57	0.56
95% confidence limits	± 0.04	± 0.06	± 0.01	± 0.01	± 0.01	± 0.01	± 0.01	± 0.01	± 0.01
Average current, amp,	17.8	21.4	15.1	16.0	13.7	13.9	13.3	15.5	15.3
95% confidence limits	± 1.5	± 1.7	± 0.1	± 0.2	± 0.2	± 0.4	± 0.2	± 0.5	± 0.2
Average pulse duration, msec,	4.3	6.5	8.3	10.0	11.7	16.3	19.6	25.3	41.9
95% confidence limits	± 0.1	± 0.3	± 0.4	± 0.1	± 0.3	± 0.4	± 0.4	± 1.2	± 1.6

would more than make up for the decreases in potential and current. Thus 66 μF appears to be the most advantageous capacitance to use, with a maximal voltage of 1000 volts, maximal current of 28 amperes, and pulse duration of about 13 msec.

B. CONDENSER DISCHARGE MODIFIED BY AN IRON CORE INDUCTANCE

The 0.25 henry inductance had a resistance of 20 ohms and was inserted in series. This group of observations included 379 tests (table 1B). Figure 2B shows the results in graphic form, including voltage, current and
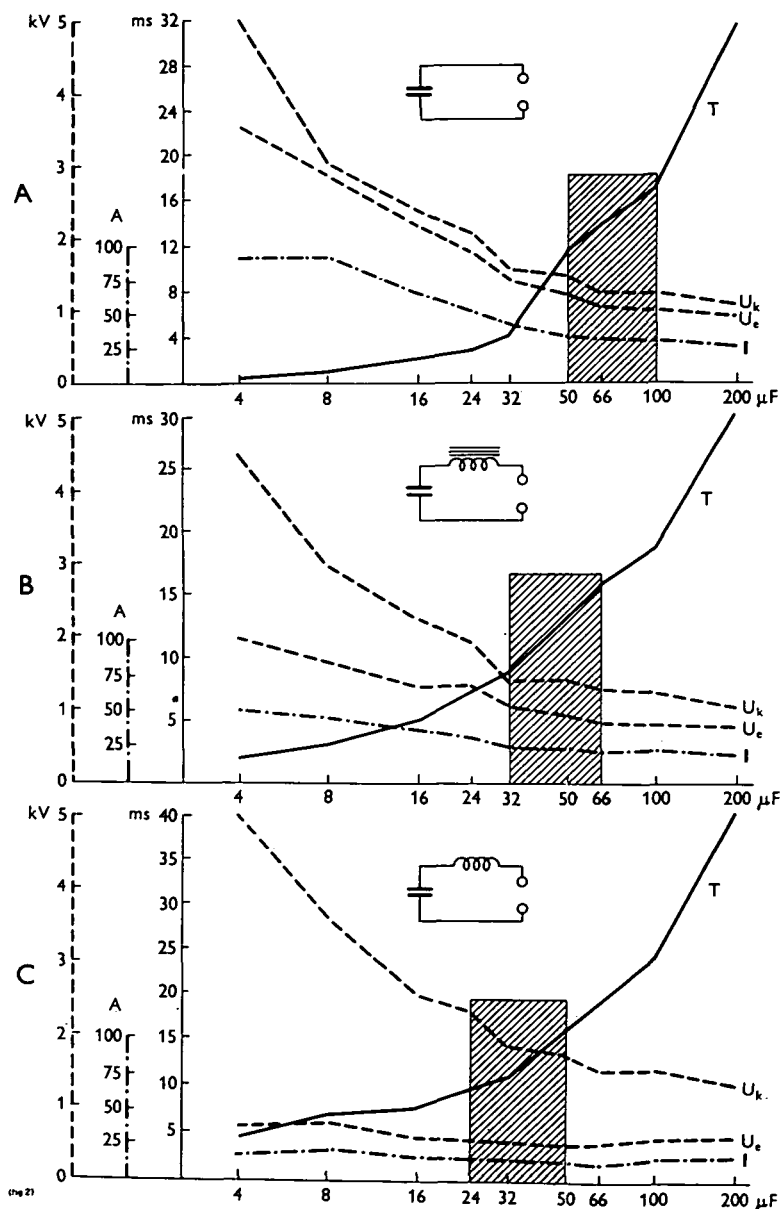

FIGURE 2

Electrical parameters of defibrillation impulses. A: pure condenser discharge; B: condenser discharge through an iron-core inductance of 0.25 henry, 20 ohms; C: condenser discharge through inductance without core, 0.29 henry, 27 ohms. U_k: condenser voltage, U_e: electrode voltage, I: current, T: pulse duration. Crosshatching indicates optimal parameters.
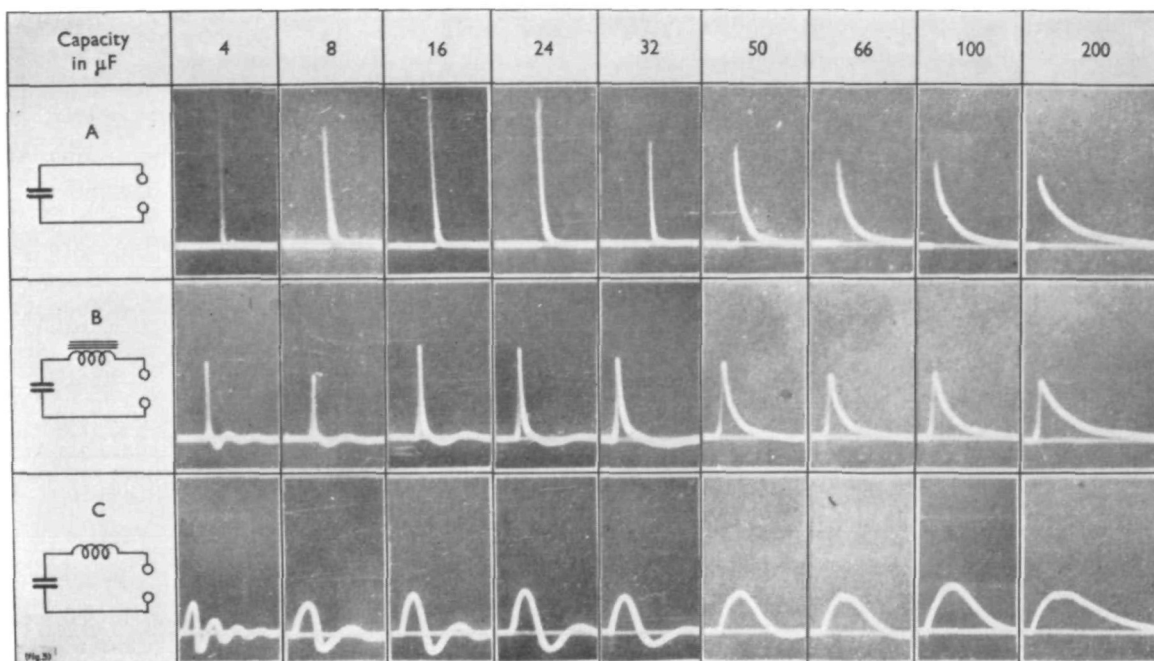
FIGURE 3

Oscillograms of wave forms of defibrillation pulses. A: pure condenser discharge; B: iron-core inductance, 0.25 henry, 20 ohms; C: inductance without core, 0.29 henry, 27 ohms.

durations of impulses. Here we can see the marked difference between condenser voltage and electrode voltage. For example, at 4 μF the electrode voltage is 50% of the condenser voltage. Optimal capacitance in this instance was between 50 and 66 μF, beyond which both voltage and current remained constant and only pulse duration increased. The corresponding wave forms are shown in figure 3B.

C. CONDENSER DISCHARGE MODIFIED BY AN INDUCTANCE WITHOUT A CORE

The 0.29 henry inductance had a resistance of 27 ohms, and this set of tests included 381 measurements. Table 1C, figures 2C, and 3C give the appropriate data. In this instance we found the greatest differences between condenser and electrode voltages. Maximal electrode potential was 850 volts at 8 μF, and the smallest values were found in the range 24 to 60 μF. The smallest current value was found at 66 μF, but was associated with a considerably longer pulse duration. When the smallest capacitance (4 μF) was used, the voltage at the condenser (U_k) was seven times as large as the electrode voltage (U_e). The

smallest electrode voltage measured was 510. Optimal capacitance here was between 24 and 50 μF.

From these results it appears that a pure condenser discharge is the least advantageous of the three circuits tested. With a capacitance range of 4 to 200 μF, maximal values of threshold voltage, measured at the electrodes, varied from 3500 to 900 volts, and current from 89 to 25 amp. Pulse durations ranged from 0.7 to 28.6 msec. The most advantageous capacitances with this wave form were 50, 66, and 100 μF.

With an iron-core inductance in series, lower defibrillation threshold values were found. Thus, in the same capacitance range, maximal electrode voltages ranged from 2000 to 770 volts, current from 60 to 22 amp, and pulse duration from 1.7 to 31.6 msec. The optimal capacitance range was 32 to 66 μF.

The most advantageous parameters were found with an inductance minus the iron core. Maximal voltage was 850, with current of 21 amp. Minimal values were 510 and 13 respectively. The most advantageous capacitances
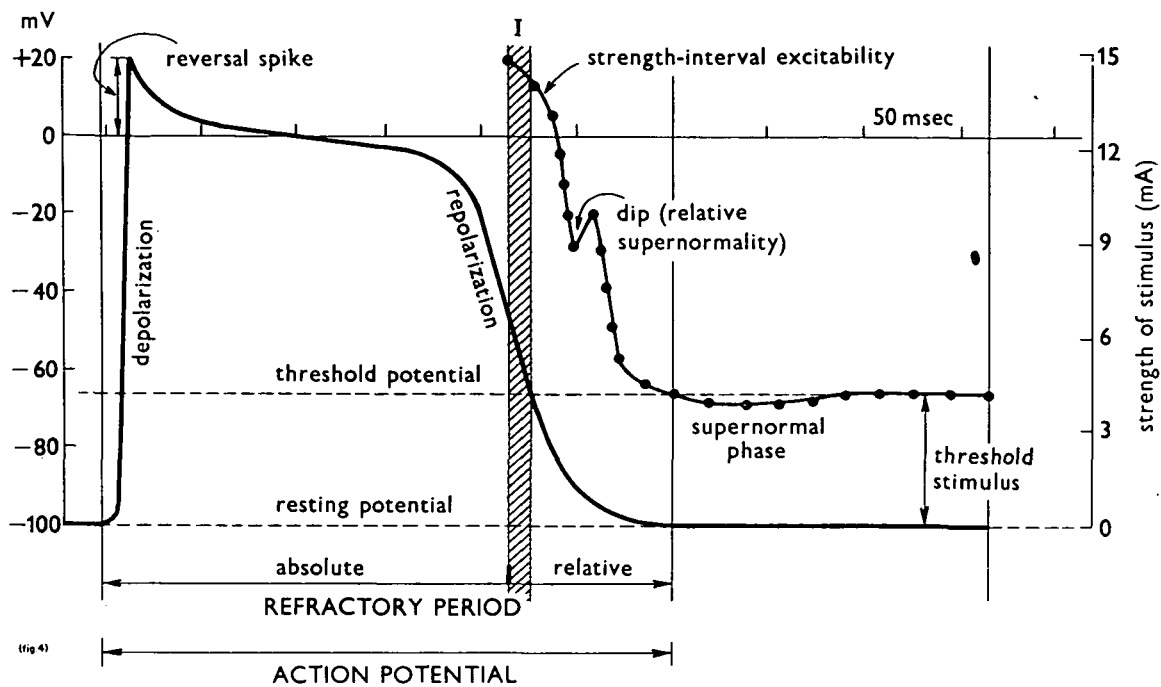
FIGURE 4

Action potential of cardiac fibers. I: localization and probable optimal pulse duration for condenser discharge to produce synchronization of myocardial excitability.

were 24, 32, and 50 μF, with pulse durations of 10, 11.7, and 16.3 msec.

Discussion

Defibrillation thresholds and their relationships have been studied by many investigators under different conditions.[8-12] Some of these reports have emphasized the importance of voltage or current, others capacitance, and some, the total delivered energy. These values are interrelated, but some are of greater biological importance than others for the given objective. On the basis of our previous results[1, 2, 13] we can define the optimal defibrillation impulse as that which produces the least functional and morphological damage to the myocardium. The relative importance of the various physical parameters would appear to be: 1) minimal voltage and current, and 2) minimal delivered electrical energy.

When the above parameters are optimal, pulse duration becomes important. If we compare the parameters of the discharges in figure 2, where crosshatching indicates optimal values, it can be seen that pulse duration is

about the same in this region for all three types of discharge, ranging from 8.5 to 16.6 msec with mean of 12 msec. Capacitance values less than those in the crosshatched area produce shorter pulse durations with increased voltage and current, an undesirable effect. With higher capacitances neither threshold current nor voltage decreased, but pulse duration was immoderately prolonged, and with it the total delivered energy. Again these are undesirable effects, not only biologically but also in terms of efficiency with battery instruments. Further studies, in which inductance was changed and capacitance remained constant, have confirmed the importance of pulse duration. The lowest threshold voltage was found again in the same range of pulse duration. Decreasing of inductance has a limit, after which defibrillation thresholds again start to rise.

Theoretically, this relationship to pulse duration might be explained on the basis of factors indicated in figure 4, which shows the course of cardiac potentials and excitability during a single cycle. Defibrillation involves a synchro-

nization of all the fibers in the heart, bringing them all into the same phase, i.e., the absolute refractory period (ARP). Fibers in the excitable period (EP) can be transformed into the ARP with weak currents. It is important to bring fibers from the relative refractory period (RRP) to the absolute refractory period, particularly those at the start of the excitability, that are in transition from ARP to RRP, and have a low excitability and high threshold. In other words, the duration of the defibrillation pulse should be long enough to carry over the relatively inexcitable fibers to the stage of excitability. This duration is 12 to 15 msec and the crosshatched column I in figure 4 shows this. Detailed investigations into the effects of pulses of different durations would have both biological and technical importance.

Prolongation of pulse duration beyond 16 msec does not involve a decrease of defibrillation threshold. Indirect defibrillation uses alternating current, 440 volts for 0.25 sec. If this value of voltage is transformed into a maximal value (peak-to-peak), the impulse voltage is about 620 volts. Even if maximal values of voltage, alternating current, etc. do not differ much from those of a condenser discharge, pulse duration is 15 times longer. It would appear that this duration is too long, and for that reason, of low efficiency. Lown et al.[14] have also presented evidence that condenser discharge is more effective than alternating current in producing defibrillation.

Summary

The defibrillation threshold for various wave forms of condenser discharge, using capacitors from 4 to 200 μF, has been measured. Condenser discharge alone was used, or condenser discharge 0.25 henry (20 ohms) with an iron core series inductance, or condenser discharge, 0.29 henry (27 ohms) inductance, but without the iron core. Statistical analysis of the results showed that the last of these three circuits gave the lowest threshold voltage values. Optimal parameters of inductance-altered discharges are obtained with values of 24, 32, and 50 μF.

Detailed analysis of the separate physical parameters of the discharge show that optimal pulse duration is 8.5 to 16.6 msec. Further increase of duration does not decrease the voltage or current for threshold shocks, but merely increases the energy delivered. Pulse duration appears to be one of the more important parameters for successful defibrillation, and for this reason, a series inductance is also important.

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