FATIGUE OPTIMAL SELECTIVE ELECTROBLOCK PARAMETERS IN THE LINEAR CONTROL OF PARALYZED MUSCLE FORCE

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ABSTRACT

The fatigue properties of the Selective ElectroBlock (SEB) are investigated as a function of drive frequency, SEB frequency and SEB level in order to demonstrate the clinical potential of rate and recruitment control in paralyzed muscles.

It was shown that simultaneous control of rate and recruitment is feasible with no apparent induction of fatigue if drive frequencies of less than 50 pps are used in conjuntion with the SEB.

It was also shown that less than 10% additional fatigue (above normal) are present for drive frequencies of 50 pps regardless of SEB frequencies or levels. Optimal drive and SEB parameters are presented for application in the linear control of muscle contractile force with minimal fatigue induction.

INTRODUCTION

In a previous paper, "A New Technique for Funcitonal Neuromuscular Stimulation" (1), we discussed the feasibility of simultaneous control of rate and recruitment in paralyzed muscles by employing the selective ElectroBlock. In order to demonstrate the clinical potentioal of such a technique, it is necessary to test and define the extent of muscle fatigue under the various stimulation conditions.

The following sections will present an experimental set-up, data and their analysis relating the extent of muscle fatigue due to drive frequency, blocking effectiveness, and block frequency. Further insite is presented as to the optimal drive and block parameters that will minimize muscle fatigue and that will thereby render the proposed technique as clinically feasible.

METHODS

Six adult cats were used. The cats were anesthetized with a solution of chloralose and urethane (1% and 10% respectively). This anesthetic agent was chosen as it does not appreciably affect the excitability of motor endpalates, as may barbituate, steroid and some gaseous anesthetic agents. A lumbosacral laminectomy was performed, and the lumbar, hip and leg regions denervated except for the medial gastrocnemius or soleus muscle. The nerves to one of these muscles were dissected free over a distance of 2 to 4 cm, and the attempt made to free it from its sheath. At the heel, fascial extensions of the hamstring muslces and the plantar tendon were cut, and a fine steel cable with adjustable length was fixed into the severed tendon of the muscle understudy for later attachment to a strain gage. The animal was then firmly fixed in a frame by: a pelvic support, a clamp on a spinous process, and pins through the femoral condyles, with the thigh and lower leg partially extended. Oil pools were formed at spinal, trochanteric and popliteal levels, which premitted placement of electrodes on the S_1 ventral root, the sciatic nerve at the trochanteric or mid-femoral level, and on the muscle nerve. Usually, bipolar hook Ag-AgCl electrodes of 5 mm interpolar distance were used, though wider spacing, tripolar electrodes and wrap around electrodes were also used. In early experiments, the stimuli were delivered by Grass model S4 and S8 stimulators, using capacity coupling at the Grass Voltage regulated isolation units. In subsequent experiments, a "Fired Haer" stimulus generation system and Tektronix Type 2620 voltage regulated stimulus isolators were used. Rest periods were experimentally selected as needed to prevent evidence of fatigue on a subsequent trial. Muscle tension registered either by a Statham strain gage or Grass FT-10 force transducer was recorded on a polygraph. Temperature was monitored by a needle thermode inserted into the anterior compartment of the lower leg and the popliteal oil pool kept at about 37°C by radiant heat. Body temperature was separately maintained by radiant heat.

PROTOCOL

In order to assess the effect of the selective electroblock on muscle fatigue, the following procedure was employed. The drive stimulus was set at 25 pps and suprathreshold level, and was left on for 30 seconds. The muscle was allowed to recover for 3 minutes, and the stimulus was turned on again. This time, a block corresponding to 25% force reduction was applied for 2 seconds, as soon as the muscle force reached its tetanic level. The muscle was allowed to remain contracted for the rest of the 30 seconds. This procedure was repeated for moderate (50% and 75%) and complete (90%) block levels, and for block frequencies of 600, 2K, 5K, 10K, 15K and 20K pps. The residual force at the end of the 30 seconds was measured and compared to the normal residual force without block. Drive frequencies of up to 70 pps were also tested at 10 pps increments. Block pulse width was constant at 40 μs throughout the experiment.

RESULTS

A typical fatigue test sequence is presented in Figure 1. The first recording is the normal fatigue response without block. The following four recordings show fatigue at approximately 25%, 50%, 75% and 90% block levels.

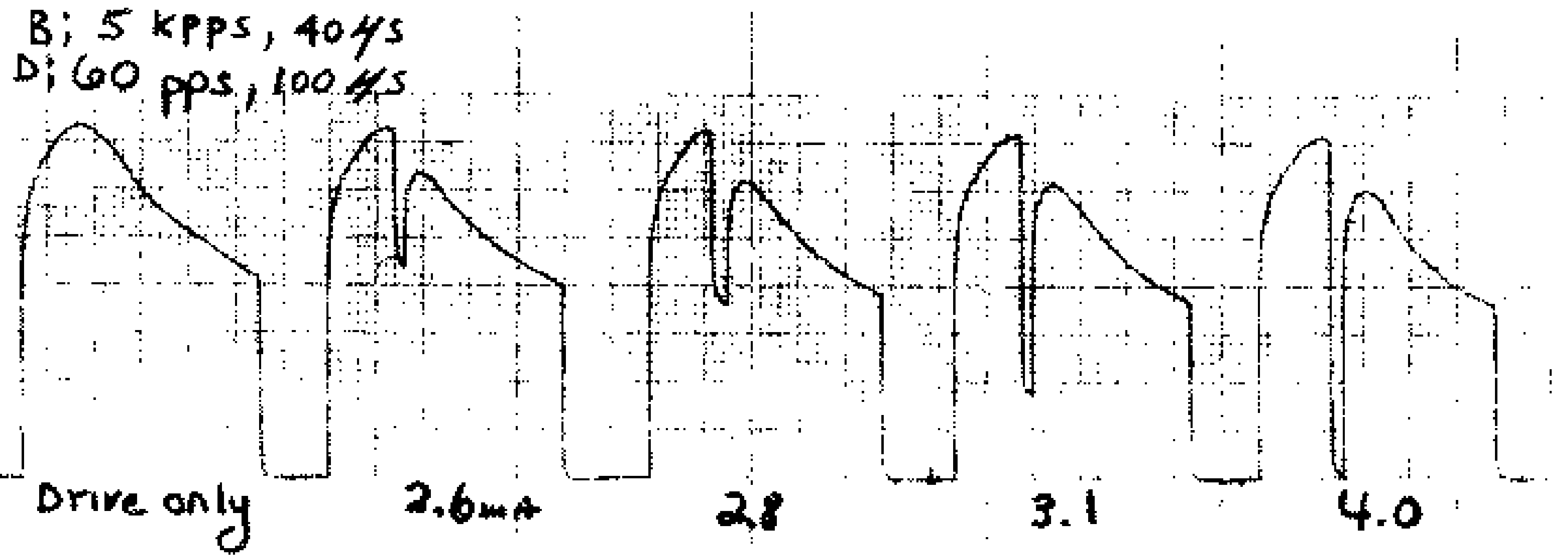

FIGURE 1. MUSCLE FATIGUE RESPONSE FOR SEVERAL BLOCK LEVELS.

In order to assess the muscle fatigue induced by the electroblock, the following relationship is introduced defining the Fatigue Factor (FF):

$$FF = \frac{F_N - F_B}{F_N} \times 100\%$$

where

F_N is the residual force of the muscle at the end of 30 seconds uninterrupted contraction.

F_B is the residual force of the muscle at the end of 30 seconds including 2 seconds block.

FF, therefore, is a relative expression of the muscle fatigue when block is induced during 30 second stimulation.

Expressing the data of Figure 1 in terms of FF as a funciton of BE for several drive frequencies results in the curves of Figure 2. As could be observed from the figure, the fatigue induced is linearly related to the BE, i.e., high BE levels produce more fatigue than lower levels. Furthermore, utilization of high drive frequencies substanitally increases the slope of the curves, i.e., drive frequencies of 70 pps are fast fatigue inducing frequencies. Drive frequencies below 50 pps are less susceptible to fatigue.

Figure 3 illustrates the relationships of the FF to the BE for the various block frequencies, and for the two drive frequencies. It is obvious that drive frequencies of 50 pps result in less than 10% additional fatigue at worst case. At 60 pps, however, FF of over 25% are apparent. Furthermore, it could be observed that some variations in fatiguability are present for the various block frequencies. No definite pattern was detected from one preparation to another to clearly identify the block frequency resulting in the highest fatigue. Additional work is underway to define any such pattern.

Figure 4 represents the same data as FF versus drive frequency for several block frequencies. It is apparent that drive frequencies of less than 50 pps result in an acceptable FF of less than 10%, which is highly promising from the clinical standpoint. Thus, drive frequencies over 50 pps should be avoided in clinical systems.

Figure 5 is presented in order to relate the relative fatigue discussed so far with the tetanic muscle force. It could be observed that the tetanic force completely recovered following the removal of the block signal. Furthermore, in all preparations, the maximal tetanic force maintained itself throughout the 30 seconds test without substantial reduction for drive frequencies less than 40-45 pps. It could be concluded, then, that as long as drive frequencies of less than 50 pps are employed, no significant fatigue is present for the duration of 30 seconds. Such findings are extremely encouraging in regard to the clinical applications of the proposed technique

CONCLUSIONS

The following tentative conclusions could be drawn regarding the fatiguability of the muscle force due to the selective electroblock.

1. Fatigue in muscle force under electroblock is dependent on:
   a. Drive frequency
   b. Block frequency

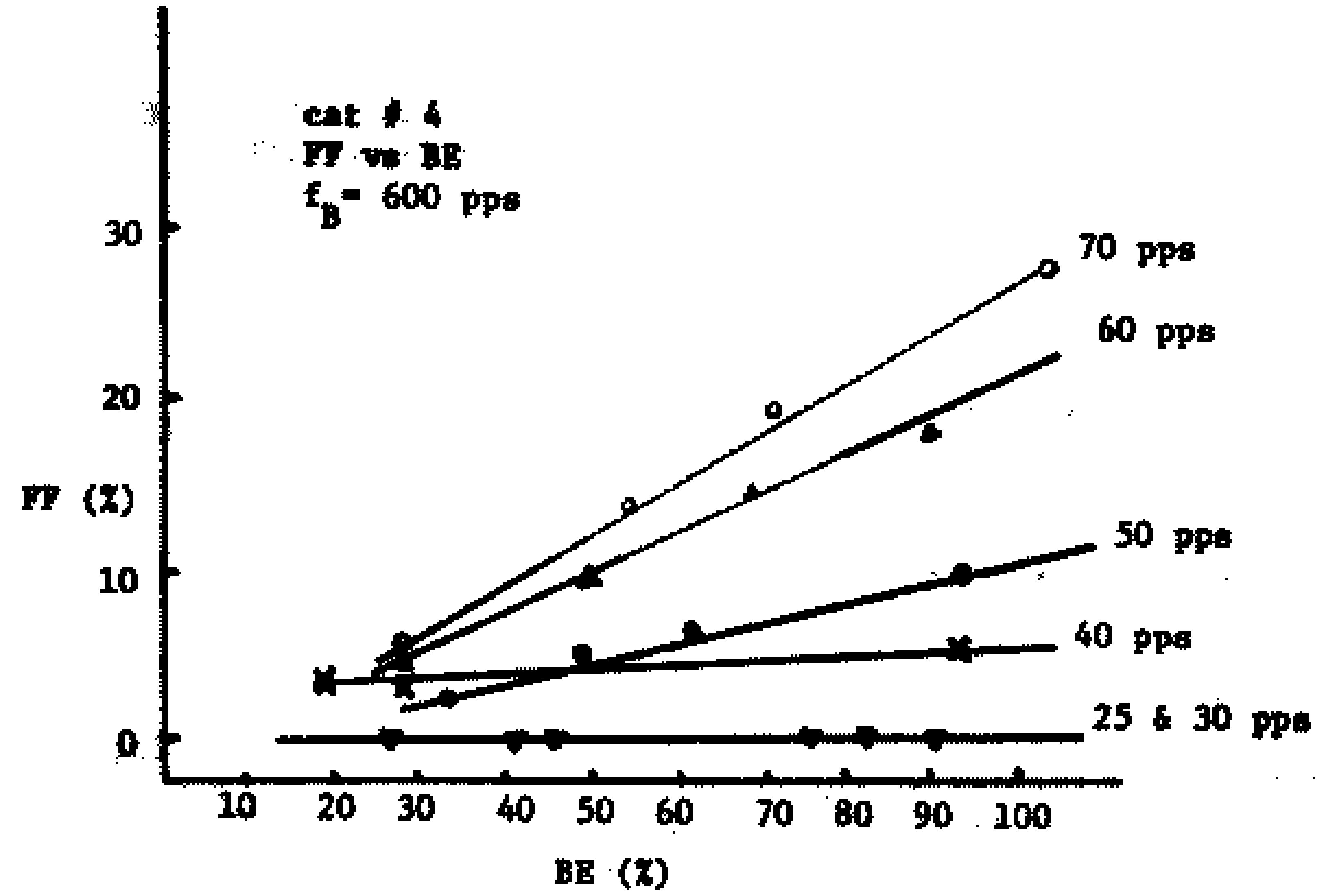

Figure 2. Fatigue Factor as a function of Blocking Effectiveness for several Drive Frequencies.

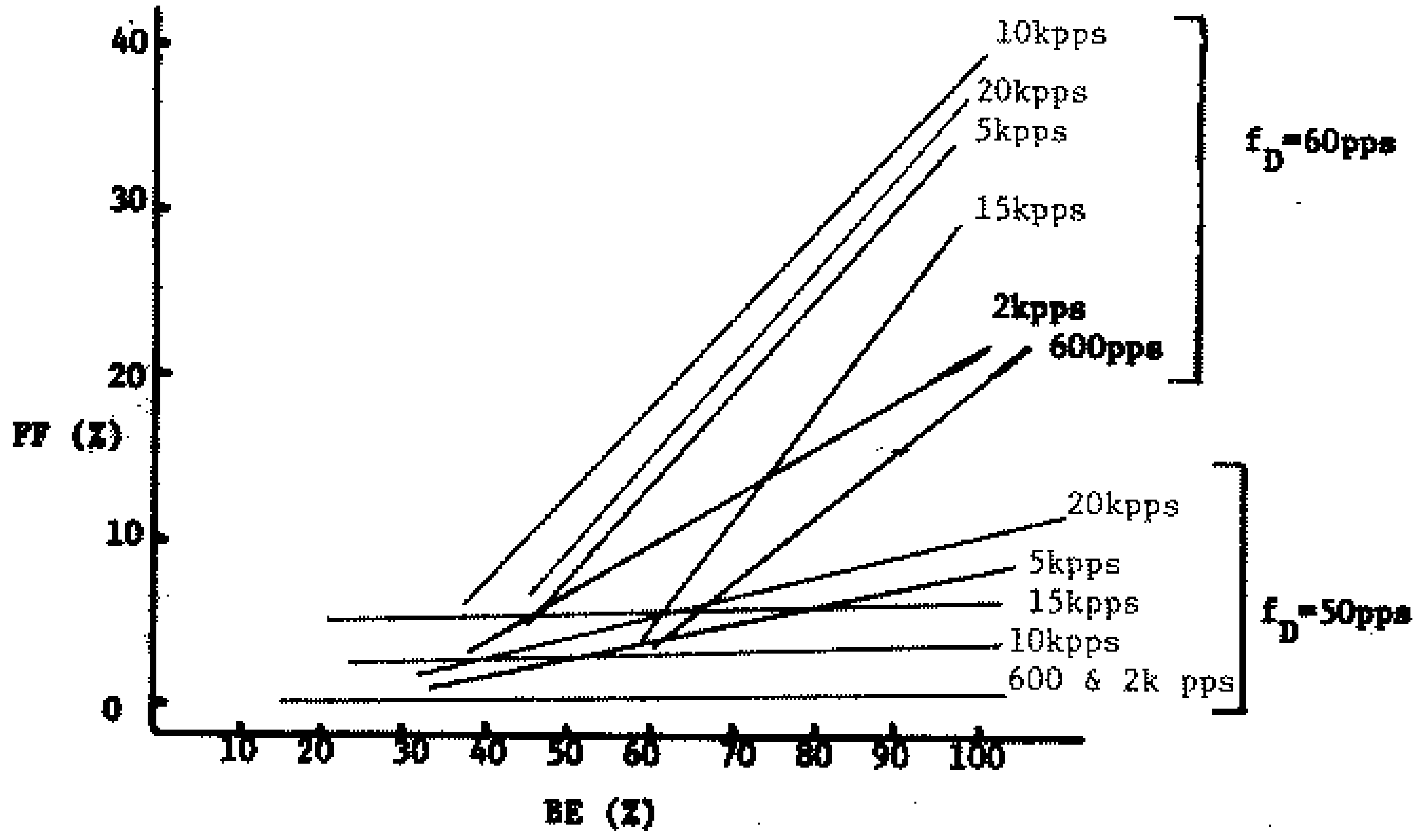

Figure 3. Fatigue Factor as a function of Blocking Effectiveness for several Block Frequencies and for two Drive Frequencies.

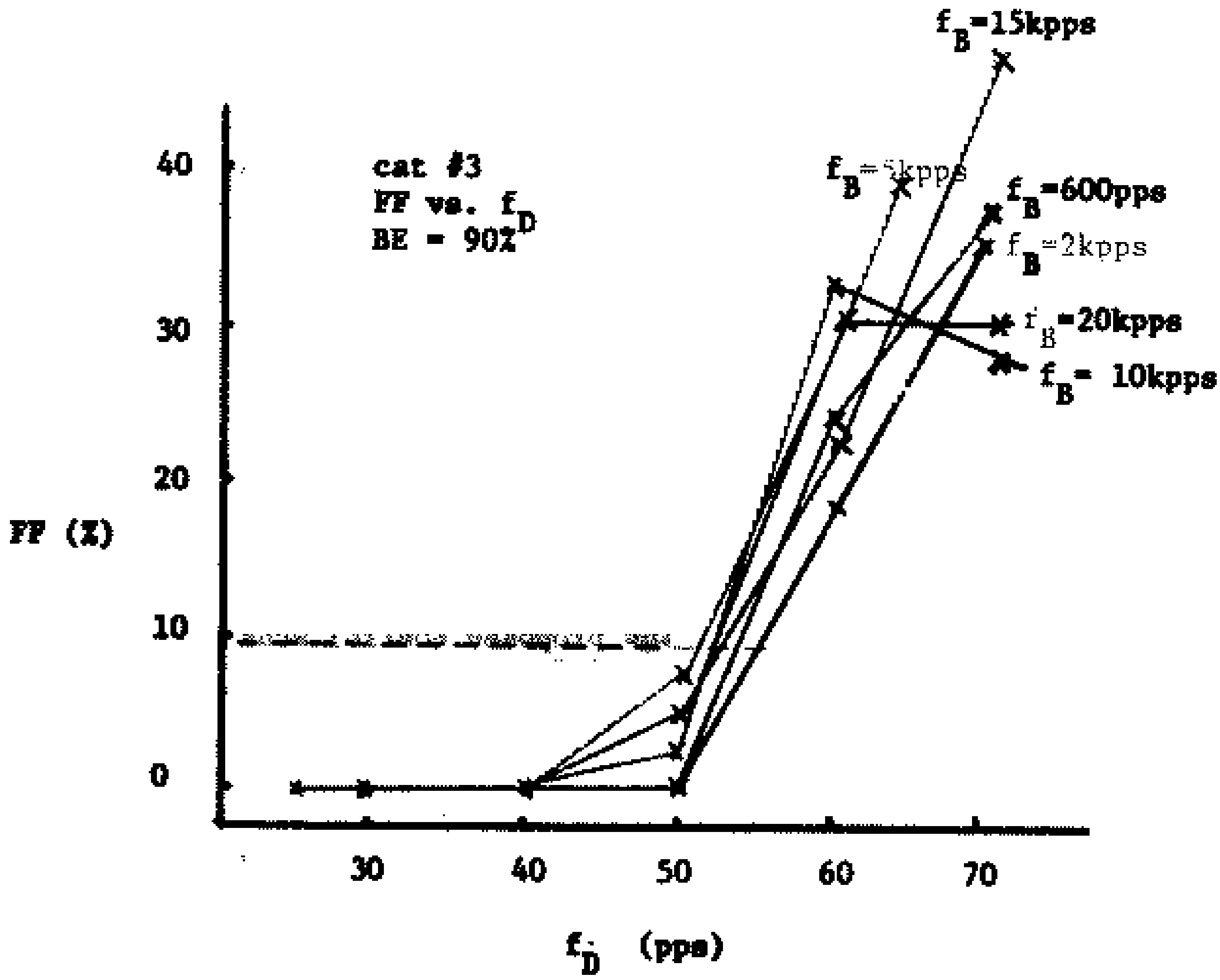

Figure 4. Fatigue Factor as a function of drive frequency for several block frequencies at 90% Blocking Effectiveness

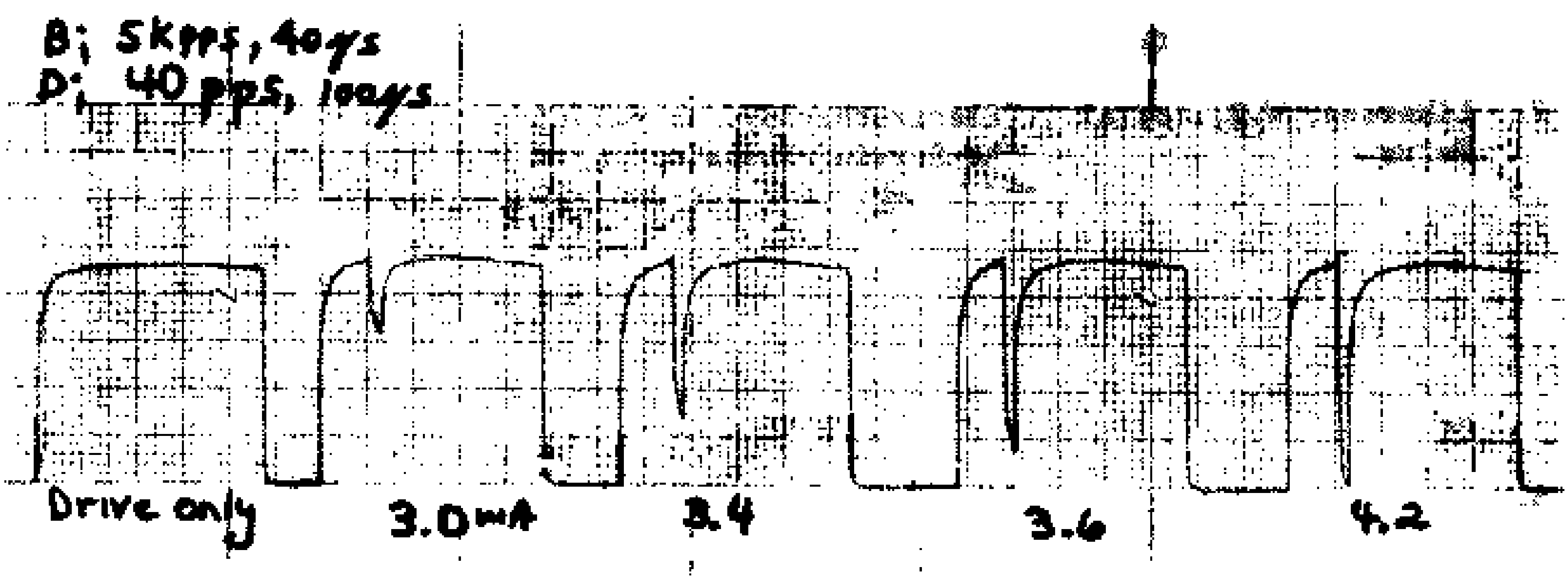

Figure 5. Muscle fatigue response to several block levels at drive frequency of 40 pps.

c. Block level

2. Maximal muscle force could be maintained without fatigue for 30 seconds, for block levels of 0-95% if drive frequencies, of 50 pps or less are employed.
3. Drive frequencies of 50 pps result in less than 10% FF in worst conditions.
4. Increasing block levels and frequencies induce more fatigue than lower levels.

For clinical applications, drive frequencies of 40-45 pps should be used in order to avoid fatigue. Such drive frequency generate sufficient force for most fine to moderate daily activities. Furthermore, it is a fair assumption that such activities do not require more than 30 seconds for completion, (for example; drinking, walking cycle, standing up, etc.)

In summary, the fatigue properties of the proposed control scheme were identified and the optimal drive frequency was defined as 40-45 pps. Such drive frequency does not produce fatigue during 30 seconds contraction and is below the frequency range where block parameters contribute to fatigue.

Furthermore, it is evident that with block frequencies of less than 2,000 pps, muscle fatigue is not observed for drive frequencies of up to 50 pps (Figure 4). From the optimization point of view then, drive frequencies of up to 50 pps could be possible for block frequencies of up to 2,000 pps without induction of fatigue.

Acknowledgement

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