4

Role of Electrical Parameters in Functional Electrical Stimulation

Winfried Mayr

4.1 Introduction

Functional electrical stimulation (FES) is a powerful tool in the hands of capable therapists, but by far underrepresented in clinical use yet, far beneath exploiting the evident opportunities. On the one hand the necessary technical and physiological basic education is not considered enough in curricula for neurorehabilitation professionals, which would be crucial for building up confidence for safe and effective application. On the other hand, the vast multiplicity of positive, negative and sometimes contradictory application reports in scientific literature, public media and even in manufacturers' documents can provoke uncertainty and doubts, or else, exaggerated expectations and disappointment. A main goal of this chapter is to support a low-threshold entry in the use of stimulation equipment and guide towards qualified selection and alignment of electrical parameters for useful, effective and safe therapeutic intervention.

▶ Functional electrical stimulation (FES) is a powerful and versatile tool for rehabilitation, provided that adequate basic understanding of physiological mechanisms, capabilities and limits, as well as principles of application safety are given.

4.1.1 Selection and Evaluation of Stimulators

Stimulators are available in numerous variations and in vastly different cost segments. Stimulators offered as certified medical products are usually more expensive as they undergo strict and complex approval procedures, and need to comply with mandatory quality management processes in production and sales, which are associated with increased internal costs and fee-based monitoring by governmental authorities. These are the tools of choice for clinical practice for ensuring best possible patient safety and scientifically validated efficacy. Unfortunately, costs are often an impregnable obstacle for availability for patients, in case health insurance refuses to cover costs and devices are not affordable for purchase at their own expense.

The market segment "sports and fitness" offers rather similar devices with comparable technical specifications but for substantially lower prices, due to sparing costs for requirements of medical product regulations. Regarding applicability, a distinction is often difficult. FES-supported neuromuscular training is a topic of interest in neurorehabilitation as well as in sports. Finally, therapeutic responsibility and legal standards are to be weighted as decisive factors for the choice of appropriate devices. Additionally, there is a third, hardly controllable source for stimulators: internet shops. Unvalidated promises and low

---

W. Mayr (✉)
Medical University of Vienna, Vienna, Austria
e-mail: winfried.mayr@meduniwien.ac.at

T. Schick (ed.), *Functional Electrical Stimulation in Neurorehabilitation*,
https://doi.org/10.1007/978-3-030-90123-3_4

prices can appear attractive, but product and documentation quality can turn out to be questionable, unfiltered recommendations and unverified technical properties can even get health-endangering. Anyhow, stimulation technology should only be applied under competent medical advice to ensure safe and effective conditions.

4.1.2 What Really Matters

Despite all diversity of offered devices, stimulators remain pulse sources that interact with an organism via various electrode configurations, generally non-invasive with electrodes attached to the intact skin surface, in special applications invasive via implanted electrodes.

4.2 Monophasic/Biphasic Pulses/ DC Component

Even though the marked offers stimulators with alternative voltage or current output waveforms, the vast majority relies on monophasic or biphasic rectangular pulses delivered in various pulse trains via bipolar electrode configurations. Therefore, we focus on such pulse forms and discuss how they interact with the organism. Further, we will discuss, how we can systematically influence this interaction, what limits we face and how far safety-relevant aspects need to be considered.

▶ Essential requirement: charge balance!

For the classical monophasic rectangular pulses there are three basic parameters that can be varied: pulse amplitude, pulse width and pulse frequency respectively the associated period between the leading edges of subsequent pulses. In the meantime, the majority of stimulators relies on biphasic rectangular pulses, where immediately after a monophasic pulse (first phase) an equal pulse of opposite polarity (second phase) follows. Adjustable parameters are the same, only pulse width becomes a pulse phase width, which is to be defined for positive and negative phase. Usually, both pulse phases are equal, but occasionally there are reasons for using asymmetric ones (Fig. 4.1).

4.2.1 Monophasic and Biphasic Pulse Forms and Parameter Definitions for Nerve and Muscle Stimulation

It is a matter of decisive relevance to—except for a few special applications, which have to be handled with great care—avoid DC components in stimulation wave forms. This can be ensured by appropriate design of the output stage of the stimulator electronics and is usually considered by the device manufacturers. Still, we can find even certified medical devices on the market, that have a potentially critical DC component in their output pattern. Therefore, it remains important to carefully check for this feature whenever purchase, recommendations or prescriptions are undertaken. Charge balance without DC component is reliably ensured, if each stimulus, shifting a certain amount of electrical charge across the electrode contact into an organism, is followed by a recharge pulse of opposite polarity with a compensatory backflow of an equal amount of charge. A simple, safe and cost-effective solution is insertion of a capacitor in the output lead between stimulator output stage and electrode connector. A capacitor is a passive component that blocks DC and forces continuous charge balance of traversing alternating currents, even if the shape is complex like in variable sequences of stimuli.

In symmetric biphasic rectangular stimuli, the two subsequently delivered pulse phases of opposite polarity directly compensate residual charge to zero. The influence of an inserted coupling capacitor on pulse shape is minimal. In case of monophasic stimuli capacitive coupling leads to a strong deformation of the wave form, as every pulse is followed by an asymmetric forced recharge phase, usually a spike with exponential decay with dependence on the given electrode tissue impedance—safe in the application, but with some disadvantages regarding control characteristics and efficiency of stimulation, in com-

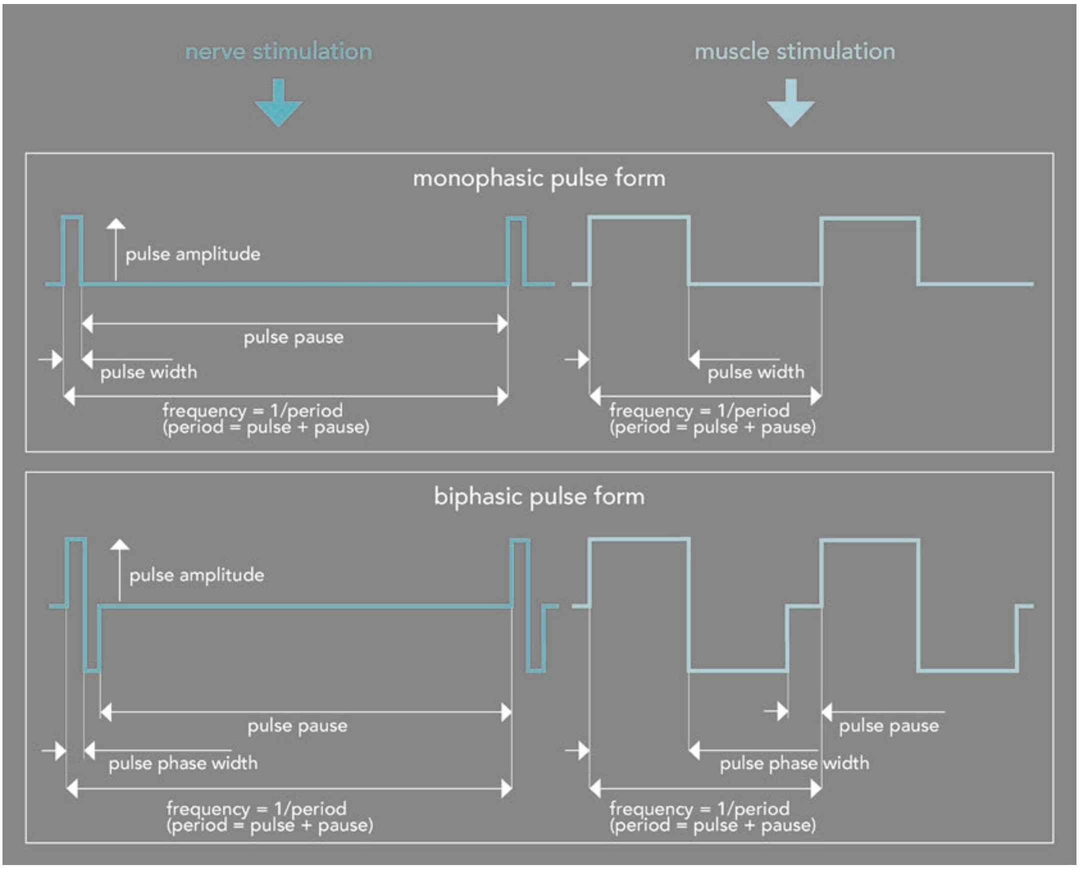

Fig. 4.1 Monophasic and biphasic pulse forms and parameter definitions for nerve and muscle stimulation

parison to symmetric biphasic stimuli. As DC-decoupled monophasic stimuli are often named “biphasic” in the technical device specifications it is important to specially scrutinize this essential feature, to judge on suitability of an electrical stimulator.

▶ **Note** Caution: DC or “hidden” DC component in a pulse pattern!

An alternative to forced DC-decoupling with capacitors is active control of flow and backflow of electrical charge within a biphasic stimulus via electronic provisions for continuously maintaining charge balance. Monophasic stimuli delivered without DC-decoupling are always associated with a DC-component which varies with adjustment of pulse parameters (Fig. 4.2.).

4.3 Monopolar/Bipolar Electrode Configurations

A potential source of misunderstanding is the difference between application of “mono- or biphasic stimuli” and “mono- or bipolar stimulation.” The latter relates to an electrode configuration, which is the first to be optimized for an application setup. The decision on the suitable pulse form and allocation of anode and cathode are of high importance.

A bipolar electrode configuration of two identical electrodes, placed over an anatomical target area, is the classical and most common approach. The locally concentrated electrical impulse field elicits action potentials in sensory and motor neurons as soon as the specific threshold intensity is exceeded. In case of peripheral denerva-

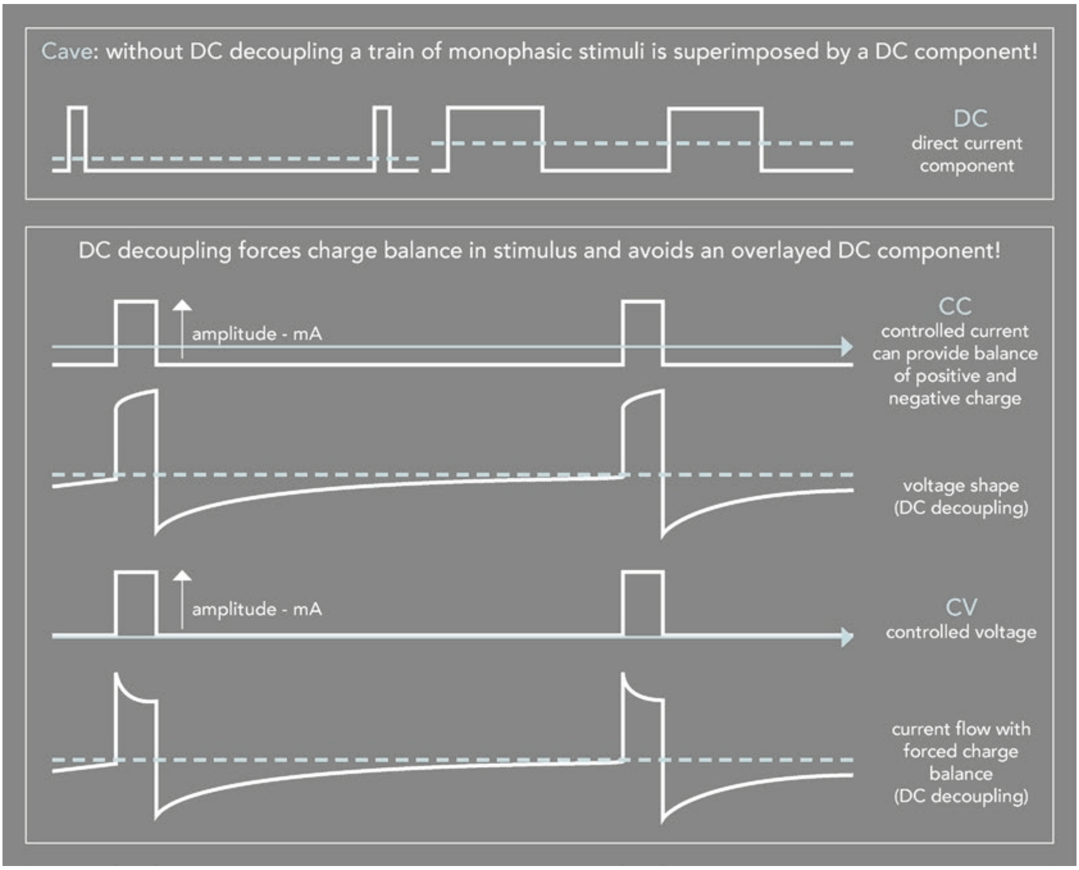

Fig. 4.2 Monophasic pulse forms undergo some deformation, when delivered through safety-relevant DC-decoupling means, usually capacitors in the output lines, differently for controlled current (CC) or controlled voltage (CV) modes. DC-decoupling respectively charge balance is given, if the area below the trace of the positive pulse phase is exactly counterbalanced by the one enclosed by the negative phase, in relation to the zero line

tion, and only in this condition, appropriate stimuli can also elicit action potentials directly on muscle fibres. Usually this is the arrangement of choice for smooth and efficient activation of neurons or muscle fibres under and in-between the electrodes.

For application of monophasic stimuli, we observe a significantly lower threshold for neural structures close to the cathodic electrode in comparison to the anodic one. If biphasic stimuli are applied, we have the lowest threshold in neurons close to the anode of the first pulse phase (“anode first” polarity).

▶ **Note** For monophasic stimuli nerve structures close to the cathode respond at a significantly lower threshold than structures near the anode.

For biphasic stimuli this polarity rule reverses with reference to the first pulse phase: the lower threshold appears near the anodic electrode (“anode first”).

For selective activation of a locally restricted area a monopolar electrode arrangement can be the best choice. This can be necessary for diagnostic tests as well as for therapeutic intervention, when small target areas should be activated without co-activating anatomically adjacent structures. Examples are local denervation with intact sensory-motor nerve structures around, local hypersensitivity, selective activation of agonist and antagonistic in the treatment of muscles imbalances, or for avoiding electrical field induction in implants or wounds close to therapeutic targets. Preferential electrode arrangements rely on a smaller active cathode in combination with a larger anodic reference. A pronounced depth effect can be accomplished, when the reference electrode is placed anatomically opposite to the active cathode, e.g., when placing electrodes at the trunk or the extremities. Regarding polarity the same rules apply as for bipolar electrode arrangements.

Conclusion

The best possible selectivity in activating nerve structures can be accomplished using a small size active electrode, which is chosen as cathode for monopolar stimuli or as anode of the first phase of a biphasic stimulus.

4.4 Controlled Current (CC)/Controlled Voltage (CV) Stimulus Delivery

A further important device-related question is the electronic control mode of the stimulation output. It can either be based on controlled current (CC) or controlled voltage (CV) . CC means that the desired pulse shape is exactly followed by the current flow, whereas the voltage appears deformed under influence of the electrical resistance properties at the electrode/tissue interfaces and the traversed tissue in the current path (load impedance). CV delivers an exact voltage shape, whereas the current is adapting to the generally non-linear impedance properties (Fig. 4.2).

Basically, the effect of both operation modes is equal if the transverse resistance of the electrode to skin interface and the anatomical contour in the application area remain unaltered during stimulus delivery.

But there is an important safety aspect to be considered, when long-duration pulses with high charge transfer per pulse are applied for direct stimulation of denervated muscles, or in nerve stimulation with very small electrodes: especially in CC a locally excessive current density may occur, which, in a worst case, can lead to irreversible electrochemical processes in the electrode-skin interface with some risk of tissue damage.

In case the load impedance of a stimulator output varies during stimulus delivery, CC mode forces unchanged current flow in the default shape by continuous re-adjustment of the driving voltage source. This provides the advantage that the induced electrical field in the tissue interaction with nerves and muscles remains more or less unaltered. At the same time a risk emerges if worsening of the electrode to skin resistance properties occurs, for example, by partial contact loss of self-adhesive hydrogel electrodes or drying out of contact media between conductive rubber electrodes and skin surface. In such case CC mode ensures unaltered current delivery and forces flow of the entire current through an eventually significantly reduced contact area, with the consequence of a potential risk of electrochemical skin damage. Also, excessive local current density can occur at spots of locally increased mechanical contact pressure like at electrode edges under tension of elastic fixation means. This needs special attention in particular in conjunction with direct stimulation of denervated muscles.

Similar changes of contact properties are far less critical in CV mode, as an increase of load impedance results in concurrent reduction of current. The user notices a decline in stimulation response, but risks of skin damage are neglectable.

Most, but not all the commercially available stimulators rely on CC mode. Preference for choosing CC or CV finally depends on application scenarios and a critical assessment of functional expectations versus tolerable risks.

4.5 Role of the Parameter's Amplitude and Pulse Width

Most stimulators offer possibilities for pre-adjustment of pulse width and frequency within a certain range, whereas variation of amplitude is freely variable for intensity adjustments in test procedures and therapeutic application. Occasionally, devices rely on constant pre-adjusted amplitude and modulation of pulse width for control of intensity. For nerve respectively neuromuscular stimulation useful amplitude ranges cover 0–120 mA or 0–120 V, a pulse width range between 100 μs and 1 ms, both related to a pulse phase, and a frequency range between 1 and 120 Hz.

The role of intensity adjustment is a variation of recruitment of neurons, usually situated in bundled form in a neural structure. Regardless of using amplitude or pulse width for recruitment modulation there is always a low-intensity range without any neuron activation, meaning that no action potentials are elicited. Gradual increase first results in reaching a sensory threshold, at least if sensory perception is intact, and with further increase a motor threshold with first signs of muscle activation. With further growing intensity increasing sensory perception and enforced muscle contraction are induced. High intensity saturates the responses and can even lead to blocking phenomena that suppress propagation of action potentials in neurons (Fig. 4.3).

If and at what intensity an action potential is elicited in a neuron depends on the distance to the electrodes respectively the electrical field configuration acting on the neuron, and the diameter of the neuron. The larger a neuron is, the lower is the threshold for an action potential. This has multiple implications for the impact electrical stimulation can have on neural functions.

The largest neurons, with diameters up to 20 μm, are "proprioceptive afferents," which are responsible for feedback on body image, muscle lengths and joint angles. So-called "cutaneous afferents," associated with skin sensor information, have a size spectrum from approximately 14 μm down to 5 μm. Further there is a pool of even smaller fibres in the size range around 1 μm which are mainly related to deep pain feedback.

These afferent sensory neurons proceed in bundles, together with efferent motor fibres, with their diameter range between 18 and 8 μm. Larger

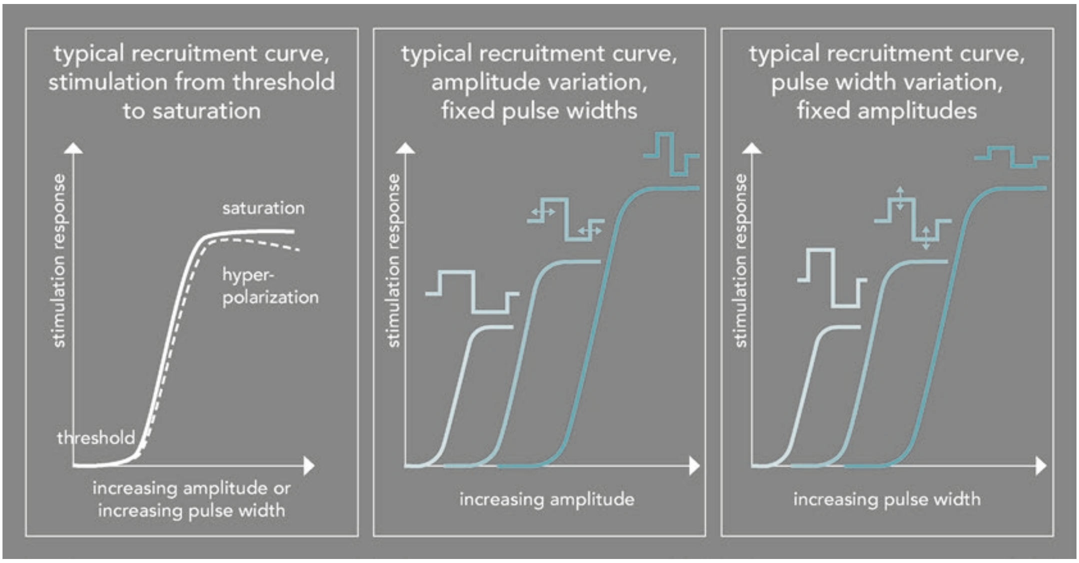

Fig. 4.3 An increase of stimulation intensity, beginning with "0" leads first to reaching of a threshold, followed by a linear increase of recruitment of nerve or muscle fibres until a saturation plateau is reached and most sensitive fibres can even get hyperpolarised with block of propagation of action potentials. Recruitment can be controlled by either modulating amplitude or pulse width

motor neurons control groups of fast and strong contracting, but fast fatiguing muscle fibres (Type 2, glycolytic metabolism), smaller ones activate fatigue resistent but slower and weaker muscle fibres (Type 1, aerobic metabolism). The combination of a motor neuron cell, situated as integral part in spinal interneuron networks, the associated peripheral motor neuron, its peripheral branching and all connected muscle fibres are called a "motor unit" (MU). In relation to conduction speed, contraction speed and endurance MUs are often classified as "fast" versus "fatigue resistant." Physiological recruitment of MUs relies predominantly on fatigue-resistant ones and co-recruits fast ones only for special demands in force and movement speed (Henneman principle, natural recruitment).

In the size spectrum of neurons, we also find smaller efferent neurons, which interact with muscle spindles, and finally, with diameters below 1 μm, neurons related to the autonomous nerve system and reacting only to electrical stimuli of very high intensity.

Another important consideration is the fact that the number of sensory neurons in a mixed nerve is far higher than that of motor neurons. For the entire nerve supply of the upper extremity with all emerging spinal nerve roots the relation is 90–10%; in anatomical branches this relation can vary considerably.

In summary, we need to be aware of limitations in selectivity of reaching specific or even single neurons by electrical stimulation and must scrutinize interpretation of physiological responses. We need to respect that due to the size depending excitation threshold of nerve fibres fast, rapidly fatiguing MUs are primarily recruited at low stimulation intensities and fatigue-resistant MUs can only be co-recruited with growing stimulus strength ("inverse recruitment" in comparison to natural recruitment). On the other hand, this should not discourage us from taking advantage of the many positive opportunities FES is offering. With some background knowledge and smart handling of electrodes, parameters and intervention strategies, superb therapeutic and functional results can be accomplished.

▶ **Note** In neuromuscular electrical stimulation with growing intensity first only fast, rapidly fatiguing motor units are activated, at higher intensities fatigue-resistant MUs are co-recruited—inverse recruitment.

4.6 Role of the Parameter Frequency

A fundamentally different role than amplitude and pulse width, which control fibre recruitment, has the parameter frequency, or to be more precise, two quite different roles. On one hand, if afferent sensory nerve stimulation is addressed, frequency has a strong influence on spinal and supraspinal interneuron processing with its essential involvement in movement control as well as sensory perception. On the other hand, in neuromuscular electrical stimulation, frequency has strong influence in contraction dynamics and fatigue behaviour of the activated muscles.

As the recruitment order with increasing intensity starts with selectively activating the largest neurons at lowest threshold, initially only large sensory neurons are reached. This offers effective opportunities for reducing neuropathic pain, modifying spasticity and augment movement functions. For these applications, meticulous assessment of altered neural functions and individually optimized intensity and frequency values and appropriate electrode setups need to be configured.

If stimulation intensity is increased beyond the motor threshold, obvious responses are muscular contractions, though in the background sensory neurons are unavoidably co-activated at the same time. This can add positive, disturbing, or unobtrusive side effects, that may require some attention. For example, in patients with spinal cord injury in some cases neuromuscular FES training can be accompanied by undesirable increase of spasticity, whereas in other patients the same neuromuscular FES is accompanied by even a reduction of spasticity. But, with individual optimization of the application protocol it is possible to find satisfactory solutions in the majority of cases.

For neuromuscular FES the role of frequency is twofold:

1. The co-activation of afferent (sensory) neurons has a frequency-dependent influence on central interneuron processing.
2. The frequency of motor neuron activation strongly influences biomechanical and metabolic properties in the activated muscle.

For neuromuscular training or neuromuscular activation of paralyzed or weakened musculature so-called phasic stimulation patterns are applied, meaning that contraction is induced for limited time intervals followed by inactivation pauses. Consequently, additional parameters, as well as intensity and frequency, become relevant: activation and pause intervals (on/off time) and in general also ramp times for on-off-transitions, which make onset of muscle contractions and muscle deactivation smoother and more comfortable. Appropriate selection of the parameter sets for muscle building and maintenance has decisive influence on effectiveness of the training.

Specific parameter sets and application management are required for direct muscle stimulation that have lost their nerve supply. Differences to neuromuscular FES are addressed later in Sect. 4.7.

4.6.1 Application of Single Stimuli

Single stimuli or repetitive stimuli delivered with very slow repetition rate play an important role in neuromuscular testing procedures, e.g., recruitment threshold detection, but can also have relevance for fostering muscular perfusion or rebuilding of excitability of denervated muscle fibres.

A typically useful test frequency is 1 Hz, which is slow enough to rule out influence of most neurophysiological post-activation activities. It is useful for finding sensory and motor thresholds, as for example needed for proper adjustment of intensity for tonic afferent nerve stimulation. Motor threshold and saturation intensity define the control range for neuromuscular or muscle stimulation, both can be comfortably determined with slowly repeated single stimuli and intensity variation. Further, slowly repeated single stimuli are useful for tests on innervation respectively denervation status of muscles and excitability of denervated muscle fibres.

There is one aspect that needs some attention: single stimuli usually do not cause sensible discomfort even if delivered with very high intensity, but as soon as trains of stimuli with usual application frequencies are delivered discomfort is perceived at much lower intensity levels. Therefore, if sensory perception is intact it is not possible to determine a tolerable intensity maximum with single stimuli. It is strongly recommended to start with low intensity and determine the individual discomfort threshold with the intended application parameter set and slowly increased intensity.

4.6.2 Application of Low Frequencies

Pulse frequencies below 10 Hz are often applied for a warmup period ahead to neuromuscular FES training, in so-called “active relaxation” pauses between contractions or in a terminal active regeneration periods after exercise. Stimulation evokes no fused muscle contraction, but a shaking movement that can enhance muscle perfusion and support washout of metabolites.

4.6.3 Frequencies Eliciting Fused Contractions

Shortening the time between subsequent stimuli, which is equal to increasing frequency, conflates muscle responses from single twitches to unsteady compound “shaking contractions.” With further increased frequency to a so-called “fusion frequency” a burst of stimuli induces a smooth tetanic contraction. Further growing frequency leads to gain in contraction force and onset speed, but at the same time rapid muscular fatigue phenomena, which cause problems in functional applications and can lead to metabolic overuse and even muscle damage (Fig. 4.4).

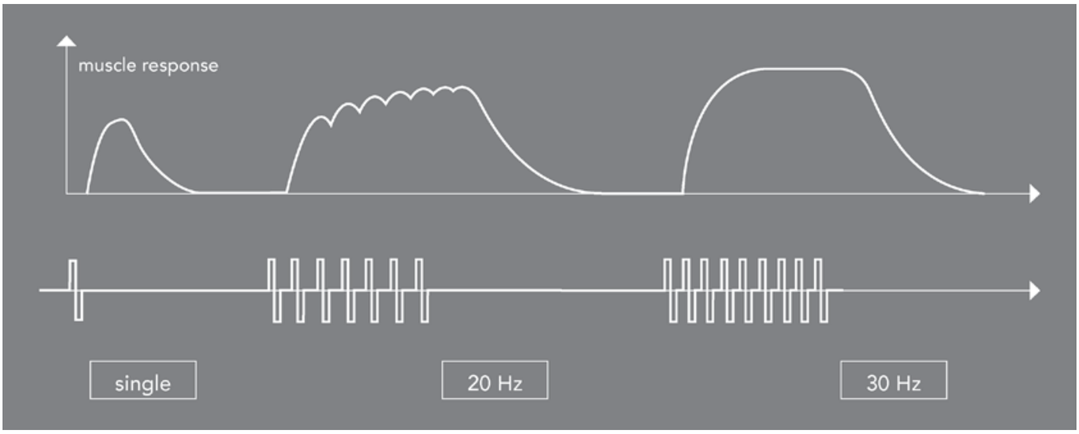

Fig. 4.4 The muscle response to one stimulus is a compound twitch of all recruited muscle fibres. Growing repetition rate of stimuli results in merging twitches to unsteady ("shaking") and beyond "fusion frequency" tetanic contractions. The displayed curves stand for isometric contractions against a firm resistance

For most applications, a cautious start of training is recommended. Frequency should be selected for just starting to fuse in contraction, eventually with a residual minimal unsteadiness. Fusion frequency is not a sharp absolute value and influenced by metabolic factors in the muscle. Subjective perception of contraction smoothness usually starts in the range of 25–30 Hz and gets more pronounced with further increase. The recommendation of a cautious start of training also relates to strength and duration of contractions, relaxation pauses between contractions and strict avoidance of excessive fatigue. In the further course, length of training sessions, stimulation intensity, frequency and on-off timing can be adapted to a more intense training load in order to build muscles and gain in force and endurance.

4.7 Special Case FES of Denervated Muscles

Maintenance of denervated muscles is less for immediate functional restoration but rather for longer term improvements in quality of life and preserving health of utmost importance. Effective validated methods and instrumentation have not been available till the recent past, as outcome from the European R & D project RISE [1, 2]. The applicable parameters and intervention protocols differ substantially from those for neuromuscular muscle training, mainly due to differences in the electrically excitable membrane properties of nerve and muscle cells: action potentials travel along motor neurons with 50–100 m/s, whereas along healthy muscle fibres with only 2–5 m/s, in atrophied and degenerated muscle fibres far slower. This refers directly to suitable pulse parameters for eliciting action potentials on the respective membranes, for neurons pulses with a phase width of 100–1000 μs (0.1 to bis 1 ms) are most efficient. Longer pulses do not increase fibre recruitment in relation to intensity but lead to growing charge transfer across the electrode-tissue interface with unnecessary increase of safety risks. In direct comparison, even completely intact and well trained denervated muscles are not excitable with pulses below 15–20 ms per phase. With growing atrophy respectively, after longer denervation, degeneration of muscles the required pulse phase length increases towards 250 ms, in extreme case up to even 500 ms. It is strongly recommended to start stimulation of denervated muscles as early as possible after denervation on a regular basis, which is of vital importance for best possible maintenance of muscle in quantity and function. If excitability is high enough for shortest pulse length and inter-pulse pauses stimulation bursts with 25–30 Hz can elicit fused tetanic contractions [3] which is in turn essential for efficient training and functional use. Analogous principles like for neuromuscular FES training remain applicable (Fig. 4.5).

Main objective of training is maintenance of muscles for an anticipated re-innervation or, provided regular long-term application, comprehensive tissue preservation [4], mainly for effective decubitus prophylaxis. If atrophy, in the first year after denervation, or muscle degeneration, as usually beginning in the second year, are progressing longer, a longer minimal pulse width gets necessary for eliciting muscle twitch contractions, which make fused tetanic contractions impossible [4, 6]. There is a feasible option to recondition excitability of muscle fibres and reach a reduction of the necessary minimal pulse duration to an extend that re-enables stimulation-induced fused contractions and tetanizing rebuilding of muscle mass, force, and endurance, at least in part (Fig. 4.6). But there are limitations, which can be minimized with an early start and consequent compliance: the longer disuse is persisting the longer rebuilding will last and the severer limitations in achievable results get.

As a specific requirement for FES of denervated muscles, specific adaptations of stimulation parameters for test procedures and therapy protocols are of vital importance. Primarily, rectangular biphasic long-duration pulses above 15 ms per phase are necessary. For testing of the degree of denervation in incompletely denervated muscles and neuromuscular activation of residual motor units also short duration pulses with phase length below 1 ms can get relevant as complementary modality. There are important alternative pulse forms, biphasic long ramp shaped (exponential) pulses with phase length above 80–100 ms, which feature elevation of thresholds for nerve activation above those for denervated muscle fibres, based on an effect called “accommodation” (Fig. 4.7). Accommodation means that the fast-reacting electrical properties of neurons maintain an equilibrium of diffusion currents, when exposed to slowly raising electrical field strength, whereas the same field conditions induce electrical discharge in the less sensitive membrane of denervated muscle fibre.

▶ **Note** Long ramp shaped pulses with a phase length above 80–100 ms open the opportunity for activating denervated muscle fibres without co-activating near sensory or motor neurons.

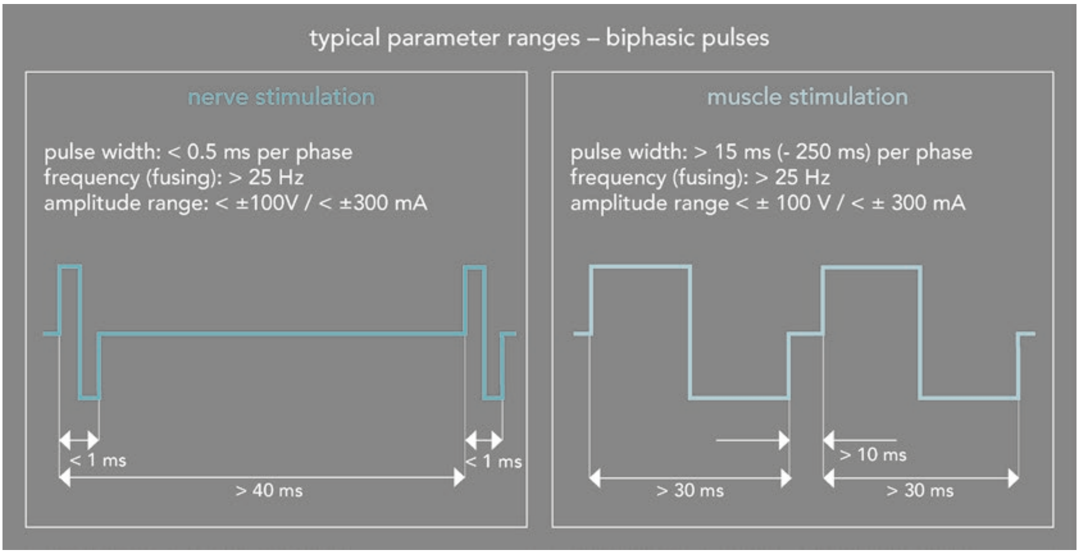

Fig. 4.5 Parameter ranges for nerve and neuromuscular stimulation in comparison to those for direct stimulation of denervated muscles: the main difference is given in the necessary pulse width, with strong implication to training strategies and safety provisions

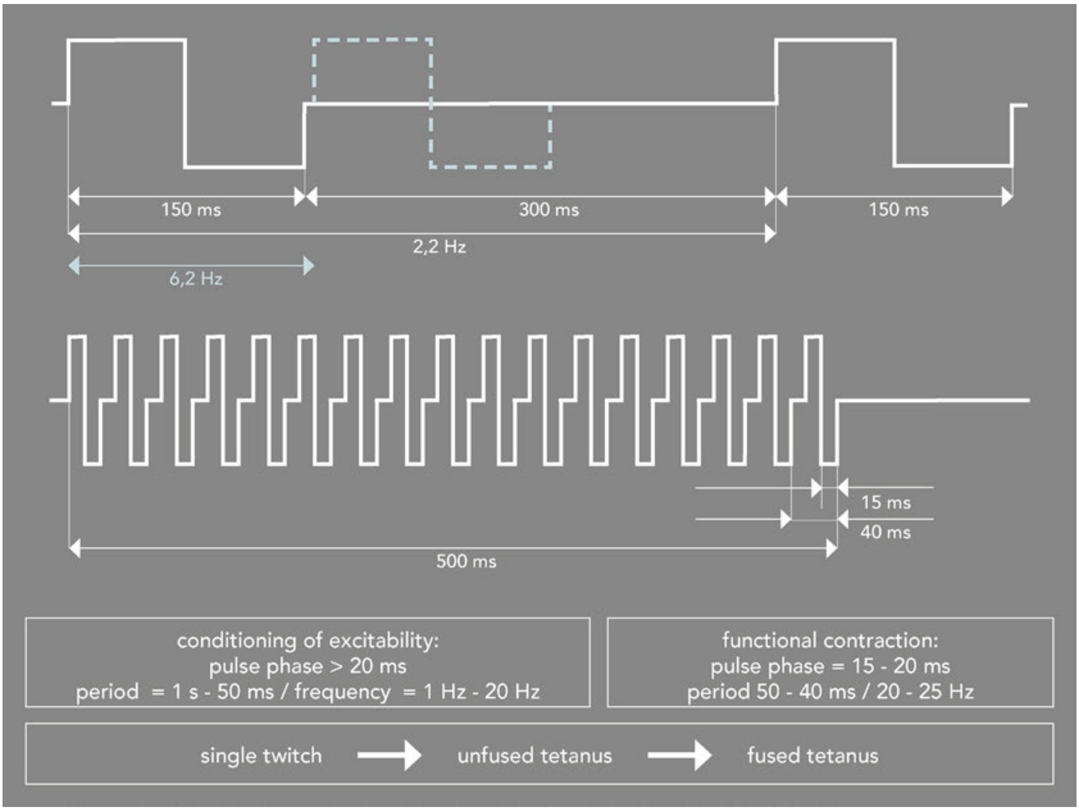

Fig. 4.6 In electrical stimulation of denervated muscles it is challenging to accomplish fused tetanic muscle contractions, due to the required long stimulus duration. In dependence of inactivity time after denervation a prolonged period for rebuilding of muscle excitability, beginning with single twitch conditioning, is necessary

Ramp shaped pulses can also be applied with shorter phase duration, though accommodation effects can appear clearly reduced. Nevertheless, it is always worth trying if at least gradually reduced co-activation of sensory or motor neurons can be accomplished. Not to be underestimated: this pulse form can also reduce charge transfer per pulse, which is to some extend safety relevant (Fig. 4.8).

4.8 Electrode and Parameter Management for Testing and Treatment of Completely or in Part Denervated Muscles

The start of the first assessment should be as soon as possible after denervation, the earlier the better status of and the lower efforts for muscle maintenance will get. Electrode configuration should as far as possible cover the entire dermatome above the target muscle, as eliciting action potentials in each single muscle fibre are necessary for complete activation.

For the first test single pulses, or slow trains with 1 Hz, should be chosen for identifying intact MUs and estimating to what extend partly or complete denervation is given. If a considerable response appears, neuromuscular training of the still nerve supplied part can be considered with the goal of hypertrophy in innervated motor units and eventual promotion of reinnervation processes in other muscle parts.

In case the muscle is not reacting to short pulses, next tests with longer pulses should be undertaken, phase length chosen depending on the time since denervation, for acute cases in a range of 15–30 ms, for less recent cases gradually more, typically above 100 ms. Initially a maximal twitch contraction is to be searched by

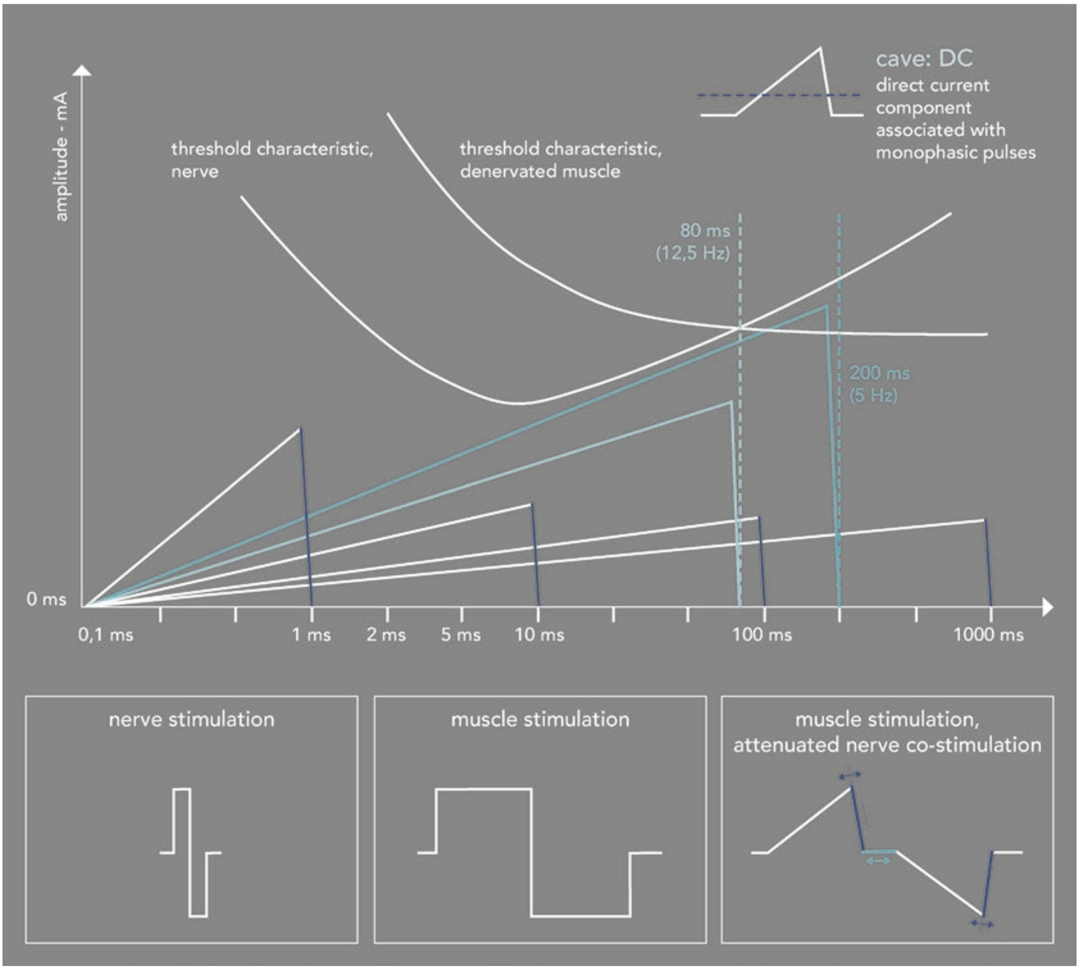

Fig. 4.7 For testing and training of denervated muscles (completely or in part) short pulses for eventual residual MU activation, and long-duration rectangular and ramp shaped pulses for muscle fibre activation are needed. Ramp shaped pulse with phase lengths above 80–100 ms can provide an elevation of the threshold for neurons above threshold for denervated muscle fibres

increasing intensity and eventual lengthening of pulse width, next a stepwise reduction of pulse length is applied to find a threshold where a drop of reachable twitch strength occurs. For conditioning respectively training the shortest pulse width eliciting a substantial twitch is the best choice. For beginning therapy slow repetitive stimuli with contant intensity should be applied first for a period until visible weakening of responses is noticed. Later, based on regular follow-up tests, improvements in excitability and endurance should be noticeable, in time period dimensions of weeks.

As soon as excitability allows application of phase durations of 15–20 ms, a transition to tetanizing contractions and classical muscle building, but with special attendance to avoiding excessive fatigue and metabolic overload, can be considered [2, 5, 6].

If intact sensibility or disturbing co-activation of neighbouring innervated muscles limit the applicable stimulation intensity too much, ramp shaped long duration pulses can be considered as an alternative for the above outlined test and application procedures.

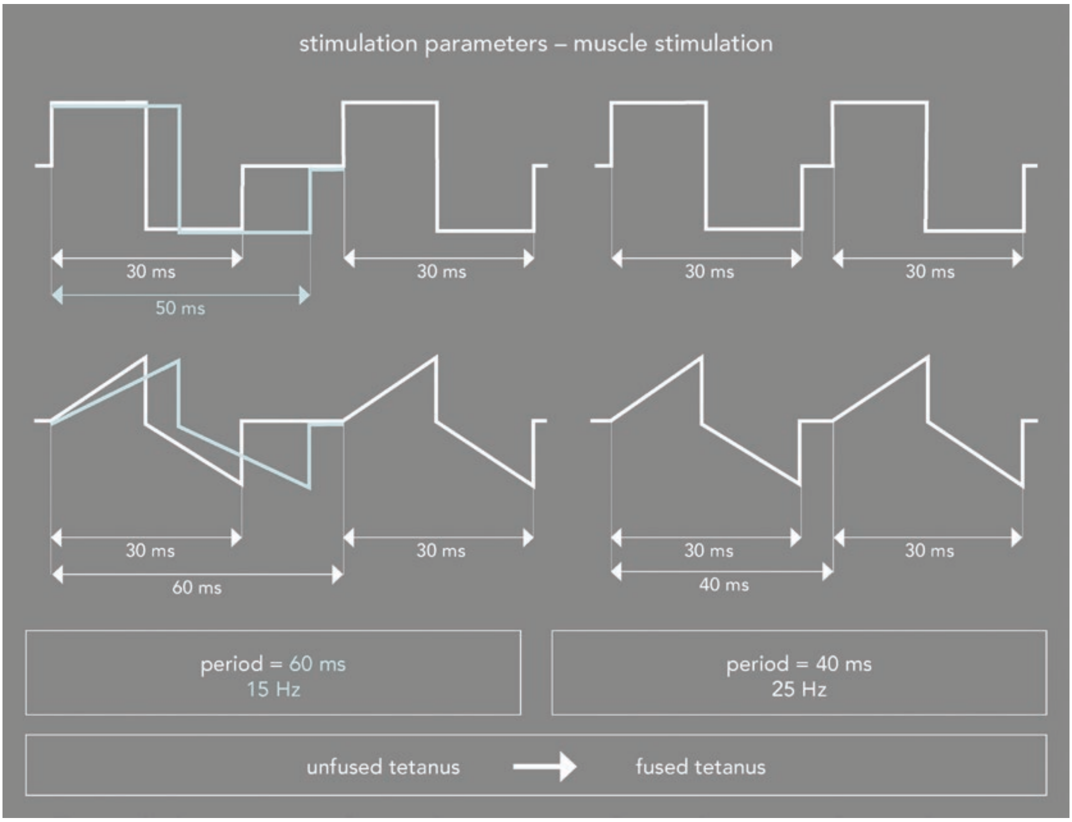

Fig. 4.8 Ramp shaped pulses can provide advantages regarding reduction of coactivation of sensory and motor neurons in the same anatomical region. Charge transfer per pulse phase gets lower, associated with reduced risks of skin damage

References

1. Kern H, Carraro U, Adami N, Biral D, Hofer C, Forstner C, Mödlin M, Vogelauer M, Pond A, Boncompagni S, Paolini C, Mayr W, Protasi F, Zampieri S. Home-based functional electrical stimulation rescues permanently denervated muscles in paraplegic patients with complete lower motor neuron lesion. Neurorehabil Neural Repair. 2010;24(8):709–21. [Epub ahead of print]
2. Gallasch E, Rafolt D, Kinz G, Fend M, Kern H, Mayr W. Evaluation of FES-induced knee joint moments in paraplegics with denervated muscles. Artif Organs. 2005;29(3):207–11.
3. Mayr W, Hofer C, Bijak M, Rafolt D, Unger E, Sauermann S, Lanmueller H, Kern H. Functional electrical stimulation (FES) of denervated muscles: existing and prospective technological solutions. Basic Appl Myol. 2002;12:287.
4. Carraro U, Rossini K, Mayr W, Kern H. Muscle fiber regeneration in human permanent lower motoneuron denervation: relevance to safety and effectiveness of FES-training, which induces muscle recovery in SCI subjects. Artif Organs. 2005;29(3):187–91. PubMed PMID: 15725214
5. Kern H, Carraro U, Adami N, Hofer C, Loefler S, Vogelauer M, Mayr W, Rupp R, Zampieri S. One year of home-based daily FES in complete lower motor neuron paraplegia: recovery of tetanic contractility drives the structural improvements of denervated muscle. Neurol Res. 2010;32(1):5–12.
6. Kern H, Hofer C, Strohhofer M, Mayr W, Richter W, Stöhr H. Standing up with denervated muscles in humans using functional electrical stimulation. Artif Organs. 1999;23(5):447–52.