

# Appropriate use of muscle relaxants in anaesthesia, intensive and emergency care

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## Abstract

In this short review are the physiological processes involved in neuromuscular transmission described. Muscle relaxants are used in clinical anaesthesia to block this transmission and the requirements for an ideal drug are defined. The disadvantages of the currently available drugs are summarized including those for succinylcholine. Some focus is placed on rocuronium. The main disadvantage, i.e. residual paralysis, can be treated and/or prevented by reversal of such a block. However, currently used compounds have serious adverse effects and are not always efficacious. Therefore also the requirements for an ideal reversal agent are defined. Against this profile is sugammadex discussed. The possibility to replace succinylcholine with a combination of succinylcholine and sugammadex is discussed.

**Keywords:** neuromuscular transmission, neuromuscular block, succinylcholine, rocuronium, residual block, sugammadex

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The introduction of muscle relaxants into routine clinical anaesthesia in 1942 by Griffith and Johnson has tremendously changed the practice of anaesthesia and increased the surgical possibilities to the benefit of mankind. Nowadays muscle relaxation is an irreplaceable part of anaesthesia, intensive and emergency care. Its use is indicated for endotracheal intubation, facilitation of surgery, and immobilisation of patients. When administered appropriately it contributes to the safety of the patient, but when used inappropriately it leads to increased morbidity and mortality. Knowledge of the pharmacology of the muscle relaxants therefore is very important for the clinician administering this type of drugs to their patients.

## Neuromuscular transmission

The motor endplate is the place where the stimulus is transferred from the nerve to the skeletal muscle [1]. The transfer of the stimulus is chemically mediated

by acetylcholine, which is produced in the mitochondria of the nerve cell, and is stored in presynaptic vesicles. Upon stimulation of the nerve a fast sodium channel opens, starting depolarization of the nerve membrane. Upon such depolarization is an acetylcholine vesicle mobilized and moves from the acetylcholine stored toward the presynaptic membrane, where it approaches the active zone. The number of vesicles and thus the amount of acetylcholine mobilized depends on the rate of nerve stimulation. The vesicles bind via an avalanche of peptide interactions (v-snares and t-snares) to the cell wall, and the vesicle membrane fuses with the cell membrane. This process of mobilization, binding and fusion of vesicles is called vesicle trafficking or exocytosis. Thus acetylcholine is released by fusion of the membranes into the synaptic cleft and it then diffuses across this cleft to reach the postsynaptic membrane where it binds to the acetylcholine receptors. This binding activates the receptor where upon its ion channel opens, causing a depolarization of the muscle cell membrane. The depolarization opens L-type voltage-gated calcium channels (dihydropyridine receptors) in the t-tubule membrane. Conformational changes in L-type calcium channels following depolarization allow calcium to enter the skeletal muscle sarcoplasm. The conformational change in L-type calcium channels induces a conformational change in

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an adjacent calcium release channel (Ryanodine receptor) located in the membrane of the sarcoplasmic reticulum (SR) of the muscle cell. This results in a rapid calcium influx, which calcium binds to troponin C on the actin myofilament, and leads to the initiation of cross-bridge cycling of the muscle in the process known as excitation-contraction coupling [2]. This causes the muscle to contract. Then acetylcholine dissociates from the receptor and repolarization of the membrane can occur, allowing the next depolarization. Acetylcholine is partly metabolized by acetylcholinesterase in the synaptic cleft, and partly it is taken up again in the presynaptic terminal (recycling). Also the vesicle membrane is recycled and used again for the production of new vesicles. This process of recycling is called endocytosis [3]. Many drugs and toxins (snake bites etc.) do interfere with the vesicle trafficking process and result in paralysis or muscle weakness.

Recycled and newly synthesized acetylcholine is collected in vesicles. The process of the mobilization of acetylcholine vesicles is influenced by presynaptic acetylcholine receptors. When increase in muscle activity occurs, then there is decrease in the amount of acetylcholine released, when there is decrease in activity there is increase in acetylcholine release and also receptor production stimulation. Occupation of these receptors by non-depolarizing relaxants result in fading in the response to train of four or tetanic stimulation. The constituents of the postsynaptic acetylcholine receptors are produced in the muscle cells and assembled into receptors under the influence of peptides released from the nerve terminal together with acetylcholine. When there is no release of acetylcholine in the neuromuscular junction (immobilization or denervation) the production of receptor elements increases (up regulation) and the receptors spread along the muscle membrane. When there is acetylcholine release the receptors concentrate and are fixed at the motor endplate. A number of peptides is involved in the process of assembly and fixation of the receptors. If the release of acetylcholine increases the number of receptors decreases (down regulation). This up and down regulation results clinically in respectively tachyphylaxis and sensitization for muscle relaxants [4].

### The ideal neuromuscular blocking agent

None of the presently available muscle relaxants meets the criteria for the ideal neuromuscular blocking agent as described by Savarese and Kitz. They defined 3 types of relaxants: fast onset and short duration, intermediate duration, or long duration, all without side effects and with a non-depolarizing mechanism of action [5]. It has been recognised that the onset of action of the relaxants is depending on the potency of

the compounds; i.e. the less potent the faster the onset [6]. Also other requirements for an ideal relaxant have been defined: i.e. non-depolarising mechanism of action, fast onset, non-cumulative, without cardiovascular side-effects or histamine release, prompt and complete reversal with anticholinesterases, rapid elimination from the body independent from renal and/or liver function or transformation into inactive metabolites [7]. Muscle relaxants seem to be responsible for 50% of the adverse reactions during anaesthesia. The most frequent reactions are tachycardia, cardiovascular collapse, urticaria, and bronchospasm. Such reactions most frequently occur after succinylcholine, followed by the benzyloquinoline relaxants, whereas they are rarely noticed after steroidal relaxants. Skin tests demonstrated the relative freedom of histamine release with the steroidal relaxants [8]. Especially pipercuronium, vecuronium are free from adverse effects. With rocuronium pain on injection and a slight increase in blood pressure and heart rate may occur. With rocuronium a higher incidence of anaphylactoid reactions than with other relaxants has been reported from France, Norway and New Zealand, *but not from other countries*. It is the substituted ammonium groups in the relaxants which evoke the allergic reactions. It has been proven that such an effect coincides with the use of pholcodine containing drugs [9, 10]. Studies revealed that pholcodine sensitizes the immune system, leading to increased IgE release. This drug is in the mentioned countries free available and can explain the higher incidence of anaphylactoid reactions to muscle relaxants and especially rocuronium in those countries.

### Neuromuscular blocking agents

The currently used neuromuscular blocking agents affect the nicotinic acetylcholine receptor at the postjunctional membrane in the neuromuscular junction. Some of the compounds, mainly older, also have an inhibiting effect on other acetylcholine receptors, which results in side effects. The clinically used relaxants can be divided in depolarizing and non-depolarizing relaxants with respectively an agonistic and antagonistic effect on the receptor. The only clinically used depolarizing relaxant is succinylcholine. The non-depolarizing relaxants can be roughly divided in compounds with a benzyloquinoline structure (d-tubocurarine, atracurium, cisatracurium, mivacurium, doxacurium) and steroidal relaxants (pancuronium, pipercuronium, vecuronium, rocuronium). Besides some non-depolarizing relaxants with other structures are available (gallamine, alloferine), but their clinical use has largely diminished. A depolarizing neuromuscular blockade is characterized by a fast onset of action, the occurrence

of muscle fasciculations (because of its agonistic effect) and the lack of fading in the response to train of four or tetanic stimulation. A non-depolarizing neuromuscular blockade does not have fasciculations, and shows fade in the response to train of four or tetanic stimulation. Succinylcholine has to occupy about 25% of the receptors before its effect is shown in decreased muscle contractility, whereas the non-depolarizing relaxants have to occupy 70-75% of the receptors to show such an effect [11]. The effect of succinylcholine cannot be reversed whereas acetylcholinesterase inhibitors (neostigmine, pyridostigmine, edrophonium) can reverse a non-depolarizing neuromuscular blockade. The benzylisoquinoline relaxants are known to be able to cause histamine release with bronchoconstriction, hypotension, and tachycardia. In some cases anaphylactoid reactions occur with all muscle relaxants. The newer benzylisoquinolines are metabolized in the plasma by Hoffman degradation and ester hydrolysis, they are largely independent from organ function. Most steroidal relaxants are metabolized in the liver and excreted via urine, they thus depend for their pharmacodynamic profile on organ function.

### Succinylcholine

Succinylcholine was introduced in the clinic in 1951. Fast metabolism by plasma (pseudo)-cholinesterase causes a quick recovery of the resulting blockade. Plasma cholinesterase is produced in the liver and is available in an abundant amount in the plasma. This indicates that the duration of action of succinylcholine is prolonged in severe liver disease. Succinylcholine is, because of its usually short duration of action, mainly used for endotracheal intubation of the patients. For longer lasting effects can it be administered by continuous infusion, but than a so called phase II block can occur. Such phase II block has the characteristics of a non-depolarizing neuromuscular blockade, can be reversed by neostigmine and is most likely caused by desensitization of the acetylcholine receptor. Succinylcholine provides excellent intubation conditions in most cases. Most anaesthetists believe the duration of action to be 5 minutes. However, it is well known that the duration of action of succinylcholine in the usual intubating dose of 1 mg/kg is having a duration of action between 10 and 15 minutes with a large variability. Such variability depends on the plasma cholinesterase activity in the individual patient [12]. Many factors cause variability in plasma cholinesterase activity:

- a. genetic disorders causing either low concentration or presence of atypical cholinesterase
- b. inhibition of plasma cholinesterase by drugs like metoclopramide, ubretid, esmolol, echotiophate, donepezil, terbutaline, and cyclophosphamide

- c. malnutrition or presence of solenoids from potatoes
- d. plasmapheresis, cardiopulmonary bypass and hemodialysis
- e. organophosphate intoxication
- f. chronic administration of neostigmine or pyridostigmine
- g. massive blood transfusion or blood exchange
- h. burn trauma

Succinylcholine has many side effects such as bradycardia, especially on repeated administrations, muscle fasciculations, myalgia, increase in intraocular, intracranial, and intragastric pressure, and potassium release resulting in hyperkalaemia. Such potassium release occurs when there is up-regulation of acetylcholine receptors, which leads to extra-junctional fetal receptor types [13].

### What are the main clinical problems with the non-depolarizing muscle relaxants?

Non-depolarizing neuromuscular blocking agents can have adverse effects [14]. The benzylisoquinoline relaxants are known to be able to cause histamine release with bronchoconstriction, hypotension, and tachycardia. In some cases anaphylactoid reactions occur. A common problem with all relaxants is the wide variability in the pharmacodynamic behaviour. The pharmacodynamic effect of non-depolarizing muscle relaxants is depending on numerous factors:

- a. pharmacological profile of the relaxant (long, intermediate, short)
- b. concurrent diseases (liver, kidney, inflammation, neuromuscular)
- c. concurrent medication (antibiotics, anti-epileptics, etc.)
- d. body temperature
- e. acid-base balance (acidosis, alkalosis)
- f. type and depth of anaesthesia (inhalational, MAC)
- g. gender of the patient
- h. age
- i. body weight / composition of the patient (volume of distribution)
- j. haemodynamics in the patient (slow, fast circulation)

Because all these factors can differ from patient to patient, the variability in effect of muscle relaxants is not surprising. Variability in effect may result in residual paralysis which in turn may cause postoperative pulmonary complications [15-17]. The incidence of postoperative residual paralysis is at average 40-50%, frequently despite routine administration of neostigmine [18-20]. Full recovery only exists when the train of four ratio is above 0.9, because below this value disturbances in hypoxic drive, insufficient airway patency maintenance, and swallowing disorders do occur. From the many studies can it be concluded that there are

three important factors in preventing residual paralysis: 1. only using the available shortest acting muscle relaxants, 2. routinely objective monitoring of neuromuscular transmission, and 3. routinely reverse neuromuscular block. For this reason most anaesthetists currently only use intermediate long acting muscle relaxants (rocuronium, vecuronium, atracurium, cis-atracurium). However, routine monitoring is globally rarely practised, whereas routine reversal is practised only in a few countries.

### **Rocuronium bromide**

Rocuronium is an amino-steroidal relaxants with a fast onset and an intermediate duration of action [21]. The ED<sub>90-95</sub> is 0.3-0.4 mg/kg. After a dose equal to two times the ED<sub>90-95</sub> dose, i.e. 0.9-1.0 mg/kg, the intubation under good to excellent conditions is possible in 60-90 seconds [22]. Rocuronium can cause a slight increase in heart rate and a small rise in blood pressure, presumably due to the pain on injection. Pain on injection occurs more frequently in female than in male [23]. It has been demonstrated that this pain can be prevented by previous administration of ketamine, dexmedetomidine, lidocaine, and by diluting the solution with saline. However also magnesium, sodium carbonate, fentanyl, and alfentanil seem to be effective. This indicates that the pain originates from an unspecific mechanism of action. From my own and others experiences must it be concluded that this pain is only observed during light planes of anaesthesia. The pain is without further sequels like thrombo-phlebitis. There is some fear that rocuronium causes a higher incidence of anaphylactoid reactions than other non-depolarizers. However, allergy and anaphylactoid reactions after its administration has been mainly reported from France, Norway, and Australia, but not in other countries [24-26]. This is possibly related to the free use of pholcodine, which sensitizes the immune system, in those countries. Since this was noticed is pholcodine taken of the market in Norway and has the reporting of anaphylactoid reactions with rocuronium there decreased.

### **Reversal of neuromuscular blockade**

The ability to reverse the effect of the muscle relaxants is one of basic requirements for muscle relaxation. Until recently only the anti-cholinesterases neostigmine, pyridostigmine and edrophonium were clinically used for this purpose. Acetylcholinesterase plays an important role in neuromuscular transmission by eliminating the acetylcholine molecules from the cleft through hydrolytic transformation. Only 50% of the acetylcholine molecules liberated from the nerve terminal actually reach the postsynaptic receptors, the

rest is hydrolysed before that. Although anticholinesterases do also have a direct presynaptic effect, it is believed that their main reversing mechanism is through inhibition of acetylcholinesterase. The presynaptic effects lead to repetitive firing and increased acetylcholine release. These effects also contribute to the reversing activity. For the reversal of neuromuscular blockade neostigmine is considered the standard compound. The onset of action of neostigmine is slow, for complete reversal 10 minutes or more are needed depending on at what degree of blockade the agent was administered. A problem with the cholinesterase inhibitors is that their effect depends on the type and depth of anaesthesia. Furthermore can deep blockades not be reversed by neostigmine, because of a ceiling effect indicating that if all cholinesterase is blocked no further blockade of the enzyme can take place [27]. Besides, anticholinesterases cause an increase of acetylcholine at all receptor places (nicotinic and muscarinic), resulting in side effects like bradycardia, arrhythmia, excessive secretions from salivary and bronchial glands, and increased bronchial and intestinal smooth muscle tone. The adverse effects are dose dependent, and are most pronounced with neostigmine and least pronounced with edrophonium [28]. The drugs, except edrophonium, also inhibit plasma cholinesterase activity, thus they prolong the effect of succinylcholine and mivacurium. The decrease in plasma cholinesterase activity lasts for 30-60 minutes. At repeated dosages of anti-cholinesterases neuromuscular block may occur from transient depolarisation of the receptors, and blockade of open confirmation channels [29, 30].

Atropine, but especially glycopyrrolate prevents many of the cardiovascular effects of the anticholinesterases, but, it is not able to prevent the intestinal effects. At least for neostigmine in one study it has been demonstrated that it increases the incidence of nausea and vomiting in the immediate postoperative period [31, 32]. For a long time, because of all these side-effects, an ideal reversal agent has been searched. At first new cleaner compounds with an anticholinesterase effect were studied, but proved to have similar side-effects as neostigmine [33]. Then a completely new method of reversal was developed, using molecular encapsulation [34]. Finally sugammadex (org 25969), a modified  $\gamma$ -cyclodextrine that encapsulates vecuronium and rocuronium and thereby inactivates these molecules, was selected as a potential ideal reversing agent [35].

### **What is an ideal reversal agent?**

In the process of developing new drugs the requirements for such a drug have to be defined. This is also

applied to the development of drugs reversing the effect of neuromuscular blocking agents. Especially the many side effects of the anticholinesterases had to be absent in such a drug. Therefore in my opinion the requirements for an ideal neuromuscular block reversing agent should be that the drug must:

- a. provide full reversal within 1-3 minutes
- b. reverse each depth of neuromuscular block
- c. be independent from type and level of anaesthesia
- d. be independent from acid-base balance
- e. reverse relaxant-drug combination block (antibiotics, magnesium, etc.)
- f. be free from adverse-effects
- g. reverse in patients with organ disease (liver, kidney)
- h. not leave the possibility of recurarization
- i. be rapidly excreted from the body, or be readily metabolised
- j. be free from allergic reactions
- k. be effective in patients with neuromuscular disease
- l. be applicable in all age groups
- m. be effective against all relaxants
- n. be not affected by hypothermia

### Sugammadex

Sugammadex is a specific binding agent (encapsulation) for steroidal muscle relaxants [36, 37]. The compound is not metabolised, but both sugammadex and the sugammadex-rocuronium complex are rapidly excreted in the urine. It has a dose depending fast onset of action, which allows complete recovery of a neuromuscular block of any degree within 2-4 minutes [38, 39]. It, however, is only effective with steroidal, but not with benzyliisoquinoline muscle relaxants [40]. It reverses successfully superficial, deep and profound neuromuscular blockades induced by rocuronium or vecuronium [41-43]. It is also effective after repeated doses or continuous infusion of rocuronium or vecuronium [44, 45]. Contrary to neostigmine the effect is independent from the type and depth of anaesthesia [46], from temperature, and from acid-base balance. Because of its mechanism of action (encapsulation of the rocuronium-vecuronium molecule) does it not interfere with acetylcholine, its receptor, or any other receptor, therefore is it unlikely that relevant adverse effects on the cardiovascular system or respiratory tract will occur. Sugammadex has been successfully administered in elderly and children [47], in patients with pulmonary disease, and in patients with cardiovascular disturbances [48]. Also in patients with renal dysfunction it was effective and the recurarization did not occur [49]. If after administration of sugammadex a new neuromuscular blockade is requested, either a non-steroidal relaxant or a higher dose of rocuronium

can be used [50]. The recovery of a combination of rocuronium and sugammadex is faster than the recovery of succinylcholine, and provides identical intubation conditions [51]. Sugammadex does not encapsulate endogenous substances or other drugs.

### Can rocuronium replace succinylcholine?

There is a number of disadvantages to the use of succinylcholine. As explained above succinylcholine is a drug with many side-effects, but with an excellent pharmacodynamic profile (fast onset, short duration, fast recovery). In my opinion, because of its side effects and especially the possibility of hyperkalaemia, it is obsolete in Intensive Care patients and should be replaced in anaesthesia whenever this is possible.

It is impossible to reach acceptable intubation conditions in all patients with succinylcholine in the usually administered doses (0.5-1.0 mg/kg) [52]. Therefore nowadays doses of 1.0-1.5 mg/kg are advised. The duration of action of succinylcholine is widely variable because of the large variability in plasma cholinesterase activity. Although many anaesthetists believe the duration of action of an intubating dose (1-1.5 mg/kg) to be only 5 minutes it is in many cases longer than 10 minutes. This can easily lead to unacceptable hypoxia. Benumoff et al. modelled oxygen saturation during succinylcholine-induced apnoea, and found remarkable result [53]. They stated that “...in the large majority of patients with 1 mg/kg of succinylcholine induced apnea, significant life threatening haemoglobin desaturation will occur before functional recovery”. In a study by Heier et al. these results were verified in patients [54]. Significant haemoglobin desaturation occurred in one third of the subjects during the period of apnoea from a dose of 1 mg/kg succinylcholine, despite only young healthy subjects were included in the study. The degree of desaturation correlated with the duration of apnoea. Especially children are prone to early hypoxia because they have a smaller functional residual capacity. Patients with pre-existing disease processes that compromise lung function have a higher risk to develop desaturation because their functional residual capacity is markedly lower than in young healthy subjects. Patients in labour and those with obesity or sepsis have considerably accelerated arterial desaturation, while the oxygen consumption is also higher [55]. It is known that during apnoea the rate of desaturation is rapidly increasing because the volume in the alveoli is decreasing, leading to alveolar collapse and increasing ventilation/perfusions disturbances, leading to shunting [56]. In obese patients and pregnant patients can pre-oxygenation in the sitting position delay the desaturation with about 1 minute [57]. This, however, may be insufficient to prevent hypoxia,

due to the variability of succinylcholine's effect. Furthermore, at values of saturation below 80%, the saturation curve enters the steep part and the saturation than changes more rapidly with small changes in arterial oxygen partial pressure. Some authors have suggested that lower dosages of succinylcholine increase the margin of safety for hypoxia because of a shorter duration of the apnea, while providing acceptable intubation conditions [58, 59]. However, in such cases the intubation conditions were poor, resulting in delayed intubation and increased risk on hypoxia. It has recently been shown that patients who received succinylcholine as the neuromuscular blocking agent for intubation developed significantly faster oxygen desaturation than those who received rocuronium [60]. There was a relation with the severity of the fasciculations after succinylcholine, also an increase in CO<sub>2</sub> excretion was observed.

All these facts indicate that succinylcholine is far from an ideal relaxant agent and that is not as safe as most anaesthetists believe.

For this reason has it long been looked for a steroidal non-depolarising replacement drug. However, none of the potential drugs were free from severe side-effects and therefore were not further developed [61, 62]. In order to replace succinylcholine must the compound have a fast onset and short duration of action with rapid recovery and must it provide excellent to good intubating conditions. Rocuronium appeared to be a candidate for the replacement of succinylcholine because of its short onset of action, which in high dosages is similar as that of succinylcholine, and because of its rather clean safety profile. However, in the doses required rocuronium has a markedly longer duration of action than succinylcholine. From all the currently available non-depolarising relaxants rocuronium has the fastest onset of action that provide the possibility to have excellent to good intubating conditions within 1-1.5 minutes, similar to succinylcholine [63-65]. This also is true in paediatric cases [66-68]. An advantage of rocuronium over succinylcholine is that it does not cause bradycardia and does not increase intraocular and intracranial pressure [69]. In many institutions throughout the world, because of its better safety profile, rocuronium replaced succinylcholine for rapid sequence intubation. The only disadvantage that rocuronium is having compared to succinylcholine, is a longer duration of action. But the specific steroidal relaxant binding compound sugammadex has been proven to be able to reverse a rocuronium blockade of any degree within 2-3 minutes when administered in adequate doses [70-73]. It reverses contrary to neostigmine, independent from the type and depth of anaesthesia [74, 75]. Sugammadex reverses much faster than neostigmine to full recovery within a few

minutes [76, 77]. This may be an opportunity to customize the duration of action of rocuronium for intubating situations. While a large dose of rocuronium approaches succinylcholine in onset, the rapid reversal of rocuronium with sugammadex exceeded the speed of spontaneous recovery from succinylcholine. This indeed has been proven in patients and we are awaiting the results of further studies in this direction [78, 79]. Together, the rocuronium-sugammadex sequence promises to achieve what other novel neuromuscular blocking and reversing drugs have not provided: to reverse succinylcholine. The combination indeed has clinical value [80]. Not only the old slogan "*So Long, Sux!*", but also "*So Long, Neostigmine!*" may come true if sugammadex proves itself in clinical practice [81]. It now appears that suxamethonium can be replaced even for its final remaining indications.

## Conclusion

Residual paralysis is a real problem in the post-operative period and contributes to the morbidity and mortality of anaesthesia. Administration of neostigmine, besides the possibility of many adverse effects, is no guarantee to prevent such residual paralysis. Sugammadex is currently the most ideal reversing agent and can prevent residual blockade in all situations. It furthermore provides in combination with rocuronium a possibility to exclude succinylcholine from further use.

## References

1. Shear TD, Martyn JA. Physiology and biology of neuromuscular transmission in health and disease. *J Crit Care* 2009; 24: 5-10
2. Goodman BE. Channels active in the excitability of nerves and skeletal muscles across the neuromuscular junction: basic function and pathophysiology. *Adv Physiol Educ* 2008; 32: 127-135
3. Fagerlund MJ, Eriksson LI. Current concepts in neuromuscular transmission. *Br J Anaesth* 2009; 103: 108-114
4. Martyn JA, White DA, Gronert GA, Jaffe RS, Ward JM. Up-and-down regulation of skeletal muscle acetylcholine receptors. Effects on neuromuscular blockers. *Anesthesiology* 1992; 76: 822-843
5. Savarese JJ, Kitz RJ. Does clinical anesthesia need new neuromuscular blocking drugs? *Anesthesiology* 1975; 42: 236-239
6. Bowman WC, Rodger IW, Houston J, Marshall RJ, McIndewar I. Structure-action relationships among some desacetoxo analogues of pancuronium and vecuronium in the anesthetized cat. *Anesthesiology* 1988; 69: 57-62
7. Booi LHDJ, Crul JF. A comparison of vecuronium with the hypothetical ideal neuromuscular blocking drug. In: Agoston S et al. (eds). *Clinical experiences with Norcuron (Org NC 45, vecuronium bromide)*. Amsterdam, Excerpta Medica, Current Clinical Practice Series 11, 1983: 3-8
8. Robertson EN, Booi LHDJ, Fragen RJ, Crul JF. Intradermal histamine release by 3 muscle relaxants. *Acta Anaesthesiol Scand* 1983; 27: 203-205

9. Florvaag E, Johansson SGO, Öman H, Harboe T, Nopp A. Pholcodine stimulates a dramatic increase of IgE in IgE-sensitized individuals. A pilot study. *Allergy* 2006; 61: 49-55
10. Harboe T, Johansson SGO, Florvaag E, Öman H. Pholcodine exposure raises serum IgE in patients with previous anaphylaxis to neuromuscular blocking agents. *Allergy* 2007; 62: 1445-1450
11. Paton WDM, Waud DR. The margin of safety of neuromuscular transmission. *J Physiol* 1967; 191: 59-90
12. Vanlinthout LE, van Egmond J, de Boo T, Lerou JG, Wevers RA, Booiij LHDJ. Factors affecting magnitude and time course of neuromuscular block produced by suxamethonium. *Br J Anaesth* 1992; 69: 29-35
13. Martyn JA, Richtsfeld M. Succinylcholine-induced hyperkalemia in acquired pathologic states: etiologic factors and molecular mechanisms. *Anesthesiology* 2006; 104: 158-169
14. Claudius C, Garvey LH, Viby-Mogensen J. The undesirable effects of neuromuscular blocking drugs. *Anaesthesia* 2009; 64 (suppl 1): 10-21
15. Berg H, Roed J, Viby-Mogensen J, et al. Residual neuromuscular block is a risk factor for postoperative pulmonary complications. A prospective, randomised, and blinded study of postoperative pulmonary complications after atracurium, vecuronium and pancuronium. *Acta Anaesthesiol Scand* 1997; 41: 1095-1103
16. Eriksson LI. The effects of residual neuromuscular blockade and volatile anesthetics on the control of ventilation. *Anesth Analg* 1999; 89: 243-251
17. Arbous MS, Meursing A, van Kleef JW, et al. Impact of anesthesia management characteristics on severe morbidity and mortality. *Anesthesiology* 2005; 102: 257-268
18. Murphy GS, Szokol JW, Marymont JH, Franklin M, Avram MJ, Vender JS. Residual paralysis at the time of tracheal extubation. *Anesth Analg* 2005; 100: 1840-1845
19. Baurain MJ, Hoton F, D'Hollander AA, Cantraine FR. Is recovery of neuromuscular transmission complete after the use of neostigmine to antagonize block produced by rocuronium, vecuronium, atracurium and pancuronium? *Br J Anaesth* 1996; 77: 496-499
20. Kim KS, Lew SH, Cho HY, Cheong MA. Residual paralysis induced by either vecuronium or rocuronium after reversal with pyridostigmine. *Anesth Analg* 2002; 95: 1656-1660
21. Booiij LHDJ, Knape HT. The neuromuscular blocking effect of Org 9426. A new intermediately-acting steroidal non-depolarising muscle relaxant in man. *Anaesthesia* 1991; 46: 341-343
22. Huizinga AC, Vandenbrom RH, Wierda JM, Hommes FD, Hennis PJ. Intubating conditions and onset of neuromuscular block of rocuronium (Org 9426); a comparison with suxamethonium. *Acta Anaesthesiol Scand* 1992; 36: 463-468
23. Mencke T, Schreiber JU, Knoll H, et al. Women report more pain on injection of a precurarization dose of rocuronium: a randomized, prospective, placebo-controlled trial. *Acta Anaesthesiol Scand* 2004; 48: 1245-1248
24. Mertes PM, Laxenaire MC, Alla F; Groupe d'Etudes des Réactions Anaphylactoïdes Peranesthésiques. Anaphylactic and anaphylactoid reactions occurring during anesthesia in France in 1999-2000. *Anesthesiology* 2003; 99: 536-545
25. Guttormsen AB. Allergic reactions during anaesthesia – increased attention to the problem in Denmark and Norway. *Acta Anaesthesiol Scand* 2001; 45: 1189-1190
26. Yee R, Fernandez JA. Anaphylactic reaction to rocuronium bromide. *Anaesth Intensive Care* 1996; 24: 601-604
27. Beemer GH, Bjorksten AR, Dawson PJ, Dawson RJ, Heenan PJ, Robertson BA. Determinants of the reversal time of competitive neuromuscular block by anticholinesterases. *Br J Anaesth* 1991; 66: 469-475
28. Cronnelly R, Morris RB, Miller RD. Edrophonium: duration of action and atropine requirement in humans during halothane anesthesia. *Anesthesiology* 1982; 57: 261-266
29. Payne JP, Hughes R, Al Azawi S. Neuromuscular blockade by neostigmine in anaesthetized man. *Br J Anaesth* 1980; 52: 69-76
30. Caldwell JE. Reversal of residual neuromuscular block with neostigmine at one to four hours after a single intubating dose of vecuronium. *Anesth Analg* 1995; 80: 1168-1174
31. Ding Y, Fredman B, White PF. Use of mivacurium during laparoscopic surgery: effect of reversal drugs on postoperative recovery. *Anesth Analg* 1994; 78: 450-454
32. Tramèr MR, Fuchs-Buder T. Omitting antagonism of neuromuscular block: effect on postoperative nausea and vomiting and risk of residual paralysis. A systematic review. *Br J Anaesth* 1999; 82: 379-386
33. Palin R, Clark JK, Cowley P, et al. Novel piperidinium and pyridinium agents as water-soluble acetylcholinesterase inhibitors for the reversal of neuromuscular blockade. *Bioorg Med Chem Lett* 2002; 12: 2569-2572
34. Cameron KS, Fielding L, Mason R, et al. Anionic cyclophanes as potential reversal agents of muscle relaxants by chemical chelation. *Bioorg Med Chem Lett* 2002; 12: 753-755
35. Bom A, Bradley M, Cameron K, et al. A novel concept of reversing neuromuscular block: chemical encapsulation of rocuronium bromide by a cyclodextrin-based synthetic host. *Angew Chem Int Ed Engl* 2002; 41: 266-270
36. Booiij LHDJ, van Egmond J, Driessen JJ, de Boer HD. In vivo animal studies with sugammadex. *Anaesthesia* 2009; 64 (suppl 1): 38-44
37. Gijzenbergh F, Ramael S, Houwing N, van Iersel T. First human exposure of Org 25969, a novel agent to reverse the action of rocuronium bromide. *Anesthesiology* 2005; 103: 695-703
38. Sorgenfrei IF, Norrild K, Larsen PB, et al. Reversal of rocuronium-induced neuromuscular block by the selective relaxant binding agent sugammadex: a dose-finding and safety study. *Anesthesiology* 2006; 104: 667-674
39. Groudine SB, Soto R, Lien C, Drover D, Roberts K. A randomized, dose-finding, phase II study of the selective relaxant binding drug, Sugammadex, capable of safely reversing profound rocuronium-induced neuromuscular block. *Anesth Analg* 2007; 104: 555-562
40. de Boer HD, van Egmond J, van de Pol F, Bom A, Booiij LHDJ. Sugammadex, a new reversal agent for neuromuscular block induced by rocuronium in the anaesthetized Rhesus monkey. *Br J Anaesth* 2006; 96: 473-479
41. Suy K, Morias K, Cammu G, et al. Effective reversal of moderate rocuronium- or vecuronium-induced neuromuscular block with sugammadex, a selective relaxant binding agent. *Anesthesiology* 2007; 106: 283-288
42. de Boer HD, Driessen JJ, Marcus MA, Kerckamp H, Heeringa M, Klimek M. Reversal of rocuronium-induced (1.2 mg/kg) profound neuromuscular block by sugammadex: a multicenter, dose-finding and safety study. *Anesthesiology* 2007; 107: 239-244
43. Duvaldestin P, Kuizenga K, Saldien V, et al. A randomized, dose-response study of sugammadex given for the reversal of deep rocuronium- or vecuronium-induced neuromuscular blockade under sevoflurane anesthesia. *Anesth Analg* 2010; 110: 74-82
44. Shields M, Giovannelli M, Mirakhor RK, Moppett I, Adams J, Hermens Y. Org 25969 (sugammadex), a selective relaxant binding agent for antagonism of prolonged rocuronium-induced

- neuromuscular block. *Br J Anaesth* 2006; 96: 36-43
45. Rex C, Wagner S, Spies C, et al. Reversal of neuromuscular blockade by sugammadex after continuous infusion of rocuronium in patients randomized to sevoflurane or propofol maintenance anaesthesia. *Anesthesiology* 2009; 111: 30-35
  46. Vanacker BF, Vermeyen KM, Struys MM, et al. Reversal of rocuronium-induced neuromuscular block with the novel drug sugammadex is equally effective under maintenance anaesthesia with propofol or sevoflurane. *Anesth Analg* 2007; 104: 563-568
  47. Plaud B, Meretoja O, Hofmoeckel R, et al. Reversal of rocuronium-induced neuromuscular blockade with sugammadex in pediatric and adult surgical patients. *Anesthesiology* 2009; 110: 284-294
  48. Dahl V, Pendeville PE, Hollmann MW, Heier T, Abels EA, Blobner M. Safety and efficacy of sugammadex for the reversal of rocuronium-induced neuromuscular blockade in cardiac patients undergoing noncardiac surgery. *Eur J Anaesthesiol* 2009; 26: 874-884
  49. Staals LM, Snoeck MMJ, Driessen JJ, Flockton EA, Heeringa M, Hunter JM. Multicentre, parallel-group, comparative trial evaluating the efficacy and safety of sugammadex in patients with end-stage renal failure or normal renal function. *Br J Anaesth* 2008; 101: 492-497
  50. de Boer HD, Driessen JJ, van Egmond J, Booij LHDJ. Non-steroidal neuromuscular blocking agents to re-establish paralysis after reversal of rocuronium-induced neuromuscular block with sugammadex. *Can J Anaesth* 2008; 55: 124-125
  51. Lee C, Jahr JS, Candiotti KA, Warriner B, Zornow MH, Naguib M. Reversal of profound neuromuscular block by sugammadex administered three minutes after rocuronium: a comparison with spontaneous recovery from succinylcholine. *Anesthesiology* 2009; 110: 1020-1025
  52. Donati F. The right dose of succinylcholine. *Anesthesiology* 2003; 99: 1037-1038
  53. Benumof JL, Dagg R, Benumof R. Critical hemoglobin desaturation will occur before return to an unparalyzed state following 1 mg/kg intravenous succinylcholine. *Anesthesiology* 1997; 87: 979-982
  54. Heier T, Feiner JR, Lin J, Brown R, Caldwell JE. Hemoglobin desaturation after succinylcholine-induced apnea: a study of the recovery of spontaneous ventilation in healthy volunteers. *Anesthesiology* 2001; 94: 754-759
  55. McClelland SH, Bogod DG, Hardman JG. Pre-oxygenation and apnoea in pregnancy: changes during labour and with obstetric morbidity in a computational simulation. *Anaesthesia* 2009; 64: 371-377
  56. Fairshter RD, Williams JH Jr. Pulmonary physiology in the post-operative period. *Crit Care Clin* 1987; 3: 287-306
  57. Altermatt FR, Muñoz HR, Delfino AE, Cortínez LI. Pre-oxygenation in the obese patient: effects of position on tolerance of apnoea. *Br J Anaesth* 2005; 95: 705-709
  58. Kopman AF, Zhaku B, Lai KS. The "intubating dose" of succinylcholine: the effect of decreasing doses on recovery time. *Anesthesiology* 2003; 99: 1050-1054
  59. Naguib M, Samarkandi A, Riad W, Alharby SW. Optimal dose of succinylcholine revisited. *Anesthesiology* 2003; 99: 1045-1049
  60. Taha SK, El-Khatib MF, Baraka AS, et al. Effect of suxamethonium vs rocuronium on onset of oxygen desaturation during apnoea following rapid sequence induction. *Anaesthesia* 2010; 65: 358-361
  61. Booij LHDJ, van der Broek LA, Caulfield W, et al. Non-depolarizing neuromuscular blocking activity of bisquaternary amino di- and tripeptide derivatives. *J Med Chem* 2000; 43: 4822-4833
  62. Muir AW, Sleight T, Marshall RJ, et al. Neuromuscular blocking and cardiovascular effects of Org 9487, a new short-acting aminosteroidal blocking agent, in anaesthetized animals and in isolated muscle preparations. *Eur J Anaesthesiol* 1998; 15: 467-479
  63. Andrews JI, Kumar N, van den Brom RH, Olkkola KT, Roest GJ, Wright PM. A large simple randomized trial of rocuronium versus succinylcholine in rapid-sequence induction of anaesthesia along with propofol. *Acta Anaesthesiol Scand* 1999; 43: 4-8
  64. Weiss JH, Gratz I, Goldberg ME, Afshar M, Insinga F, Larijani G. Double-blind comparison of two doses of rocuronium and succinylcholine for rapid-sequence intubation. *J Clin Anesth* 1997; 9: 379-382
  65. Nelson JM, Morell RC, Butterworth JF 4<sup>th</sup>. Rocuronium versus succinylcholine for rapid-sequence induction using a variation of the timing principle. *J Clin Anesth* 1997; 9: 317-320
  66. Cheng CA, Aun CS, Gin T. Comparison of rocuronium and suxamethonium for rapid tracheal intubation in children. *Paediatr Anaesth* 2002; 12: 140-145
  67. Mazurek AJ, Rae B, Hann S, Kim JI, Castro B, Coté CJ. Rocuronium versus succinylcholine: are they equally effective during rapid-sequence induction of anaesthesia? *Anesth Analg* 1998; 87: 1259-1262
  68. Fuchs-Buder T, Tassonyi E. Intubating conditions and time course of rocuronium-induced neuromuscular block in children. *Br J Anaesth* 1996; 77: 335-338
  69. Robertson EN, Hull JM, Verbeek AM, Booij LHDJ. A comparison of rocuronium and vecuronium: the pharmacodynamic, cardiovascular and intra-ocular effects. *Eur J Anaesthesiol Suppl* 1994; 9: 116-121
  70. Pühringer FK, Rex C, Sielenkämper AW, et al. Reversal of profound, high-dose rocuronium-induced neuromuscular blockade by sugammadex at two different time points: an international, multicenter, randomized, dose-finding, safety assessor-blinded, phase II trial. *Anesthesiology* 2008; 109: 188-197
  71. Booij LHDJ. Cyclodextrins and the emergence of sugammadex. *Anaesthesia* 2009; 64 (suppl 1): 31-37
  72. Booij LHDJ, van Egmond J, Driessen JJ, de Boer HD. In vivo animal studies with sugammadex. *Anaesthesia* 2009; 64 (suppl 1): 38-44
  73. Mirakhur RK. Sugammadex in clinical practice. *Anaesthesia* 2009; 64 (suppl 1): 45-54
  74. Rex C, Wagner S, Spies C, et al. Reversal of neuromuscular blockade by sugammadex after continuous infusion of rocuronium in patients randomized to sevoflurane or propofol maintenance anaesthesia. *Anesthesiology* 2009; 111: 30-35
  75. Duvaldestin P, Kuizenga K, Saldien V, et al. A randomized, dose-response study of sugammadex given for the reversal of deep rocuronium- or vecuronium-induced neuromuscular blockade under sevoflurane anaesthesia. *Anesth Analg* 2010; 110: 74-82
  76. Sacan O, White PF, Tufanogullari B, Klein K. Sugammadex reversal of rocuronium-induced neuromuscular blockade: a comparison with neostigmine-glycopyrrolate and edrophonium-atropine. *Anesth Analg* 2007; 104: 569-574
  77. Jones RK, Caldwell JE, Brull SJ, Soto RG. Reversal of profound rocuronium-induced blockade with sugammadex: a randomized comparison with neostigmine. *Anesthesiology* 2008; 109: 816-824
  78. Lee C, Jahr JS, Candiotti KA, Warriner B, Zornow MH, Naguib M. Reversal of profound neuromuscular block by sugammadex

administered three minutes after rocuronium: a comparison with spontaneous recovery from succinylcholine. *Anesthesiology* 2009; 110: 1020-1025

79. Lee C. Goodbye Suxamethonium! *Anaesthesia* 2009; 64 (suppl 1): 73-81
80. McTernan CN, Rapeport DA, Ledowski T. Successful use of rocuronium and sugammadex in an anticipated difficult airway scenario. *Anaesth Intensive Care* 2010; 38: 390-392
81. Lee C, Katz RL. Clinical implications of new neuromuscular concepts and agents: so long, neostigmine! So long, sux! *J Crit Care* 2009; 24: 43-49

### **Utilizarea adecvată a relaxantelor musculare în anestezie, terapie intensivă și medicina de urgență**

#### **Rezumat**

În acest scurt referat sunt descrise procesele fiziologice implicate în transmitia neuromusculară.

Relaxantele musculare sunt utilizate în anestezia clinică pentru blocarea acestei transmisii și sunt definite cerințele pentru un relaxant ideal. Sunt prezentate în rezumat dezavantajele miorelaxantelor utilizate curent, inclusiv dezavantajele succinilcolinei. O atenție specială s-a acordat rocuroniumului. Paralizia reziduală, principalul dezavantaj, poate fi tratată și/sau prevenită prin antagonizarea unui astfel de bloc. Totuși, compușii utilizați curent prezintă efecte adverse serioase și nu sunt întotdeauna eficienți. De aceea, sunt definite și cerințele pentru un agent antagonist ideal. În acest context este discutat sugammadexul. Este prezentată posibilitatea înlocuirii succinilcolinei cu o combinație între succinilcolină și sugammadex.

**Cuvinte cheie:** transmitie neuromusculară, bloc neuromuscular, succinilcolină, rocuronium, bloc rezidual, sugammadex