REVIEW ARTICLE

David S. Warner, M.D., Editor

Magnesium—Essentials for Anesthesiologists

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ABSTRACT

Magnesium plays a fundamental role in many cellular functions, and thus there is increasing interest in its role in clinical medicine. Although numerous experimental studies indicate positive effects of magnesium in a variety of disease states, large clinical trials often give conflicting results. However, there is clear evidence for magnesium to benefit patients with eclampsia or torsades de pointes arrhythmias. In addition, magnesium seems to have antinociceptive and anesthetic as well as neuroprotective effects, yet well-designed large clinical trials are required to determine its actual efficacy in pain management or in the state of stroke or subarachnoid hemorrhage. The current review aims to provide an overview of current knowledge and available evidence with respect to physiologic aspects of magnesium and proposed indications and recommendations for its use in the clinical setting.

MAGNESIUM has a key role in numerous physiologic processes. Although experimental studies have demonstrated beneficial effects of magnesium administration in a variety of disease states, the results of clinical studies frequently are a matter of controversy. The current review aims to summarize the current knowledge on the physiology and pathophysiology of magnesium and on the proposed indications and recommendations for its use in different clinical settings.

Using MEDLINE, the Cochrane Library, and ClinicalTrials.gov, a search was performed for studies addressing experimental and clinical effects of magnesium. Key words entered were: magnesium, physiology, toxicity, anesthesia, analgesia, pheochromocytoma, preeclampsia and eclampsia, asthma, myocardial infarction, cardiac arrhythmias, stroke, and neuroprotection. The search was limited to articles in the English and German language published within the time frame of the last 30 yr. Electronic searches were updated until September 2010 and were complemented by screening bibliographies of retrieved articles and reviews.

Physiologic Properties and Homeostasis of Magnesium

Magnesium is the fourth most abundant essential ion in the human body and plays a fundamental role in many cellular functions, such as storage, metabolism, and energy utilization.[1] It serves as a cofactor for various biologic processes, including protein synthesis, neuromuscular function, and nucleic acid stability.[2] Magnesium is an intrinsic component of many adenosine 5′-triphosphatases and an endogenous regulator of several electrolytes.[3] Being a noncompetitive inhib-

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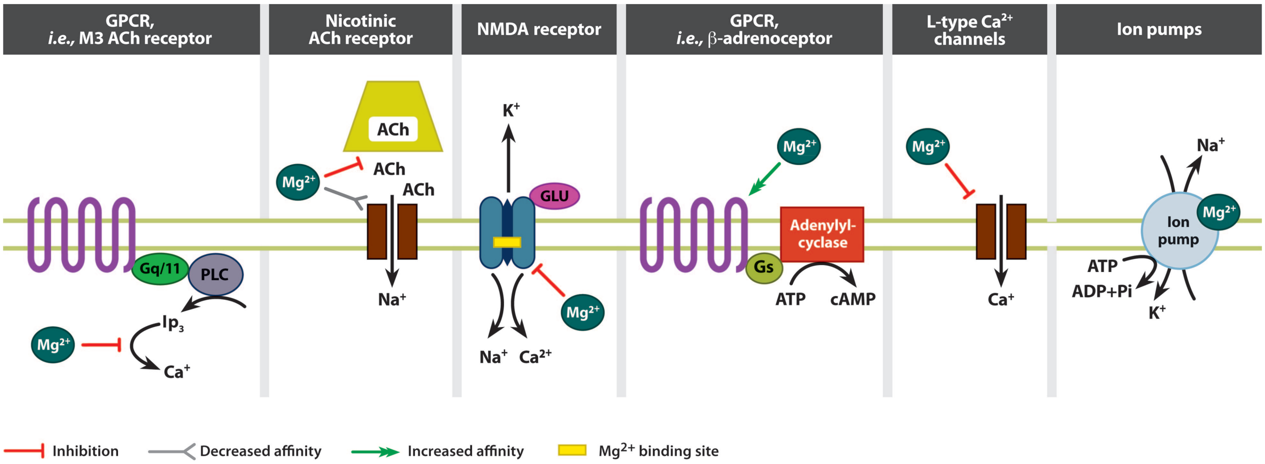

Fig. 1. Sites and mechanisms of action for magnesium. By modulating not only ion channels and ion pumps but also receptor signaling, magnesium affects numerous cellular processes. Ach = acetylcholine; ADP = adenosine diphosphate; ATP = adenosine triphosphate; cAMP = cyclic adenosine monophosphate; Glu = glutamate; GPCR = G-protein-coupled receptor; IP_3 = inositol triphosphate; NMDA = *N*-methyl-D-aspartate; Pi = inorganic phosphate; PLC = phospholipase C.

itor of inositol triphosphate-gated calcium channels, magnesium functions as an endogenous calcium antagonist by affecting its uptake and distribution.[1,4] Magnesium also shows modulatory effects on sodium and potassium currents, thus influencing membrane potential.[5,6] In the central nervous system, magnesium exerts depressant effects, acting as an antagonist at the *N*-methyl-D-aspartate (NMDA) glutamate receptor and an inhibitor of catecholamine release (fig. 1).[7,8]

A human adult body contains an average of 24 g (1 mol) magnesium, stored mainly in bone (60%) and the intracellular compartments of muscle (20%) and soft tissues (20%), primarily bound to chelators, such as adenosine 5′-triphosphate and DNA.[2] Two to three percent of intracellular magnesium is ionized and regulates intracellular magnesium homeostasis.[2] The extracellular space comprises only 1% of total body magnesium, including 0.3% found in plasma. Plasma magnesium is ionized (60%), complexed to anions (7%), or protein-bound (33%), with normal concentrations of total plasma magnesium ranging from 0.7 to 1.0 mM (1.7–2.4 mg/dl).

Maintenance of magnesium homeostasis is largely regulated by intestinal absorption and renal excretion. Magnesium is mainly absorbed in the small intestine *via* two different pathways depending on dose and formula of dietary intake: at low intraluminal concentrations predominantly by a saturable active transcellular transport and with rising concentrations through nonsaturable passive diffusion (table 1).[9] The bioavailability of organic compounds, such as magnesium aspartate or magnesium citrate, is suggested to be considerably better than that of inorganic mixtures. When magnesium content is normal, approximately 40–50% is absorbed. Underlying mechanisms of altered fractional magnesium absorption in the state of hypo- or (less commonly) hypermagnesemia remain to be identified.

Table 1. Gastrointestinal Absorption of Magnesium

Anatomical Site	Magnesium Absorption (mg/day)	% Absorption of Intake
Stomach	0	0
Duodenum	15	5
Jejunum	30	10
Proximal ileum	45	15
Distal ileum	30	10
Colon	15	5
Total	135	45

The data represented refer to a normal dietary intake of 300 mg/day. Approximately 40–50% of the dietary magnesium is absorbed.

In the kidneys, approximately 80% of plasma magnesium is ultrafiltered through the glomerulus, with more than 95% being reabsorbed by the consecutive segments of the nephron (fig. 2). The predominant site is the cortical thick ascending limb of the loop of Henle (70%), with the proximal and distal convoluted tubule accounting for only 15–25% and 5–10% of reabsorption, respectively.[10] In the loop of Henle, magnesium is passively reabsorbed *via* paracellular diffusion, driven by an electrochemical gradient, resulting from reabsorption of sodium chloride. The tight junction protein claudin 16 is believed to facilitate paracellular magnesium reabsorption because mutations in its encoding gene paracellin-1 cause a human hereditary magnesium-wasting syndrome.[11,12]

Little is known about the mechanisms underlying magnesium reabsorption in the distal convoluted tubule. As demonstrated for the small intestine, an active transcellular transport involving TRPM6, a member of the transient receptor potential family of cation channels, localized along apical distal convoluted tubule membranes and at brush-border membranes of the duodenum, seems to play a role.[13] Patients with mutation in the TRPM6 gene experience severe hypomagnesemia and secondary hypocalcemia.[14] Regulation of magnesium transport lacks a specific endocrine control, although several hormones have been suggested to alter mag-

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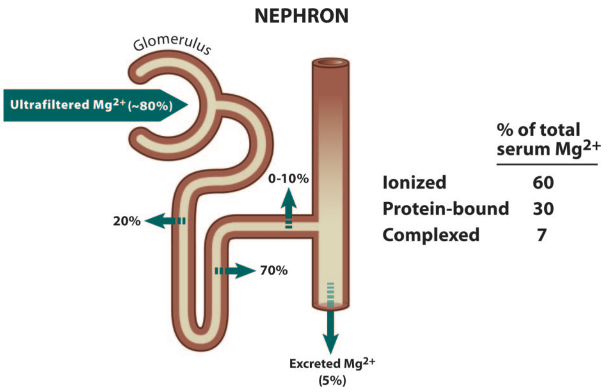

Fig. 2. Schematic representation of the renal handling of magnesium. Normally 95% of the filtered magnesium is reabsorbed by the nephron.

nesium homeostasis. Parathormone and vitamin D stimulate magnesium renal and intestinal reabsorption, respectively, whereas insulin may decrease renal excretion of magnesium and enhance its cellular uptake.[15] The human body is not able to rapidly mobilize magnesium stores and exchange them with circulating magnesium to keep plasma concentrations within normal limits. Urinary excretion of magnesium is normally 5 mmol/day if renal function is adequate but can be decreased to less than 0.5% (~ 0.03 mmol/day) in the event of magnesium deprivation caused by extrarenal losses. However, individuals are highly vulnerable to hypermagnesemia with loss of renal function.

Clinical Relevance of Magnesium Disturbances

Hypomagnesemia is defined as a plasma magnesium concentration of less than 0.7 mM and results mainly from inadequate dietary intake and/or gastrointestinal and renal losses. Clinically significant magnesium deficiency (symptoms usually occur at plasma concentrations less than 0.5 mM) is commonly associated with diarrhea, vomiting, and laxative abuse; the use of loop and thiazide diuretics, angiotensin-converting enzyme inhibitors, cisplatin, aminoglycosides, or other nephrotoxic drugs; and several endocrine disorders, such as parathyroid disease, hyperaldosteronism, and chronic alcoholism.[16,17] Diabetes mellitus is strongly associated with hypomagnesemia, possibly because of increased urinary losses. Low magnesium may aggravate insulin resistance and predispose diabetic patients to cardiovascular disease.[15] Hypomagnesemia also occurs perioperatively and is commonly found in patients undergoing cardiothoracic or major abdominal surgery or thyroidectomies.[18–21] During abdominal cancer surgery, serum magnesium concentrations have been shown to correlate with the extent of resection, but underlying mechanisms also may be factors.[20] Preoperative bowel preparation, intraoperative serum loss, and chelation of magnesium by transfusion of citrate-rich blood products as reported for liver transplantation have been proposed as contributing.[22] However, perioperative volume expansion of the extravascular fluid may decrease passive magnesium transport, thereby decreasing plasma magnesium concentrations.

Magnesium depletion has been demonstrated in 7–11% of hospitalized patients. The incidence increases to as high as 65% for patients in an intensive care unit (ICU), where hypalbuminemia, total parenteral nutrition, and the use of magnesium-wasting medications are commonly present.[23,24] Surgical ICU patients with severe head injury also seem to be at high risk for hypomagnesemia, potentially because of polyuria induced by cerebral injury.[25] Initial low serum magnesium concentrations were suggested to correlate with poor outcome after traumatic brain injury.[26] Cerebrospinal fluid magnesium appears to be increased in these patients, yet this increase does not necessarily correlate with low serum magnesium.[26,27] Mechanisms underlying the increased cerebrospinal fluid magnesium remain unclear but may include the penetration of serum magnesium into the cerebrospinal fluid because of blood–brain barrier disruption or magnesium release from damaged brain cells secondary to hypoxia.[26] In a prospective observational study, Rubeiz *et al.* reported a significantly higher in-hospital mortality in hypomagnesemic (serum magnesium [Mg] ≤ 1.5 mg/dl) patients on a general ward and a medical ICU than in their normomagnesemic counterparts, despite similar Acute Physiology and Chronic Health Evaluation II scores.[23] Similar results, at least for severe hypomagnesemia (serum Mg ≤ 1.0 mEq/l), were demonstrated for surgical ICU patients and for hypomagnesemic (serum Mg, less than 1.4 mEq/l) children in a pediatric ICU.[24,28] However, studying the role of extracellular and intracellular magnesium in outcome prediction of critically ill patients, Huijgen *et al.* could show no association of low extra- and intracellular values with increased mortality and thus suggested that hypomagnesemia is merely an epiphenomenon.[29]

Considering its physiologic properties, deficiency of magnesium typically manifests as cardiac and/or neuromuscular disorders. Clinical symptoms include nausea and vomiting, weakness, convulsions, tetany, muscle fasciculations, and changes in the electrocardiogram, for example prolonged PR and/or QT interval, diminution of the T wave, or certain arrhythmias, such as torsades de pointes and others.[30] Electrolyte abnormalities, such as hypokalemia and hypocalcemia, also are frequently associated with hypomagnesemia.

In contrast, hypermagnesemia (plasma concentrations more than 1.6 mM) is rather uncommon and occurs mainly in patients with renal failure during therapeutic administration of magnesium-containing drugs or other treatment-related causes, for example in patients treated for eclampsia.[31] However, magnesium is relatively safe to apply because toxicity may not occur before oral intake of 30 g magnesium sulfate ($MgSO_4$). At that moment, cardiac and neuromuscular changes may be observed clinically, starting with electrocardiogram changes, such as widened QRS complexes. Further increasing magnesium plasma concentrations may result in hypotension, respiratory depression, and narcosis. Cardiac

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arrest occurs at blood concentrations greater than 6.0–7.5 mM.[32,33] Treatment of severe magnesium toxicity consists of intravenous administration of calcium gluconate and, if required, ventilatory and/or circulatory support. Renal excretion of magnesium might be increased by application of loop diuretics when renal function is adequate. For patients with hypermagnesemia and renal insufficiency, hemodialysis remains a valuable tool.

Magnesium Dosing and Formulation

Magnesium supplements are available in a variety of oral and parenteral formulations. When using magnesium, the following aspects should be considered: dosing, as suggested in the literature, varies in response to the magnesium formulation used. A 10-ml vial of a 10% $MgSO_4$ solution contains 1g $MgSO_4 \cdot 7H_2O$ and thus an available magnesium fraction of 0.4 mM or, according to its molecular weight, 9.72 mg/ml. The dosing recommended for magnesium chloride or magnesium aspartate may vary because of differences in complex size, but if osmolarity is the same, the free magnesium fraction delivered will be the same. Data regarding pharmacokinetics of various magnesium salts are limited, making it difficult to recommend one preparation more than another. However, small studies suggest bioavailability of organic compounds, such as magnesium aspartate or magnesium citrate, to be considerably better than that of inorganic mixtures (except magnesium chloride), potentially because of greater water solubility. Recommended treatment regimens for different clinical settings are given in table 2. Magnesium should be applied orally whenever possible; however, in emergency situations, the intravenous route should be used. Renal function should be assessed before magnesium is administered. Contraindications are known allergies to the compound, atrioventricular block, and neuromuscular disease, such as myasthenia gravis.

Table 2. Dosing Magnesium Sulfate, Adults

Preeclampsia or eclampsia	4–6 g IV loading dose over 15–20 min (5 min in severe cases), followed by 1–2 g IV continuous infusion or 4–5 g IM in each buttock every 4 h
Torsades de pointes arrhythmia	Pulseless: 1–2 g IV over 5–20 min With pulse: 1–2 g IV over 5–60 min
Asthma	Life-threatening or severe exacerbation (unlabeled use): 2 g IV over 30–60 min
Severe deficiency	1–2 g/h IV for 3–6 h, followed by 0.5–1 g/h IV as needed

Slow administration of IV magnesium sulfate is preferable in stable patients. Renal impairment requires close monitoring for signs of hypermagnesemia.

IM = intramuscular; IV = intravenous.

Magnesium and Anesthesia

At the beginning of last century, magnesium was proposed to induce anesthesia effectively.[34] Although later studies could not support this hypothesis and seriously questioned sufficient blood–brain barrier penetration of intravenous magnesium (and thus a true central nervous system effect of the drug itself), magnesium has been suggested for reducing anesthetic requirements, attenuating cardiovascular effects from laryngoscopy and intubation, and exerting muscle-relaxing effects.[35–37]

Mechanisms of Action

Details of the mechanisms underlying the anesthesia-enhancing effects of magnesium remain unknown. A competitive antagonism on hippocampal presynaptic calcium channels that regulate neurotransmitter release in the central nervous system has been suggested.[38] Volatile anesthetics, such as isoflurane, are thought to partially induce anesthesia by inhibition of these channels.[38] Attenuation of catecholamine release from the adrenal medulla and calcium antagonistic effects on vascular smooth muscle cells also may contribute to the anesthetic effects of magnesium.[39] In terms of neuromuscular blockade, the inhibition of calcium-mediated release of acetylcholine from the presynaptic nerve terminal at the neuromuscular junction plays an important role. A decrease of postsynaptic sensitivity to acetylcholine and direct effects on the membrane potential of myocytes also may contribute.[40,41]

Experimental Data

Magnesium significantly potentiated the inhibitory effects of volatile anesthetics on NMDA receptor functioning, recombinantly expressed in *Xenopus* oocytes.[42] Increasing magnesium concentrations were associated with nonlinear reductions in halothane minimal alveolar anesthetic concentration in rats.[43] In a study on the effects of $MgSO_4$-induced neuromuscular blockade in pigs, Lee *et al.* reported that the mechanomyogram response was more depressed than that of the electromyogram at 0.1 hertz.[44] In addition, the presence of a nonfading train-of-four response at 2 Hz, as well as a tetanic ascent instead of a descent, further supported the idea of prejunctional attenuated transmitter release by magnesium.[44]

Clinical Data

There are greater differences in the results of clinical trials on anesthetic actions of magnesium. Two double-blind, randomized, and controlled trials demonstrated a reduction of propofol requirements guided by Bispectral Index monitoring after administration of intravenous $MgSO_4$ (bolus of 30 mg/kg, followed by continuous infusion of 10 $mg \cdot kg^{-1} \cdot h^{-1}$ until end of surgery) in patients undergoing spinal surgery.[45] However, in one study magnesium also significantly delayed postoperative recovery (Bispectral Index more than 80; mean ± SD, 9.84 (1.14) *vs.* 7.52 (1.16) min for patients

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receiving magnesium and control patients, respectively).[46] Pretreatment with 2.48 mmol intravenous $MgSO_4$ was found to reduce the incidence and intensity of etomidate-induced myoclonic movements during induction of anesthesia.[47] Moreover, catecholamine release and cardiovascular effects in response to tracheal intubation were found to be attenuated by intravenous magnesium in most clinical trials.[36,48] However, Durmus *et al.* observed an increased minimal alveolar concentration of sevoflurane at the time of skin incision when magnesium was administered before anesthesia induction.[48] This study was performed in 60 elective surgery patients, who were not premedicated nor received any other drugs for induction of anesthesia. Agitation and flushing, side effects observed only in magnesium-treated patients, may have counteracted potential anesthetic effects.

A similar reduction in requirements as shown for anesthetic agents was described for muscle relaxants when magnesium also was administered.[46–48] In cardiac surgery patients, $MgSO_4$ significantly prolonged duration of the intubation and maintenance dose of cisatracurium (mean ± SD, 74 (20) *vs.* 42 (6) min and 69 (16) *vs.* 35 (7) min) and thus reduced the total dose administered intraoperatively (mean ± SD, 0.19 (0.07) *vs.* 0.29 (0.01) mg/kg).[49] With rocuronium administration, the average onset of neuromuscular block was shown to be significantly shorter in patients receiving $MgSO_4$ compared with controls (mean ± SD, 77 (18) *vs.* 120 (48) s).[50] Accordingly, total recovery time, determined as time from injection until a train-of-four ratio of 0.9, was significantly longer after administration of $MgSO_4$ (mean ± SD, 73.2 (22) *vs.* 57.8 (14.2) min).[50] Similar effects were observed for several other nondepolarizing muscle relaxants, such as vecuronium.[37] The clinical effects of $MgSO_4$ on depolarizing muscle relaxants seem to be rather small. $MgSO_4$ does not interfere with onset and duration of succinylcholine-induced neuromuscular block but seems to prevent associated muscle fasciculations and may attenuate potential succinylcholine-induced increases of serum potassium.[51,52]

Summary

Although a number of studies suggest a clinically relevant effect of magnesium, its actual efficacy as an adjuvant to analgesics and anesthetics to induce and maintain general anesthesia remains unclear and requires evaluation in large clinical trials. Because magnesium prolongs muscle relaxation, continuous monitoring of neuromuscular function during surgery is required, and muscle relaxants should be applied accordingly. However, clinicians should not hesitate to use magnesium as a perioperative treatment option when indicated.

Magnesium and Analgesia

Several animal and human studies report antinociceptive effects of magnesium when administered intravenously or intrathecally.

Mechanisms of Action

Suggested mechanisms underlying these antinociceptive effects include the inhibition of calcium influx (calcium channel blockers augment morphine-induced analgesia and decrease total opioid consumption), antagonism of NMDA receptors, and the prevention of enhanced ligand-induced NMDA signaling in a state of hypomagnesemia.[53–56] In addition, magnesium seems to attenuate or even prevent central sensitization after peripheral tissue injury or inflammation because of inhibition of dorsal horn NMDA receptors.[50,57–60]

Experimental Data

In a model of postoperative pain, a single bolus of $MgSO_4$ (281–375 μg) coadministered with intrathecal morphine potentiated the opioid-induced antinociceptive effects in response to noxious thermal stimulation in opioid-naive rats and in those experiencing mechanical allodynia after surgical incision.[61] In contrast, intrathecal $MgSO_4$ alone was not associated with antinociceptive effects in rat models of acute pain (hot plate and mechanical simulation), and when using the formalin test to better mimic human pain conditions, $MgSO_4$ depressed only the late phase of the response.[62]

However, most animal studies focused on the effects of magnesium in neuropathic pain. In a model of mechanical hyperalgesia in mononeuropathic (sciatic nerve ligation) and neuropathic diabetic rats, intraperitoneal $MgSO_4$ produced significant antihyperalgesia and amplified the analgesic effect of low-dose intravenous morphine. The latter effect also was observed for the phase 2 response in the formalin test, although $MgSO_4$ alone had no effect.[63] These effects are thought to result from interference with spinal NMDA receptors.[64,65] Pain and pain-related altered behavior of animals with neuropathic pain can be positively affected by concomitant administration of magnesium and morphine.[66] When coadministered with morphine, intrathecal $MgSO_4$ potentiated antinociception to thermal stimulation and delayed morphine tolerance in rats compared with control animals.[67] However, studies in a rat model of spinal nerve ligation suggested magnesium homeostasis between serum and cerebrospinal fluid is actively maintained through the blood–brain barrier, even when NMDA receptor-gated ion channels were activated.[68]

Clinical Data

Since the early 1990s the effects of magnesium on postoperative pain and opioid consumption have been studied intensively. However, study results are varied. Whereas most studies describe decreased intra- and postoperative analgesic requirements after magnesium supplementation, a few report no or insignificant beneficial effects.[57,69,70] A systematic review in 2007 that included 14 randomized trials failed to provide convincing evidence.[71] Differences in dose and onset of magnesium administration; type of magnesium salt and pain scores used, as well as choice of patient population; standard baseline pain medication; and anesthesia may con-

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tribute to these inconsistencies in the literature. For instance, $MgSO_4$ was most recently shown to significantly decrease visual analog scale scores as well as total patient-controlled analgesia drug (morphine and ketorolac) consumption in patients undergoing total hip arthroplasty at 4–48 h after surgery.[72] Intravenous $MgSO_4$ was given as a bolus (50 mg/kg) 15 min before induction of spinal anesthesia, followed by a continuous infusion ($15\ mg \cdot kg^{-1} \cdot h^{-1}$) until the end of surgery.[72] However, Zarauza *et al.* found no beneficial effects of $MgSO_4$ on postoperative pain, as assessed by visual analog scale and morphine consumption, when given as an adjunct to general anesthesia in colorectal surgery patients.[73] An initial bolus of 30 mg/kg given 20 min after induction of anesthesia was followed by a continuous $MgSO_4$ drip for 20 h. Intraoperative anesthesia was maintained using continuous infusion of fentanyl, whereas postoperative analgesia was provided by a morphine patient-controlled analgesia device.[73] Explanations for these discrepancies in study outcome, in addition to the reasons already given, may include confounding factors, such as age, preoperative pain level and perception, and comedication, that are hard to control. Table 3 summarizes important clinical trials with respect to study design and outcome.

Magnesium and Preventive Analgesia

Preventive analgesia aims to attenuate central sensitization in response to noxious stimuli in the perioperative period.[74] Drugs considered to induce preventive analgesia were shown to decrease pain intensities and analgesic requirements far beyond their clinical duration of action. However, McCartney *et al.,* in a systematic review (including four studies and a total of 216 patients) on the effects of magnesium on preventive analgesia, failed to show any beneficial effects.[75]

Summary

The current literature of analgesic effects of magnesium is conflicting, and additional major clinical trials using well-defined dose regimens and pain scores are required to achieve more data on possible antinociceptive effects. In this respect, it might be of interest to look for potential pharmacologic interactions with other analgesics, such as the NMDA antagonist ketamine.

Magnesium and Obstetrics

Preeclampsia

Preeclampsia is a multisystem disorder of unknown origin. It complicates 3–10% of pregnancies and is a major cause of maternal and fetal morbidity and mortality.[76] Preeclampsia is defined as new-onset hypertension and proteinuria developing after the 20th week of gestation up to several weeks after delivery, and it may be aggravated by seizures or coma (eclampsia). Underlying mechanisms include an abnormal vascular response to placentation with increased systemic vascular resistance, enhanced platelet aggregation, stimulation of inflammation and coagulation, and endothelial dysfunction.[77]

Mechanisms of Action

Magnesium seems to improve clinical symptoms of preeclampsia and eclampsia primarily by systemic, cerebral, and uterine vasodilation. In addition to having a direct effect on the vessels, magnesium was shown to increase concentrations of the two endogenous potent vasodilators endothelium-derived relaxing factor and calcitonin gene-related peptide and attenuate circulating concentrations of endothelin-1, an endogenous vasoconstrictor.[78–80]

Experimental Data

By inhibition of thromboxane synthesis and calcium channel antagonism, magnesium attenuated peroxide-induced vasoconstriction in isolated human placental cotyledons.[81] In gravid ewes, it decreased maternal blood pressure, although uterine blood flow and fetal oxygenation remained unchanged.[82]

Clinical Data

Evaluation of potential risks and benefits of magnesium in preeclampsia and eclampsia requires differentiation of its administration in mild to severe forms of preeclampsia, in prevention of eclampsia or its progression, and in treatment of eclamptic convulsions.

Mild Preeclampsia. A total of 357 patients with well-defined mild preeclampsia were randomized during labor or the postpartum period in two different double-blind and placebo-controlled trials. No difference in rate of seizures (none in both groups) or in the progression to severe preeclampsia between women receiving placebo or magnesium (12.5 and 13.8%, respectively) could be observed. One study reported higher rates of postpartum hemorrhage and adverse effects in two cases after magnesium treatment.[83] However, other studies reported a beneficial effect of magnesium in this particular stage of disease. In a prospective observational study, Alexander *et al.* compared the effects of magnesium prophylaxis for all women with gestational hypertension or preeclampsia to administration of $MgSO_4$, only if mild preeclampsia progressed to severe disease.[84] They observed a 50% overall increase in the prevalence of eclampsia and a subsequent increase in maternal and neonatal morbidity when $MgSO_4$ was applied only to women with disease progression. Intravenous magnesium (1 g/h) given over 24 h substantially improved disease-mediated erythrocyte deformability and uterine perfusion, thereby increasing blood supply to the fetus in 25 women with mild preeclampsia or intrauterine growth restriction and pathologic uterine blood flow.[85] A decision analysis of whether magnesium should be used for seizure prophylaxis in patients with mild preeclampsia indicated that both clinical strategies are acceptable and should be selected based on values and preferences of the patient and clinician. Both approaches were considered essentially equiva-

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Table 3. Magnesium & Analgesia

Reference & Study Type	Study–Population	Anesthesia & Analgesia	Study Drug	Results	Favors $MgSO_4$
Buvanendran *et al.*[225] PRCT, n = 52	Labor pain	CSE (fenta, lido, bupi)	50 mg $MgSO_4$ i.t. (with opioids)	Duration of analgesia ($MgSO_4$)	+
Ko *et al.*[226] PRCT, db n = 60	abd. HE	Thiopental, isoflurane, vecuronium, succi, no intraop. analgesia, postop. PCEA (fenta, bupi)	$MgSO_4$ bolus (50 mg/kg) after induction, followed by cont. inf. for 6h (15 mg kg^{-1} h^{-1})	No effect on postop. pain	−
Levaux *et al.*[227] PRCT, db n = 24	Lumbar arthrodesis	Propofol, rocuronium, sevoflurane, N_2O remifentanil, piritramid (intraop.), piritramid-PCA (postop.)	Single–dose $MgSO_4$ (50 mg/kg) over 30 min before induction	Sign. lower piritramid consumption postop., sign. lower VAS scores and higher global satisfaction scores ($MgSO_4$)	+
O′Flaherty *et al.*[228] PRCT, db n = 80 (3–12 y/o)	TE	Sevoflurane, N_2O fenta (periop.) paracetamol, codeine (postop.)	$MgSO_4$ bolus (30 mg/kg) preop.	No effect on postop. pain or analgesic consumption	−
Seyhan *et al.*[229] PRCT, db n = 80	HE ± salpingo-oopherectomy	Propofol, atracurium, fenta (intraop.), morphine-PCA (postop.)	$MgSO_4$ bolus before induction I: 40 mg/kg II: + cont. inf. (10 mg/kg) for 4 h III: + cont. inf. (20 mg/kg) for 4 h	Dose-dependent reduction of intraop. propofol requirements and postop. morphine consumption (40%) ($MgSO_4$)	+
Tramer *et al.*[56] PRCT, db n = 42	abd. HE	Thiopental, vecuronium, isoflurane, N_2O, fenta (intraop.), morphine-PCA (postop.)	$MgSO_4$ bolus (15 ml 20%, 3 g) preop., followed by cont. inf. (2,5 ml/h) for 20 h total dose: 13 g	Sign. less morphine consumption and discomfort postop. ($MgSO_4$)	+
Turan *et al.*[230] PRCT, db n = 30	Hand surgery	IVRA (lido), if required i.v. fenta (1 μg/kg) & diclo (postop.)	$MgSO_4$ (10 ml 15%) as diluent for IVRA	Sign. accelerated onset & prolonged duration of sensory/motor block; lower VAS-scores, less fenta/diclo consumption ($MgSO_4$)	+
Tauzin–Fin *et al.*[231] PRCT, db n = 30	Radical retropubic prostatectomy	Propofol, sevoflurane, cisatracurium, sufentanil, paracetamol, tramadol-PCA (postop.)	$MgSO_4$ (50 mg/kg) over 20 min after induction; ropi (w.i.)	Sign. decreased total tramadol consumption ($MgSO_4$)	+
Bilir *et al.*[232] PRCT, db n = 50	Hip replacement	CSE (hyperbaric bupi)	PCEA (fenta ± $MgSO_4$ 50 mg & cont. inf. 100 mg/24 h)	Sign. smaller doses & total consumption of epidural fenta ($MgSO_4$)	+

(continued)

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Table 3. Continued

Reference & Study Type	Study–Population	Anesthesia & Analgesia	Study Drug	Results	Favors $MgSO_4$
Kaya *et al.*[233] PRCT, db n = 40	abd. HE	Thiopental, cisatracurium, remifentanil, sevoflurane morphine-PCA (postop.)	30 mg/kg $MgSO_4$ 15 min before induction, cont. inf. 500 mg/h	Sign. decreased total morphine consumption ($MgSO_4$)	+
Mentes *et al.*[234] PRCT, db n = 83	Lap. CCE	Fenta, propofol, cisatracurium, sevoflurane/N_2O tramadol-PCA (postop.)	50 mg/kg $MgSO_4$ intraop	Sign. lower pain scores no difference in total tramadol consumption	+/−
Ozcan *et al.*[235] PRCT, db n = 24	Thoracotomy	Propofol, fenta, vecuronium, morphine-PCA (postop.)	$MgSO_4$, 30 mg/kg cont. inf.10 mg kg^{-1} h^{-1} (postop.)	Significant decreased morphine consumption, no difference in pain scores	+/−
Steinlechner *et al.*[236] PRCT, db n = 40	Cardiac surgery	Eto, fenta, cisatracurium, sevoflurane, piritramide (postop.)	86.5 mg/kg Mg gluconate after induction, cont. inf. 13 mg kg^{-1} h^{-1} for 12 h postop.	Decreased remifentanil requirement postop, time to extubation was not prolonged	+
Tramer *et al.*[237] PRCT, db n = 200	Ambulatory ilioinguinal hernia repair or varicosis surgery	Propofol, fenta, isoflurane/N_2O diclo (ilio-inguinal-ilio-hypogastric nerve block)	4 g $MgSO_4$ after induction	No difference in time to first rescue analgesic or pain intensities	−

abd. = abdominal; bupi = bupivacaine; CCE = cholecystectomy; cont. = continuous; CSE = combined spinal epidural; db = double-blind; diclo = diclofenac; eto = etomidate; fenta = fentanyl; HE = hysterectomy; inf. = infusion; intraop. = intraoperative; i.t. = intrathecal; i.v. = intravenous; IVRA = intravenous regional anesthesia; lido = lidocaine; $MgSO_4$ = magnesium sulfate; N_2O = nitrous oxide; PCA = patient controlled analgesia; PCEA = patient controlled epidural analgesia; periop. = perioperative; postop. = postoperative; PRCT = prospective randomized placebo-controlled trial; ropi = ropivacaine; sign. = significant; succi = succinylcholine; TE = tonsillectomy; VAS = visual analog scale; w.i. = wound infiltration.

lent with regard to outcome because the no-magnesium strategy was associated with a reduction of neonatal mortality and maternal side effects but also an increased risk of maternal death and neurologically compromised neonates.[86]

Severe Preeclampsia. In addition to several case reports and smaller studies, four large trials evaluated the effects of intravenous magnesium on prevention of eclamptic convulsions in 12,673 patients with severe preeclampsia.[87–90] The main study is the Magnesium Sulfate for Prevention of Eclampsia (Magpie) Trial: a multicenter study, conducted at 175 hospitals in 33 countries that included 10,110 women (42.5% defined as having severe or imminent preeclampsia in each group). Although a significant risk reduction was found for seizures in women assigned to magnesium administration, results were criticized because of heterogeneous clinical characteristics and poorly defined aspects of patient care.[88] However, as demonstrated in an extensive review by Sibai, the overall results of these trials indicate a significantly smaller incidence of eclampsia (relative risk [RR] 0.39; 95% CI, 0.28–0.55; *P* value not reported).[91] Moreover, no adverse effects on maternal or fetal/neonatal morbidity were observed, although respiratory depression (RR 2.06; 95% CI, 1.33–3.88) was significantly higher after magnesium prophylaxis in severely preeclamptic women. A Cochrane review including nine trials evaluating the effects of magnesium in the progression of preeclampsia to eclampsia found a more than 50% risk reduction compared with placebo. No difference in neonatal and maternal mortality was observed. Approximately 25% of magnesium-treated women experienced side effects, mainly flushing.[92]

Eclampsia. The Collaborative Eclampsia Trial compared the efficacy of magnesium with other anticonvulsants in eclamptic women. Similar to various smaller randomized studies, this multicenter trial, including 1,687 patients, showed a clear benefit of magnesium on seizure recurrence (52% and 67% lower risk for additional convulsions compared with diazepam and phenytoin, respectively), but found no differences in maternal morbidity and mortality.[93] Cochrane systematic reviews confirmed that $MgSO_4$ is more effective than diazepam, phenytoin, or a "lytic cocktail" (usually a mixture

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of chlorpromazine, promethazine, and pethidine) for treatment of eclampsia.[94–96]

Preterm Birth and Fetal Neuroprotection. Preterm birth is defined as birth before 37 weeks of gestation and is associated with a significant risk of neurologic morbidity and early neonatal mortality. Its exact pathophysiology remains unknown, but different maternal and fetal factors, such as poly- or oligohydramnios, intrauterine infection, or uterine overdistension resulting in premature rupture of membranes, fetal endocrine activation, etc. seem to play a significant role in preterm labor and birth.[97] Magnesium is widely used as a tocolytic agent in different parts of the world and has been shown to attenuate uterine contractility *in vitro* and *in vivo*. Underlying mechanisms include a decrease in intracellular calcium concentration and a subsequent inhibition of myosin light-chain kinase.[98] However, results of clinical trials have not been convincing. Large clinical trials have not shown any benefit of magnesium over placebo or nifedipine in the delay of delivery.[99,100] A meta-analysis of nine trials studying the effects of magnesium on prevention of preterm birth demonstrated no benefit in delaying birth compared with control.[101] Cerebral palsy is characterized by motor and postural dysfunction caused by nonprogressive damage to the developing fetal or infant brain. Preterm birth is a risk factor for cerebral palsy, and the incidence increases with decreasing birth weight and gestational age. The multicenter, placebo-controlled and double-blind Beneficial Effects of Antenatal Magnesium Sulfate (BEAM) Trial showed no beneficial effect of antenatal $MgSO_4$ on the combined risk of moderate or severe cerebral palsy or death when given to women at imminent risk for delivery at 24 through 31 weeks of gestation ($n = 2{,}241$). However, $MgSO_4$ significantly decreased the risk of moderate or severe cerebral palsy among surviving children (1.9% *vs.* 3.5%; RR 0.55; 95% CI, 0.32–0.95; $P = 0.03$).[102] This finding was recently confirmed by a Cochrane database review evaluating five trials with a total of 6,145 neonates.[103] Antenatal magnesium given to women at risk for preterm birth substantially reduced the risk of cerebral palsy, with the number of women needed to treat of 63. There was also a significant reduction in the rate of substantial gross motor dysfunction, but pediatric mortality or other neurologic impairments were not affected.[103]

Summary

Since its approval for treatment of preeclampsia and eclampsia in the early 1990s, magnesium remains the most commonly used drug for these indications in the United States.[104] Based on available literature, there is a clear Class I, Level of Evidence A Recommendation (American Heart Association [AHA]) for the use of magnesium as an anticonvulsant in severe preeclamptic or eclamptic women. The evidence for its routine use in mild forms of preeclampsia remains uncertain, and large multicenter studies are needed to validate conclusions with respect to safety and efficacy. As recommended, $MgSO_4$ should be applied intravenously, using a loading dose of 4–6 g over 20–30 min and a subsequent maintenance dose of 1–2 g/h. The infusion should be continued for at least 24 h after delivery.[91] To avoid serious adverse effects, respiration, the presence of tendon reflexes, and urine output should be closely monitored during treatment.[105] There is no evidence supporting the use of magnesium for tocolysis in women at risk for preterm birth. However, antenatal administration may be considered because there is Level A Evidence (AHA) showing its neuroprotective effects in preterm neonates.[103]

Magnesium and Pheochromocytoma

Pheochromocytoma is a catecholamine-producing and secreting neoplasm arising primarily from the adrenal medulla with an estimated incidence of 500–1,100 cases in the United States each year.[106] The care of patients during surgical removal of pheochromocytoma poses a significant anesthetic challenge because of the well-described hemodynamic disturbances occurring when a tumor is manipulated and finally resected.

Standard preoperative treatment includes pharmacologic stabilization by α- and β-adrenergic antagonists. Several case reports have described the successful use of magnesium during pheochromocytoma crisis.[107,108]

Mechanisms of Action

Magnesium may stabilize hemodynamics by inhibition of catecholamine release from the adrenal medulla and peripheral adrenergic nerve endings, direct blockade of catecholamine receptors and vasodilation, and antiarrhythmic properties related to L-type calcium channel antagonism.[109]

Experimental Data

Magnesium has potent antiarrhythmic and α-adrenergic effects in baboons treated with continuous adrenaline infusion, leading to an increase of cardiac output and stroke volume. It appears to dilate arterial, rather than venous, vessels but did not depress myocardial function.[110,111] Zheng *et al.* studied the acute cardiovascular effects of a 30-mmol bolus in chronically instrumented awake sheep.[112] Magnesium reduced systemic vascular resistance, thereby decreasing mean arterial blood pressure by 23%, and increased cardiac output and heart rate by 38%. It had little effect on contractility and primarily increased myocardial blood flow because of direct myocardial vasodilation.

Clinical Data

Adults. Several concepts for the anesthetic care of patients undergoing surgical removal of pheochromocytoma have been described.[113] However, because of the tumor's low incidence, large prospective clinical trials are missing, and conclusions have to be drawn from a few small studies and case reports. In 1989, James published a series of 16 patients undergoing elective pheochromocytoma surgery, who had been given α- and β-adrenergic antagonists before surgery

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and received a loading dose of $MgSO_4$ (40–60 mg/kg), followed by a continuous perioperative infusion of 2 g/h.[114] Additional boli of 20 mg/kg were used to keep blood pressure within ± 30 mmHg of baseline values. A total of 8–18 g $MgSO_4$ was administered during surgery (60–150 min). In 11 of 16 patients, magnesium was highly effective in providing hemodynamic stability, although 4 patients required additional sodium nitroprusside during manipulation of the tumor.

Children. Because 20% of all pheochromocytomas occur in children, magnesium may be a treatment option.[115] In a 5-yr-old boy undergoing laparoscopic tumor resection, intraoperative hemodynamic stability was successfully achieved with a loading dose of 40 mg/kg, followed by continuous infusion of 15–30 $mg \cdot kg^{-1} \cdot h^{-1}$ $MgSO_4$. Additional administration of nicardipine was required only twice, during pneumoperitoneum and tumor manipulation.[116]

Pheochromocytoma Crisis

Hypertensive crisis caused by pheochromocytoma may be an additional indication for magnesium. Magnesium was shown to improve severe hypertension and hypertensive encephalopathy in three patients with pheochromocytoma.[117] Based on magnesium's arteriolar-dilating properties, its use might be advantageous to that of sodium nitroprusside, which dilates both arterioles and venules and may thus worsen hemodynamics, especially in hypovolemic patients. Because magnesium was shown to inhibit catecholamine receptors, it may be superior to other competitive adrenergic antagonists, such as phentolamine and doxazosin, because excessive catecholamine concentrations may be present.[117]

Summary

Magnesium may be an effective drug in adults and children for providing hemodynamic stability during pheochromocytoma surgery in addition to standard therapy. To achieve maximal effect, serum concentrations of 2–4 mM should be maintained.[116]

Magnesium and Asthma or Chronic Obstructive Pulmonary Disease

Asthma

Asthma is a common disorder affecting more than 12 million people in the United States, with an estimated 1.8 million visits to emergency departments for acute asthma each year.[118]

Mechanisms of Action. A variety of experimental data suggest that magnesium-induced bronchodilation may be mediated by several pathways: attenuation of calcium-induced muscle contractions, inhibition of cholinergic neuromuscular transmission, antiinflammatory activity, potentiation of β-agonists on adenylyl cyclase, and reversal of magnesium depletion after β-adrenergic treatment.[119–122] Evidence also exists that prostaglandin- mediated vascular smooth muscle relaxation may be magnesium-dependent, and magnesium possesses mild sedative effects that are valuable to achieving anxiolysis and relaxation in acute bronchoconstriction.[1]

Experimental Data. Magnesium was shown to relax rabbit bronchial smooth muscle at rest and during stimulation with histamine, bethanechol, or electrical impulse in a dose-dependent manner.[119] Likewise, $MgSO_4$ concentration-dependently relaxed histamine-induced contraction of guinea pig tracheal strips *in vitro* and increased the percentage of the bronchial cross-sectional area in dogs after histamine-elicited bronchoconstriction *in vivo*.[123]

Clinical Data

Intravenous Magnesium. In 2000, a Cochrane systematic review evaluated seven trials (five adult, two pediatric) with a total of 665 patients for the efficacy of intravenous magnesium as an adjunct to standard therapy (β-agonists and systemic corticosteroids) in the treatment of severe asthma.[124] The pooled results failed to show a significant benefit for magnesium with respect to pulmonary function and hospital admission. However, subgroup analysis of patients with acute severe asthma showed an improvement of peak expiratory flow rate by 52.3 l/min (95% CI, 27–77.5) and forced expiratory volume in 1 s by a mean of 9.8% of the predicted value (95% CI, 3.8–15.8), as well as a marked decrease in hospital admissions when treated with a single dose of $MgSO_4$ (2 g in adults and 25–100 mg/kg in children given over 20–35 min). The authors concluded that there is no evidence for the routine use of intravenous magnesium in all asthmatic patients but that it appears beneficial in patients presenting with acute severe asthma.[124] These data are supported by a recently published review combining new evidence of six trials (three adult, three pediatric) with the original Cochrane article now including a total of 965 patients.[125]

Magnesium seems less beneficial in chronic stable asthma. A daily dose of 450 mg magnesium chelate did not benefit chronic asthmatic adults.[126] Despite the lack of effect in chronic asthma, magnesium may be advantageous in patients with bronchial hyperreactivity. A randomized, controlled, and double-blind study demonstrated a significant improvement in methacholine-provoked bronchial hyperreactivity in 30 patients after intravenous $MgSO_4$ ($0.3\ mmol \cdot kg^{-1} \cdot h^{-1}$).[127] Several case reports support these findings, one of which describes continuous magnesium infusion to facilitate rapid extubation and recovery in a ventilated patient not responding to standard bronchodilating therapy.[128]

Inhaled Magnesium. A Cochrane review including six trials (three adult, two pediatric, one mixed) and a total of 296 patients failed to provide convincing evidence that the addition of nebulized $MgSO_4$ (95–385 mg or 250–280 mmol) to standard bronchodilator therapy (inhaled β-agonists) improves the outcome of patients presenting with acute asthma.[129] Compared with β-agonist treatment alone, pulmonary function was improved, and those with severe asthma had a significant difference when analyzed separately;

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however, there was considerable between-study heterogeneity. The total $MgSO_4$ dose applied varied, dependent on the number of nebulizations and cointerventions, such as additional administration of corticosteroids, which further impairs comparisons between studies. Inhaled $MgSO_4$ alone did not have any benefit on pulmonary function compared with β-agonists and did not influence the rate of hospital admission.[129] Aggarwal *et al.* studied the effects of nebulized $MgSO_4$ and salbutamol compared with salbutamol alone in 100 patients with acute asthma classified as severe or life-threatening. Despite nebulization three times at intervals of 20 min and increasing doses, there was no difference in spirometric or laboratory values or hospital admission between the two groups.[130]

Children. Subgroup analysis of the Cochrane review evaluating the effects of intravenous magnesium on patients with acute asthma revealed a benefit for magnesium in pediatric patients.[124] A recent meta-analysis recommended the use of magnesium in children with moderate to severe acute asthma.[131] Five randomized, placebo-controlled trials including 182 children were evaluated. Intravenous magnesium was associated with a significant absolute risk reduction for hospitalization (number needed to treat = 4), a significantly smaller risk for persistent bronchoconstriction and a significant improvement of the asthma symptom score. Because different dose regimens were used (25 mg/kg, 40 mg/kg, 75 mg/kg), and the dose–response relation differed among studies, future research should focus on the optimal dose regimen for children. In this regard, Glover *et al.* showed that a loading dose of 29.6 mg/kg $MgSO_4$ followed by a continuous infusion dose of 18 $mg \cdot kg^{-1} \cdot h^{-1}$ for the treatment of refractory wheezing in children in an ICU was a safe mode of drug application.

Chronic Obstructive Pulmonary Disease

Only a small number of studies addressed the effects of magnesium on chronic obstructive pulmonary disease. In a randomized, placebo-controlled, double-blind clinical trial, Skorodin *et al.* studied the effects of intravenous $MgSO_4$ (1.2 g) after nebulized albuterol treatment in 72 patients presenting with acute exacerbation of chronic obstructive pulmonary disease.[132] After 30–40 min, the peak expiratory flow rate was significantly improved in the magnesium group, although there was no difference with regard to dyspnea. Administration of intravenous $MgSO_4$ (2 g) in 22 patients with stable chronic obstructive pulmonary disease was associated with a reduction of lung hyperinflation and improved muscle strength.[133]

Summary. In the absence of straightforward evidence, one can rely on the 2008 revised National Asthma Education and Prevention Program guidelines for managing exacerbations of asthma.[134] In patients with life-threatening exacerbations of asthma and in those in whom exacerbations remain in the severe category after 1 h of intensive conventional therapy, the administration of magnesium sulfate can be considered (Class II, Level of Evidence A, AHA). It is also suggested that nebulized salbutamol be administered in isotonic $MgSO_4$ because it provides greater benefit than when delivered in normal saline. There is little evidence to recommend the routine use of magnesium in patients with chronic obstructive pulmonary disease.

Magnesium and Neuroprotection

Because of its diverse roles in various cellular functions, magnesium has been suggested to have beneficial effects in several neurologic disorders.

Mechanisms of Action

In addition to NMDA antagonism and especially important for the ischemic penumbra, magnesium was shown to protect neurons and glia cells by numerous other modes of action.[135] By inhibiting ischemia-induced glutamate release and calcium-dependent enzymes, magnesium exerted anti-excitotoxic properties in different animal models and prevented cellular apoptosis in hippocampal slices of newborn piglets.[136–139] In a rat model of cerebral ischemia, cortical spreading depression and anoxic depolarization were shown to be attenuated.[140] Of particular interest in subarachnoid hemorrhage, magnesium is a cerebral vasodilator, shown to increase blood flow in rat brain, as desired.[141]

Experimental Data

In a rat model of middle cerebral artery occlusion, magnesium consistently reduced cerebral infarct volume by 25–61%. This effect seemed to be dose-dependent and could be elicited in a time window of as long as 6 h after onset of ischemia.[142,143] Using the same model, Lee *et al.* demonstrated significantly improved electrophysiologic and neurobehavioral recovery, as well as reduced brain infarction after intracarotid infusion of magnesium at the beginning of reperfusion (90–120 min after onset of ischemia).[144] Administration of 250 μmol/kg $MgSO_4$ significantly attenuated motor and cognitive deficits after 4 weeks of traumatic brain injury in rats, when given 30 min after injury.[145] In a rabbit model of spinal cord ischemia, 3 mg/kg intrathecal $MgSO_4$ significantly decreased glutamate concentrations in the cerebrospinal fluid, diminished acute neuronal loss, and improved lower extremity hind limb function.[146] Süzer *et al.* observed a dose-dependent decrease of lipid peroxidation and improved spinal somatosensory evoked potentials after 300–600 mg/kg subcutaneous $MgSO_4$ was administered to 30 rats after spinal cord injury.[147] However, one study reported that 3 mg/kg intrathecal $MgSO_4$ induced severe but reversible motor dysfunction after spinal cord ischemia after aortic occlusion in rabbits.[148]

Stroke

The large multicenter Intravenous Magnesium Efficacy in Stroke (IMAGES) Trial evaluated the benefit of magnesium in the treatment of acute stroke. A total of 2,589 patients was

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randomized to receive either intravenous $MgSO_4$ (16 mmol over 15 min, then 65 mmol over 24 h) or placebo after acute stroke.[149] No difference in mortality or (permanent) disability could be observed after 90 days. Another large phase 3 clinical trial, the Field Administration of Stroke Therapy—Magnesium (FAST-MAG) Trial, currently is evaluating the benefit of field-initiated (within the first 2 h after onset of symptoms) magnesium in improving long-term functional outcome of patients with cerebral infarction and intracerebral hemorrhage. The researchers will study 1,298 patients by June 2011 (International Standard Randomized Controlled Trial Number NCT00059332).[150] A nonrandomized, open-label pilot trial in 2004 preceding the FAST-MAG Trial demonstrated dramatic early recovery in 42% of patients and good 90-day global functional outcome in 75% of patients treated with intravenous $MgSO_4$ (4-g loading dose followed by 16 g as maintenance dose) within 2 h after stroke onset.[150] Although there is little evidence for a time frame facilitating maximal neuroprotective efficacy of magnesium in stroke, the most promising window is assumed to cover the first 3 h after onset of ischemia. Thus, the lack of effect seen in the IMAGES Trial may result in part from a delay in treatment because only 3% of patients received intravenous magnesium within the first 3 h after onset of symptoms, whereas the initiation of magnesium administration averaged 12 h. Additional limitations include the lack of a reliable measure of initial stroke severity as an important predictor of outcome and verification of sufficient magnesium concentrations in ischemic tissue. An increase of blood pressure is known to improve recovery after stroke. However, magnesium did induce mild hypotension. Thus, it remains open to debate whether the net effect observed results from a mixture of neuroprotection and injury caused by decreased perfusion of ischemic tissue. Subgroup analysis revealed a potential benefit of magnesium in patients with subcortical stroke lacunar syndromes, although *post hoc* analyses need to be interpreted carefully.

Carotid Surgery

Patients undergoing carotid endarterectomy are at particular risk for postoperative cognitive deficits caused by cortical ischemia after intraoperative hypotension or embolic events. A single randomized, double-blind, placebo-controlled trial analyzed data of 92 patients with asymptomatic or symptomatic carotid artery stenosis with ≥60% scheduled for carotid endarterectomy. $MgSO_4$ given as a 2-g loading dose over 25 min and a maintenance dose of either 8 g or 16 g over 24 h significantly improved neurocognitive function on postoperative day 1 compared with placebo or higher-dose $MgSO_4$ (4-g loading dose, 16 g as maintenance dose).[151] The same group showed that the dose of $MgSO_4$ did not influence the requirement, duration, or amount of postoperative pressor support.[152] However, a truly neuroprotective effect of magnesium during carotid endarterectomy is difficult to claim because potential confounders such as residual effects of anesthetics cannot be completely ruled out considering an observation period of only 24 h after surgery in that study.

Subarachnoid Hemorrhage

Delayed cerebral ischemia is one of the main causes of death and disability after subarachnoid hemorrhage and usually occurs 4–10 days after the initial bleeding event. The placebo-controlled Magnesium Sulfate in Aneurysmal Subarachnoid Hemorrhage (MASH) Trial suggested that intravenous $MgSO_4$ as an adjuvant to nimodipine may reduce delayed cerebral ischemia by 34% (hazard ratio 0.66; 95% CI, 0.38–1.14) and subsequent poor outcome, defined as Rankin score more than 4 after 3 months, by 23% (RR 0.77; 95% CI, 0.54–1.09; numbers needed to treat = 12).[153] Administration of 64 mM/day $MgSO_4$ was started within 4 days after subarachnoid hemorrhage until 2 weeks after aneurysm occlusion.[153] Likewise, a systematic review analyzed three trials (n = 379) that compared $MgSO_4$ with placebo in addition to nimodipine, and reported borderline statistical significance for the RR of poor outcome after subarachnoid hemorrhage (RR 0.75; 95% CI, 0.57–1.00).[154] However, the most recently published Intravenous Magnesium Sulphate for Aneurysmal Subarachnoid Hemorrhage [iMASH]-Trial could not demonstrate any benefit of intravenous magnesium, given within the first 48 hours after the initial bleeding event for up to 14 days, over placebo with respect to neurological outcome (Extended Glasgow Outcome Scale 5 to 8) at 6 months in 327 patients with aneurysmal subarachnoid hemorrhage. One current clinical trial (Magnesium in Aneurysmal Subarachnoid Hemorrhage [MASH] II European Union Drug Regulating Authorities Clinical Trial [EudraCT] 2006-003523-36 including a total of 1200 patients is under way to confirm these data in a large patient population.

Traumatic Brain Injury

Traumatic brain injury is a major cause of death and disability worldwide. Its pathophysiology involves a primary event, characterized by neuronal cell death, ischemia, brain edema, and others, followed by secondary insults of multifactorial nature, which are believed to exacerbate the neurologic damage.[156] Despite considerable experimental evidence regarding the neuroprotective effects of magnesium in traumatic brain injury, clinical trials provide conflicting results. Temkin *et al.* randomized 499 patients with moderate or severe traumatic head injury to either placebo or $MgSO_4$ within 8 h after injury continuing for 5 days and targeting serum concentrations of 1.0–1.85 mM or 1.25–2.5 mM.[157] Magnesium did not have any benefit on the primary outcome measure based on mortality, seizures, functional measures, or neuropsychologic tests when assessed 6 months after injury. Patient outcome seemed to be affected rather negatively.[157] In contrast, Dhandapani *et al.* reported a favorable outcome in 30 patients with closed traumatic brain injury randomized to $MgSO_4$ within 12 h after injury (odds ratio 4.13; 95% CI, 1.39–12.27; $P = 0.009$).[158] Outcome was evaluated using

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the Glasgow Outcome Scale 3 months after injury. Patients received 4 g intravenous $MgSO_4$ and 10 g intramuscular $MgSO_4$ as a loading dose, followed by an intramuscular maintenance dose of 5 g every 4 h for 24 h. No significant side effects were observed. Because the number of patients included in that study is rather small, data should be interpreted carefully. Secondary brain insults or differences in study design with respect to inclusion/exclusion criteria and magnesium regimen may have contributed to inconsistent study results, and larger trials for definite evaluation of magnesium's effect in traumatic brain injury are certainly required.

Spinal Cord Injury

Once primary injury to the spinal cord has occurred, reduction of secondary injury and ongoing ischemia by stabilizing hemodynamics and spinal perfusion pressure is most important. Magnesium has proven its neuroprotective potential in experimental spinal cord injury. Whether these effects translate to the clinical setting remains to be evaluated in large clinical trials.

Low bioavailability has to be considered as a limiting factor of magnesium's potential positive effects on neurologic disorders, such as delayed cerebral ischemia or traumatic brain injury, and thus outcome.[135] Parenteral application of magnesium was shown to increase magnesium concentrations in the cerebrospinal fluid of animals and humans by 20–25% in some studies.[159,160] This increase was significantly smaller (15% for total magnesium and 11% for ionized magnesium, respectively) in patients with brain injury treated with intravenous magnesium for 24 h.[161] However, other studies suggest there is no correlation between plasma and cerebrospinal fluid magnesium.[156] In addition, permeability of the blood–brain barrier may differ based on types and degrees of neuronal disease.[162]

Summary

Animal and human studies investigating the neuroprotective character of magnesium show conflicting results. Onset of treatment, dosing, and duration of administration remain to be characterized. Current guidelines of the American Stroke Association do not recommend magnesium as a neuroprotective agent in the early management of ischemic stroke (Class III, Level of Evidence A, AHA).[163] This is also reflected in the 2009 guidelines for the management of aneurysmal subarachnoid hemorrhage, in which the value of calcium antagonists other than nimodipine is referred to as uncertain.[164]

Magnesium and Myocardial Infarction

Acute myocardial infarction and related arrhythmias are still one of the major causes of death in the United States and most Western countries.[165]

Mechanisms of Action

Magnesium was found to induce coronary and systemic vasodilation, to improve metabolism of cardiomyocytes, and to attenuate ischemia–reperfusion injury of myocardial tissue.[166–169] Many of these protective effects have been ascribed to calcium antagonism because calcium overload is the leading cause of myocardial cell death.[55] Na^+/K^+ adenosine 5′-triphosphatase and Ca^{2+} adenosine 5′-triphosphatase are important regulators of myocardial membrane stability. Magnesium is a cofactor of both enzymes, and additional substitution was shown to decrease membrane excitability.[170] In addition, magnesium prolongs the absolute refractory period and shortens the relative refractory period, thereby reducing the incidence of infarction-related arrhythmias.[171]

Experimental Data

Different *in vivo* experimental animal models of coronary occlusion and reperfusion demonstrated an increased infarct size and exacerbation of myocardial stunning when magnesium deficiency was present at the time of injury.[172,173] Underlying mechanisms may include increased lipid peroxidation, as shown for bovine aortic endothelial cells under magnesium-deficient conditions.[174] A protective effect of 8 mM $MgSO_4$ on cardiac function and infarct size could be demonstrated in a globally ischemic–reperfused isolated rat heart model, when magnesium was administered for 5 min starting 10 min before onset of ischemia.[175] Attenuation of up-regulated P-selectin expression and decreased myocardial necrosis may be involved.[176] Infarct size could also be limited when magnesium was administered within 15–45 min after reperfusion of the coronaries.[168,169,177]

Clinical Data

In humans, hypomagnesemia is associated with a higher incidence of lethal arrhythmias after acute myocardial infarction, whereas intravenous administration of magnesium reduced early mortality.[178,179] $MgSO_4$ (50 ml for the first 24 h and 12 mmol for the second 24 h) decreased 30-day mortality to 6.7% (17% for control patients) when given within 3 h after hospital admission.[179]

Major Clinical Trials

Because reperfusion injury after myocardial ischemia was shown to crucially affect patients' outcome, major clinical studies on the role of magnesium on ischemia–reperfusion injury have been conducted. However, inconsistent data were obtained.

Leicester Intravenous Magnesium Intervention Trial, 1992. In the second Leicester Intravenous Magnesium Intervention Trial (LIMIT-2), 2,316 patients with assumed myocardial infarction were included and received either 8 mmol $MgSO_4$ for 5 min, followed by 65 mmol for 24 h, or placebo. All-cause mortality at 28 days in the treatment group was significantly ($P = 0.04$) less than that of control patients.[180]

Fourth International Study of Infarct Survival, 1995. In the fourth International Study of Infarct Survival (ISIS-4),

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58,050 patients with suspected myocardial infarction were included and randomized to either $MgSO_4$ treatment (8 mmol for 15 min, followed by 72 mmol over 24 h) or standard care. Thrombolytic therapy was administered in both groups as indicated. Thirty-five days after hospital admission, an insignificant increase in mortality (6%) as well as a significantly higher rate of bradycardia, heart failure, and death caused by cardiogenic shock ($P < 0.001$) after magnesium treatment were observed.[181] The heart failure and death rates were suggested to result from significant induced hypotension after magnesium administration.[182]

The most probable explanations for the controversial results of LIMIT-2 and ISIS-4 relate to the differences in timing of magnesium administration, dosing, and a low control group mortality rate in ISIS-4. Cardioprotective effects of magnesium were shown to require high serum concentrations at the time of reperfusion. In LIMIT-2, the median time from onset of chest pain to randomization was 3 h compared with 8 h in the ISIS-4 Trial. According to the protocol, patients in LIMIT-2 began receiving magnesium when thrombolytic therapy was initiated, whereas patients in ISIS-4 received magnesium after, rather than before, or with thrombolytic therapy. In 30% of patients who did not undergo thrombolysis, the median time to randomization was 12 h, so a relevant number of patients might have already achieved spontaneous reperfusion.[183] The dose of magnesium administered also could have played an important role because other trials using less than 75 mM showed a significantly reduced early mortality. In previous trials, the benefit of magnesium correlated well with control group mortality. Control group mortality in ISIS-4 was only 7.2%, suggesting that most patients were at low risk and thus unlikely to benefit from magnesium therapy.

Magnesium in Coronaries Trial. The Magnesium in Coronaries (MAGIC) Trial, a multicenter, double-blind, placebo-controlled trial, was designed to resolve these controversies by evaluating whether administration of intravenous magnesium to high-risk patients, patients older than 65 yr, or those not eligible for reperfusion therapy in the course of myocardial infarction would result in better survival. A total of 6,213 patients, receiving either $MgSO_4$ (2-g bolus over 15 min, followed by 17 g [~68 mmol] over 24 h) or placebo were included, and the study drug was started within 6 h after onset of clinical symptoms (median time of 3.8 h) and before angioplasty or fibrinolysis. All patients received standard treatment. Magnesium treatment had no beneficial effects on the primary (30-day mortality) or the secondary outcome measures (incidence of heart failure).[184]

Several reasons for the lack of effect of magnesium administration were discussed. Publication bias and small sample sizes in previous trials may have overestimated magnesium's potential benefit. The cardioprotective effects of magnesium may have been covered by current therapies for myocardial infarction not being used in previous trials, the doses of $MgSO_4$ being used were too high, or magnesium simply being ineffective.

Minor Clinical Trials

Gyamlani *et al.* enrolled 100 patients with diagnosed acute myocardial infarction, who received 15 g $MgSO_4$ over 48 h starting within 2 h of admission.[170] When thrombolytic agents were applied, $MgSO_4$ was given within the following 30 min of treatment. Development of arrhythmias (8% *vs.* 34%), cardiac failure (4% *vs.* 14%), and mortality (4% *vs.* 20%) were significantly reduced by magnesium. In 150 patients undergoing angioplasty with low or intermediate risk of acute myocardial infarction, $MgSO_4$ infusion (7 g over 5 h) significantly decreased aortic systolic pressure ($P = 0.043$) before intervention. However, primary (30-day infarct size) and secondary end points (ventricular arrhythmias, death, and others) were not affected.[182]

Summary

According to the most recent Cochrane database review analyzing 26 trials that studied the effects of intravenous magnesium on acute myocardial infarction, magnesium seems unlikely to reduce mortality after early and late treatment, after thrombolytic therapy, or when used at high doses (more than 75 mM). It may reduce the incidence of ventricular fibrillation or tachycardia or severe arrhythmias but also may increase the incidence of profound hypotension, bradycardia, and flushing.[185] Taken together, there is no evidence for the routine use of magnesium in patients with acute myocardial infarction at any level of risk (Level of Evidence A, AHA).

Magnesium and Cardiac Arrest

Magnesium was reported to have a beneficial effect on the incidence of cardiac arrest after refractory ventricular fibrillation.[186,187]

Experimental Data

In a porcine model of coronary occlusion, intravenous $MgSO_4$ (80 mg/min given 10 min before, during, and 15 min after epicardial shocking) attenuated generation of free oxygen radicals and preserved left ventricular function after defibrillation.[188] Magnesium pretreatment (30 mg/kg), calcium, or a combination of both did not affect time until cardiovascular collapse or survival of hyperkalemic cardiac arrest in rats.[189]

Clinical Data

In a small prospective and controlled study (n = 22), normomagnesemia was directly correlated to successful resuscitation after cardiac arrest after ventricular fibrillation or tachycardia.[190] Evaluating the effects of 2 g $MgSO_4$ during resuscitation after cardiopulmonary arrest, Hassan *et al.* included 105 patients with refractory or recurrent ventricular fibrillation not responding to initial defibrillation.[191] Mag-

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nesium did not improve return of spontaneous circulation or discharge from hospital alive. Similarly, magnesium did not improve the rate of successful resuscitation, survival for 24 h, or survival until hospital discharge in a randomized, placebo-controlled trial studying 156 patients with cardiac arrest regardless of their initial rhythm.[192]

Summary

Based on current literature, there is no evidence for the routine use of magnesium in patients with cardiac arrest.

Magnesium and Cardiac Arrhythmias

Although magnesium is not considered a classic antiarrhythmic drug, it may convert some types of malignant arrhythmias. Accordingly, low magnesium serum concentrations were shown to be potentially proarrhythmogenic.

Mechanisms of Action

Being an endogenous calcium antagonist, magnesium slows electrical activity of the sinoatrial node, prolongs atrioventricular conductance, and finally increases the refractory period of the atrioventricular node.[193]

Clinical Data

Supraventricular Arrhythmias. Primarily studying the effects of milrinone in 1,068 patients with moderate to severe congestive heart failure (New York Heart Association III/IV), this large clinical trial also evaluated the prognostic significance of alterations in serum magnesium.[194] There was no evidence that low serum magnesium is an independent risk factor for sudden death or all-cause death. In a small prospective study, Moran *et al.* reported $MgSO_4$ to be superior to amiodarone in conversion of acute atrial tachyarrhythmias in critically ill patients.[195] Likewise, a retrospective cohort evaluation of normomagnesemic patients by Coleman *et al.* demonstrated an enhanced ability of dofetilide to successfully convert atrial fibrillation or flutter into sinus rhythm, when $MgSO_4$ was used in addition.[196] However, most of the studies have moderate quality and small patient numbers, so there is only little evidence supporting the routine use of magnesium for conversion of atrial fibrillation.

Atrial Fibrillation after Cardiac Surgery. Arrhythmias, especially atrial fibrillation, are frequently complications after cardiac surgery, with a typical time frame of 24–96 h after surgery and a peak incidence on postoperative day 2.[197–202] The underlying mechanisms are multifactorial. Hypomagnesemia, caused by cardiopulmonary bypass, high-dose diuretic therapy, surgical stress, and exogenous catecholamines, is one known risk factor for the postoperative development of atrial fibrillation. Clinical trials studying the effects of perioperative magnesium prophylaxis gave conflicting results. In 200 patients undergoing coronary artery bypass grafting, Toraman *et al.* reported that preoperative, intraoperative, and early postoperative administration of 6 mmol $MgSO_4$ significantly reduced postoperative atrial fibrillation (2% *vs.* 21% in the control group).[203] In a meta-analysis on the prophylactic use of magnesium during surgery, Alghamdi *et al.* described a significant risk reduction (RR 0.64; 95% CI, 0.47–0.87; $P = 0.004$, numbers needed to treat = 11) of atrial fibrillation after magnesium administration.[204] Eight studies with a total of 1,033 patients were included. $MgSO_4$ doses ranged from 7.5 to 25 g, administered between 2 and 5 days after surgery. Reviewing 15 randomized controlled trials, Shepherd *et al.* found atrial fibrillation to be less likely the longer prophylaxis lasted and the earlier it was initiated.[205] However, one has to be careful in interpreting these data because a statistically significant heterogeneity was present. In recent large clinical trials in which magnesium was used concomitantly with β-blockers as standard therapy, magnesium showed little or no effect.[206,207] A dose of 5 g intravenous $MgSO_4$ given in addition to an established oral β-blocker protocol until postoperative day 4 did not reduce the incidence of atrial arrhythmias in 927 nonemergent cardiac surgery patients.[207] Considering all of the data, current evidence for beneficial effects of magnesium in the prophylaxis of life-threatening arrhythmias after surgery is controversial. Studies conducted were small, and significant heterogeneity between different trials was present. A definite answer of whether magnesium replacement in a state of hypomagnesemia in that patient population is or is not of potential depends on the results of more large, well-designed clinical trials.

Ventricular Arrhythmias. Current treatment options consist of cardioversion, amiodarone, and normalization of serum electrolytes, including magnesium. Two small studies demonstrated reduced and even suppressed episodes of nonsustained monomorphic ventricular tachycardia after magnesium administration.[208,209] However, to date there is no solid clinical evidence recommending magnesium in the treatment or prophylaxis of monomorphic ventricular tachycardia.[210]

Torsades de Pointes. Torsades de pointes tachycardias certainly benefit from administration of magnesium. Malfunction of potassium channels results in delayed ventricular repolarization and inactivation of calcium channels.[212] The late calcium influx combined with the prolonged repolarization causes early after-depolarizations, leading to torsades de pointes and associated long QT intervals.[213] Magnesium attenuates these pathologic changes by inhibiting calcium currents, as shown by a variety of experimental and clinical data.[213–216] As an urgent measure, 2 g $MgSO_4$ (25–50 mg/kg in children[212]) should be the drug of choice, followed by electrolyte stabilization and efforts to accelerate the basic heart rate.[212,217]

Digoxin-induced Arrhythmias. Magnesium is well established in the management of digoxin-induced tachyarrhythmias.[218] Digoxin antibodies are the basic treatment, but in hypomagnesemic patients, especially those susceptible to digoxin-induced arrhythmias, intravenous administration of magnesium should be part of the immediate standard ther-

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Table 4. Drug Interactions

Calcitriol	May increase magnesium serum concentrations
Calcium channel blockers	Magnesium may enhance hypotensive effects
Antibiotics	Magnesium may decrease absorption of quinolone and tetracycline antibiotics as well as nitrofurantoin; aminoglycoside antibiotics may lower magnesium serum concentrations
Digoxin	May increase renal excretion of magnesium; magnesium may decrease effects of digoxin
Neuromuscular blockers	Magnesium enhances the neuromuscular blockade
Antidiabetics	Magnesium may increase absorption of glipizide and glyburide
Prednisone	May lower magnesium serum concentrations
Diuretics	Loop and thiazide diuretics may lower magnesium serum concentrations

apy until Fab antibodies are available (Class IIa, Level of Evidence B, AHA).[219]

Summary

Magnesium has an essential role in normal cardiac electrophysiology, and altered serum concentrations may contribute to a variety of cardiac arrhythmias.

Reflecting the current controversy of existing evidence, the majority of guidelines (American College of Cardiology, AHA, American College of Chest Physicians, European Society of Cardiology) for managing atrial fibrillation or postoperative cardiac arrhythmias does not recommend magnesium for standard therapy, whereas the European Association for Cardio-Thoracic Surgery approves prophylaxis with magnesium for minimizing the incidence of atrial fibrillation in patients undergoing cardiac surgery.[220–222] However, there is a clear recommendation for $MgSO_4$ in patients with long QT syndrome and episodes of torsades de pointes (Class IIa, Level of Evidence B, AHA).[219]

Magnesium and Side Effects

Intravenous administration of magnesium generally is associated with minor side effects. It may provoke burning sensation or pain on injection and induce agitation, drowsiness, and nausea. Patients also may experience headache, dizziness, and muscle weakness or report hypotension and bradycardia.[48] In eclampsia, approximately 25% of women treated with magnesium experience side effects, mainly flushing.[223] Magnesium may increase the risk of postpartum hemorrhage and respiratory depression.[91] Because magnesium crosses the placenta, it may induce neonatal lethargy, hypotension, and rarely respiratory depression after prolonged administration (more than 48 h).[224] Several interactions with drugs commonly used in the clinical setting exist. A summary is given in table 4.

Conclusion

Magnesium plays a key role in numerous physiologic processes, and various indications have been proposed for its use as a therapeutic agent. Despite promising experimental data, large clinical trials often have provided conflicting results, questioning the expected efficacy of magnesium in several clinical settings. Additional research is required to complete our understanding of when and how to use magnesium therapeutically. Nevertheless, there are conditions that benefit from magnesium therapy, such as preeclampsia, eclampsia, and torsades de pointes arrhythmias. Maintenance of magnesium serum concentrations within normal physiologic limits is desirable, and with respect to its well-established safety profile, one may consider magnesium an additional alternative for the specific described pathologies when standard therapy fails.

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References

1. Fawcett WJ, Haxby EJ, Male DA: Magnesium: Physiology and pharmacology. Br J Anaesth 1999; 83:302–20
2. Elin RJ: Magnesium: The fifth but forgotten electrolyte. Am J Clin Pathol 1994; 102:616–22
3. Toyoshima C, Mizutani T: Crystal structure of the calcium pump with a bound ATP analogue. Nature 2004; 430:529–35
4. Mak DO, Foskett JK: Effects of divalent cations on single-channel conduction properties of Xenopus IP3 receptor. Am J Physiol 1998; 275:179–88
5. Bara M, Guiet-Bara A, Durlach J: Regulation of sodium and potassium pathways by magnesium in cell membranes. Magnes Res 1993; 6:167–77
6. Horie M, Irisawa H, Noma A: Voltage-dependent magnesium block of adenosine-triphosphate-sensitive potassium channel in guinea-pig ventricular cells. J Physiol 1987; 387:251–72
7. Monyer H, Sprengel R, Schoepfer R, Herb A, Higuchi M, Lomeli H, Burnashev N, Sakmann B, Seeburg PH: Heteromeric NMDA receptors: Molecular and functional distinction of subtypes. Science 1992; 256:1217–21
8. Shimosawa T, Takano K, Ando K, Fujita T: Magnesium inhibits norepinephrine release by blocking N-type calcium channels at peripheral sympathetic nerve endings. Hypertension 2004; 44:897–902
9. Fine KD, Santa Ana CA, Porter JL, Fordtran JS: Intestinal absorption of magnesium from food and supplements. J Clin Invest 1991; 88:396–402
10. Konrad M, Schlingmann KP, Gudermann T: Insights into the molecular nature of magnesium homeostasis. Am J Physiol Renal Physiol 2004; 286:599–605
11. Kausalya PJ, Amasheh S, Gunzel D, Wurps H, Muller D, Fromm M, Hunziker W: Disease-associated mutations affect intracellular traffic and paracellular Mg2+ transport function of Claudin-16. J Clin Invest 2006; 116:878–91

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12. Simon DB, Lu Y, Choate KA, Velazquez H, Al-Sabban E, Praga M, Casari G, Bettinelli A, Colussi G, Rodriguez-Soriano J, McCredie D, Milford D, Sanjad S, Lifton RP: Paracellin-1, a renal tight junction protein required for paracellular Mg2+ resorption. Science 1999; 285:103–6
13. Voets T, Nilius B, Hoefs S, van der Kemp AW, Droogmans G, Bindels RJ, Hoenderop JG: TRPM6 forms the Mg2+ influx channel involved in intestinal and renal Mg2+ absorption. J Biol Chem 2004; 279:19–25
14. Walder RY, Landau D, Meyer P, Shalev H, Tsolia M, Borochowitz Z, Boettger MB, Beck GE, Englehardt RK, Carmi R, Sheffield VC: Mutation of TRPM6 causes familial hypomagnesemia with secondary hypocalcemia. Nat Genet 2002; 31:171–4
15. Saris NE, Mervaala E, Karppanen H, Khawaja JA, Lewenstam A: Magnesium. An update on physiological, clinical and analytical aspects. Clin Chim Acta 2000; 294:1–26
16. Agus ZS: Hypomagnesemia. J Am Soc Nephrol 1999; 10:1616–22
17. Sanders GT, Huijgen HJ, Sanders R: Magnesium in disease: A review with special emphasis on the serum ionized magnesium. Clin Chem Lab Med 1999; 37:1011–33
18. Booth JV, Phillips-Bute B, McCants CB, Podgoreanu MV, Smith PK, Mathew JP, Newman MF: Low serum magnesium level predicts major adverse cardiac events after coronary artery bypass graft surgery. Am Heart J 2003; 145:1108–13
19. Aglio LS, Stanford GG, Maddi R, Boyd JL, III, Nussbaum S, Chernow B: Hypomagnesemia is common following cardiac surgery. J Cardiothorac Vasc Anesth 1991; 5:201–8
20. Schwarz RE, Nevarez KZ: Hypomagnesemia after major abdominal operations in cancer patients: clinical implications. Arch Med Res 2005; 36:36–41
21. Wilson RB, Erskine C, Crowe PJ: Hypomagnesemia and hypocalcemia after thyroidectomy: A prospective study. World J Surg 2000; 24:722–6
22. Scott VL, De Wolf AM, Kang Y, Altura BT, Virji MA, Cook DR, Altura BM: Ionized hypomagnesemia in patients undergoing orthotopic liver transplantation: A complication of citrate intoxication. Liver Transpl Surg 1996; 2:343–7
23. Rubeiz GJ, Thill-Baharozian M, Hardie D, Carlson RW: Association of hypomagnesemia and mortality in acutely ill medical patients. Crit Care Med 1993; 21:203–9
24. Chernow B, Bamberger S, Stoiko M, Vadnais M, Mills S, Hoellerich V, Warshaw AL: Hypomagnesemia in patients in postoperative intensive care. Chest 1989; 95:391–7
25. Polderman KH, Bloemers FW, Peerdeman SM, Girbes AR: Hypomagnesemia and hypophosphatemia at admission in patients with severe head injury. Crit Care Med 2000; 28:2022–5
26. Stippler M, Fischer MR, Puccio AM, Wisniewski SR, Carson-Walter EB, Dixon CE, Walter KA: Serum and cerebrospinal fluid magnesium in severe traumatic brain injury outcome. J Neurotrauma 2007; 24:1347–54
27. Kafadar AM, Sanus GZ, Is M, Coskun A, Tanriverdi T, Hanimoglu H, Uzan M: Prolonged elevation of magnesium in the cerebrospinal fluid of patients with severe head injury. Neurol Res 2007; 29:824–9
28. Singhi SC, Singh J, Prasad R: Hypo- and hypermagnesemia in an Indian Pediatric Intensive Care Unit. J Trop Pediatr 2003; 49:99–103
29. Huijgen HJ, Soesan M, Sanders R, Mairuhu WM, Kesecioglu J, Sanders GT: Magnesium levels in critically ill patients. What should we measure? Am J Clin Pathol 2000; 114:688–95
30. Whang R, Hampton EM, Whang DD: Magnesium homeostasis and clinical disorders of magnesium deficiency. Ann Pharmacother 1994; 28:220–6
31. Onishi S, Yoshino S: Cathartic-induced fatal hypermagnesemia in the elderly. Intern Med 2006; 45:207–10
32. Morisaki H, Yamamoto S, Morita Y, Kotake Y, Ochiai R, Takeda J: Hypermagnesemia-induced cardiopulmonary arrest before induction of anesthesia for emergency cesarean section. J Clin Anesth 2000; 12:224–6
33. Birrer RB, Shallash AJ, Totten V: Hypermagnesemia-induced fatality following epsom salt gargles(1). J Emerg Med 2002; 22:185–8
34. Peck CH, Meltzer SJ: Anesthesia in human beings by intravenous injection of magnesium sulphate. JAMA 1916; 67:1131–3
35. Somjen G, Hilmy M, Stephen CR: Failure to anesthetize human subjects by intravenous administration of magnesium sulfate. J Pharmacol Exp Ther 1966; 154:652–9
36. Puri GD, Marudhachalam KS, Chari P, Suri RK: The effect of magnesium sulphate on hemodynamics and its efficacy in attenuating the response to endotracheal intubation in patients with coronary artery disease. Anesth Analg 1998; 87:808–11
37. Fuchs-Buder T, Wilder-Smith OH, Borgeat A, Tassonyi E: Interaction of magnesium sulphate with vecuronium-induced neuromuscular block. Br J Anaesth 1995; 74:405–9
38. Sasaki R, Hirota K, Roth SH, Yamazaki M: Extracellular magnesium ion modifies the actions of volatile anesthetics in area CA1 of rat hippocampus in vitro. Anesthesiology 2002; 96:681–7
39. Douglas WW, Rubin RP: The mechanism of catecholamine release from the adrenal medulla and the role of calcium in stimulus–secretion coupling. J Physiol 1963; 167:288–310
40. Ghoneim MM, Long JP: The interaction between magnesium and other neuromuscular blocking agents. Anesthesiology 1970; 32:23–7
41. Del CJ, Engbaek L: The nature of the neuromuscular block produced by magnesium. J Physiol 1954; 124:370–84
42. Hollmann MW, Liu HT, Hoenemann CW, Liu WH, Durieux ME: Modulation of NMDA receptor function by ketamine and magnesium. Part II: Interactions with volatile anesthetics. Anesth Analg 2001; 92:1182–91
43. Thompson SW, Moscicki JC, DiFazio CA: The anesthetic contribution of magnesium sulfate and ritodrine hydrochloride in rats. Anesth Analg 1988; 67:31–4
44. Lee C, Zhang X, Kwan WF: Electromyographic and mechanomyographic characteristics of neuromuscular block by magnesium sulphate in the pig. Br J Anaesth 1996; 76:278–83
45. Telci L, Esen F, Akcora D, Erden T, Canbolat AT, Akpir K: Evaluation of effects of magnesium sulphate in reducing intraoperative anaesthetic requirements. Br J Anaesth 2002; 89:594–8
46. Gupta K, Vohra V, Sood J: The role of magnesium as an adjuvant during general anaesthesia. Anaesthesia 2006; 61:1058–63
47. Guler A, Satilmis T, Akinci SB, Celebioglu B, Kanbak M: Magnesium sulfate pretreatment reduces myoclonus after etomidate. Anesth Analg 2005; 101:705–9
48. Durmus M, But AK, Erdem TB, Ozpolat Z, Ersoy MO: The effects of magnesium sulphate on sevoflurane minimum alveolar concentrations and haemodynamic responses. Eur J Anaesthesiol 2006; 23:54–9
49. Pinard AM, Donati F, Martineau R, Denault AY, Taillefer J, Carrier M: Magnesium potentiates neuromuscular blockade with cisatracurium during cardiac surgery. Can J Anaesth 2003; 50:172–8
50. Czarnetzki C, Lysakowski C, Elia N, Tramer MR: Time course of rocuronium-induced neuromuscular block after pre-treatment with magnesium sulphate: A randomised study. Acta Anaesthesiol Scand 2010; 54:299–306
51. Schreiber JU, Lysakowski C, Fuchs-Buder T, Tramer MR: Prevention of succinylcholine-induced fasciculation and

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myalgia: A meta-analysis of randomized trials. Anesthesiology 2005; 103:877–84

52. James MF, Cork RC, Dennett JE: Succinylcholine pretreatment with magnesium sulfate. Anesth Analg 1986; 65:373–6
53. Omote K, Sonoda H, Kawamata M, Iwasaki H, Namiki A: Potentiation of antinociceptive effects of morphine by calcium-channel blockers at the level of the spinal cord. Anesthesiology 1993; 79:746–52
54 Hasegawa AE, Zacny JP: The influence of three L-type calcium channel blockers on morphine effects in healthy volunteers. Anesth Analg 1997; 85:633–8
55. Iseri LT, French JH: Magnesium: Nature's physiologic calcium blocker. Am Heart J 1984; 108:188–93
56. Tramer MR, Schneider J, Marti RA, Rifat K: Role of magnesium sulfate in postoperative analgesia. Anesthesiology 1996; 84:340–7
57. Koinig H, Wallner T, Marhofer P, Andel H, Horauf K, Mayer N: Magnesium sulfate reduces intra- and postoperative analgesic requirements. Anesth Analg 1998; 87:206–10
58. Garthwaite G, Garthwaite J: Receptor-linked ionic channels mediate N-methyl-D-aspartate neurotoxicity in rat cerebellar slices. Neurosci Lett 1987; 83:241–6
59. Feria M, Abad F, Sanchez A, Abreu P: Magnesium sulphate injected subcutaneously suppresses autotomy in peripherally deafferented rats. Pain 1993; 53:287–93
60. Woolf CJ, Thompson SW: The induction and maintenance of central sensitization is dependent on N-methyl-D-aspartic acid receptor activation; implications for the treatment of post-injury pain hypersensitivity states. Pain 1991; 44:293–9
61. Kroin JS, McCarthy RJ, Von Roenn N, Schwab B, Tuman KJ, Ivankovich AD: Magnesium sulfate potentiates morphine antinociception at the spinal level. Anesth Analg 2000; 90:913–7
62. Ishizaki K, Sasaki M, Karasawa S, Obata H, Nara T, Goto F: The effect of intrathecal magnesium sulphate on nociception in rat acute pain models. Anaesthesia 1999; 54:241–6
63. Begon S, Pickering G, Eschalier A, Dubray C: Magnesium increases morphine analgesic effect in different experimental models of pain. Anesthesiology 2002; 96:627–32
64. Begon S, Pickering G, Eschalier A, Mazur A, Rayssiguier Y, Dubray C: Role of spinal NMDA receptors, protein kinase C and nitric oxide synthase in the hyperalgesia induced by magnesium deficiency in rats. Br J Pharmacol 2001; 134:1227–36
65. Xiao WH, Bennett GJ: Magnesium suppresses neuropathic pain responses in rats via a spinal site of action. Brain Res 1994; 666:168–72
66. Ulugol A, Aslantas A, Ipci Y, Tuncer A, Hakan KC, Dokmeci I: Combined systemic administration of morphine and magnesium sulfate attenuates pain-related behavior in mononeuropathic rats. Brain Res 2002; 943:101–4
67. McCarthy RJ, Kroin JS, Tuman KJ, Penn RD, Ivankovich AD: Antinociceptive potentiation and attenuation of tolerance by intrathecal co-infusion of magnesium sulfate and morphine in rats. Anesth Analg 1998; 86:830–6
68. Jeong SM, Hahm KD, Shin JW, Leem JG, Lee C, Han SM: Changes in magnesium concentration in the serum and cerebrospinal fluid of neuropathic rats. Acta Anaesthesiol Scand 2006; 50:211–6
69. Tramer MR, Glynn CJ: An evaluation of a single dose of magnesium to supplement analgesia after ambulatory surgery: Randomized controlled trial. Anesth Analg 2007; 104:1374–9
70. Schulz-Stubner S, Wettmann G, Reyle-Hahn SM, Rossaint R: Magnesium as part of balanced general anaesthesia with propofol, remifentanil and mivacurium: A double-blind, randomized prospective study in 50 patients. Eur J Anaesthesiol 2001; 18:723–9
71. Lysakowski C, Dumont L, Czarnetzki C, Tramer MR: Magnesium as an adjuvant to postoperative analgesia: A systematic review of randomized trials. Anesth Analg 2007; 104:1532–9
72. Hwang JY, Na HS, Jeon YT, Ro YJ, Kim CS, Do SH: I.V. Infusion of magnesium sulphate during spinal anaesthesia improves postoperative analgesia. Br J Anaesth 2010; 104:89–93
73. Zarauza R, Saez-Fernandez AN, Iribarren MJ, Carrascosa F, Adame M, Fidalgo I, Monedero P: A comparative study with oral nifedipine, intravenous nimodipine, and magnesium sulfate in postoperative analgesia. Anesth Analg 2000; 91:938–43
74. Kissin I: Preemptive analgesia: terminology and clinical relevance. Anesth Analg 1994; 79:809–10
75. McCartney CJ, Sinha A, Katz J: A qualitative systematic review of the role of N-methyl-D-aspartate receptor antagonists in preventive analgesia. Anesth Analg 2004; 98:1385–400
76. MacKay AP, Berg CJ, Atrash HK: Pregnancy-related mortality from preeclampsia and eclampsia. Obstet Gynecol 2001; 97:533–8
77. Sibai B, Dekker G, Kupferminc M: Pre-eclampsia. Lancet 2005; 365:785–99
78. Belfort MA, Moise KJJr: Effect of magnesium sulfate on maternal brain blood flow in preeclampsia: A randomized, placebo-controlled study. Am J Obstet Gynecol 1992; 167:661–6
79. Halhali A, Wimalawansa SJ, Berentsen V, Avila E, Thota CS, Larrea F: Calcitonin gene- and parathyroid hormone-related peptides in preeclampsia: Effects of magnesium sulfate. Obstet Gynecol 2001; 97:893–7
80. Sagsoz N, Kucukozkan T: The effect of treatment on endothelin-1 concentration and mean arterial pressure in preeclampsia and eclampsia. Hypertens Pregnancy 2003; 22:185–91
81. Walsh SW, Romney AD, Wang Y, Walsh MD: Magnesium sulfate attenuates peroxide-induced vasoconstriction in the human placenta. Am J Obstet Gynecol 1998; 178:7–12
82. Vincent RD Jr, Chestnut DH, Sipes SL, Weiner CP, DeBruyn CS, Bleuer SA: Magnesium sulfate decreases maternal blood pressure but not uterine blood flow during epidural anesthesia in gravid ewes. Anesthesiology 1991; 74:77–82
83. Witlin AG, Friedman SA, Sibai BM: The effect of magnesium sulfate therapy on the duration of labor in women with mild preeclampsia at term: A randomized, double-blind, placebo-controlled trial. Am J Obstet Gynecol 1997; 176:623–7
84. Alexander JM, McIntire DD, Leveno KJ, Cunningham FG: Selective magnesium sulfate prophylaxis for the prevention of eclampsia in women with gestational hypertension. Obstet Gynecol 2006; 108:826–32
85. Schauf B, Mannschreck B, Becker S, Dietz K, Wallwiener D, Aydeniz B: Evaluation of red blood cell deformability and uterine blood flow in pregnant women with preeclampsia or iugr and reduced uterine blood flow following the intravenous application of magnesium. Hypertens Pregnancy 2004; 23:331–43
86. Cahill AG, Macones GA, Odibo AO, Stamilio DM: Magnesium for seizure prophylaxis in patients with mild preeclampsia. Obstet Gynecol 2007; 110:601–7
87. Belfort MA, Anthony J, Saade GR, Allen JC, Jr.: A comparison of magnesium sulfate and nimodipine for the prevention of eclampsia. N Engl J Med 2003; 348:304–11
88. Altman D, Carroli G, Duley L, Farrell B, Moodley J, Neilson J, Smith D: Do women with pre-eclampsia, and their babies, benefit from magnesium sulphate? The Magpie Trial: A

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randomised placebo-controlled trial. Lancet 2002; 359: 1877–90

89. Coetzee EJ, Dommisse J, Anthony J: A randomised controlled trial of intravenous magnesium sulphate versus placebo in the management of women with severe pre-eclampsia. Br J Obstet Gynaecol 1998; 105:300–3
90. Moodley J, Moodley VV: Prophylactic anticonvulsant therapy in hypertensive crises of pregnancy - The need for a large, randomised trial. Hypertens Pregnancy 1994; 13: 245–52
91. Sibai BM: Magnesium sulfate prophylaxis in preeclampsia: Lessons learned from recent trials. Am J Obstet Gynecol 2004; 190:1520–6
92. Duley L, Gulmezoglu AM, Henderson-Smart DJ: Magnesium sulphate and other anticonvulsants for women with pre-eclampsia. Cochrane.Database.Syst.Rev. 2003; CD000025
93. The Eclampsia Trial Collaborative Group: Which anticonvulsant for women with eclampsia? Evidence from the Collaborative Eclampsia Trial. Lancet 1995; 345:1455–63
94. Duley L, Henderson-Smart D: Magnesium sulphate versus phenytoin for eclampsia. Cochrane Database Syst Rev 2003; CD000128
95. Duley L, Henderson-Smart D: Magnesium sulphate versus diazepam for eclampsia. Cochrane Database Syst Rev 2003; CD000127
96. Duley L, Gulmezoglu AM: Magnesium sulphate versus lytic cocktail for eclampsia. Cochrane.Database.Syst.Rev. 2001; CD002960
97. Goldenberg RL, Culhane JF, Iams JD, Romero R: Epidemiology and causes of preterm birth. Lancet 2008; 371:75–84
98. Simhan HN, Caritis SN: Prevention of preterm delivery. N Engl J Med 2007; 357:477–87
99. Lyell DJ, Pullen K, Campbell L, Ching S, Druzin ML, Chitkara U, Burrs D, Caughey AB, El-Sayed YY: Magnesium sulfate compared with nifedipine for acute tocolysis of preterm labor: A randomized controlled trial. Obstet Gynecol 2007; 110:61–7
100. Cox SM, Sherman ML, Leveno KJ: Randomized investigation of magnesium sulfate for prevention of preterm birth. Am J Obstet Gynecol 1990; 163:767–72
101. Crowther CA, Hiller JE, Doyle LW: Magnesium sulphate for preventing preterm birth in threatened preterm labour. Cochrane Database Syst Rev 2002; CD001060
102. Rouse DJ, Hirtz DG, Thom E, Varner MW, Spong CY, Mercer BM, Iams JD, Wapner RJ, Sorokin Y, Alexander JM, Harper M, Thorp JM Jr, Ramin SM, Malone FD, Carpenter M, Miodovnik M, Moawad A, O'Sullivan MJ, Peaceman AM, Hankins GD, Langer O, Caritis SN, Roberts JM: A randomized, controlled trial of magnesium sulfate for the prevention of cerebral palsy. N Engl J Med 2008; 359:895–905
103. Doyle LW, Crowther CA, Middleton P, Marret S, Rouse D: Magnesium sulphate for women at risk of preterm birth for neuroprotection of the fetus. Cochrane Database Syst Rev 2009; CD004661
104. Lucas MJ, Leveno KJ, Cunningham FG: A comparison of magnesium sulfate with phenytoin for the prevention of eclampsia. N Engl J Med 1995; 333:201–5
105. Duley L: Evidence and practice: The magnesium sulphate story. Best Pract Res Clin Obstet Gynaecol 2005; 19:57–74
106. Hull CJ: Phaeochromocytoma. Diagnosis, preoperative preparation and anaesthetic management. Br J Anaesth 1986; 58:1453–68
107. James MF: The use of magnesium sulfate in the anesthetic management of pheochromocytoma. Anesthesiology 1985; 62:188–90
108. Fawcett WJ, Edkins CL: Phaeochromocytoma diagnosed during labour. Br J Anaesth 2001; 86:288–9
109. O'Riordan JA: Pheochromocytomas and anesthesia. Int Anesthesiol Clin 1997; 35:99–127
110. James MF, Cork RC, Harlen GM, White JF: Interactions of adrenaline and magnesium on the cardiovascular system of the baboon. Magnesium 1988; 7:37–43
111. James MF, Cork RC, Dennett JE: Cardiovascular effects of magnesium sulphate in the baboon. Magnesium 1987; 6:314–24
112. Zheng D, Upton RN, Ludbrook GL, Martinez A: Acute cardiovascular effects of magnesium and their relationship to systemic and myocardial magnesium concentrations after short infusion in awake sheep. J Pharmacol Exp Ther 2001; 297:1176–83
113. Prys-Roberts C: Phaeochromocytoma–recent progress in its management. Br J Anaesth 2000; 85:44–57
114. James MF: Use of magnesium sulphate in the anaesthetic management of phaeochromocytoma: A review of 17 anaesthetics. Br J Anaesth 1989; 62:616–23
115. Kaufman BH, Telander RL, van Heerden JA, Zimmerman D, Sheps SG, Dawson B: Pheochromocytoma in the pediatric age group: Current status. J Pediatr Surg 1983; 18:879–84
116. Minami T, Adachi T, Fukuda K: An effective use of magnesium sulfate for intraoperative management of laparoscopic adrenalectomy for pheochromocytoma in a pediatric patient. Anesth Analg 2002; 95:1243–4
117. James MF, Cronje L: Pheochromocytoma crisis: The use of magnesium sulfate. Anesth Analg 2004; 99:680–6
118. Mannino DM, Homa DM, Akinbami LJ, Moorman JE, Gwynn C, Redd SC: Surveillance for asthma–United States, 1980–1999. MMWR Surveill Summ 2002; 51:1–13
119. Spivey WH, Skobeloff EM, Levin RM: Effect of magnesium chloride on rabbit bronchial smooth muscle. Ann Emerg Med 1990; 19:1107–12
120. Cairns CB, Kraft M: Magnesium attenuates the neutrophil respiratory burst in adult asthmatic patients. Acad Emerg Med 1996; 3:1093–7
121. Skorodin MS, Freebeck PC, Yetter B, Nelson JE, Van de Graaff WB, Walsh JM: Magnesium sulfate potentiates several cardiovascular and metabolic actions of terbutaline. Chest 1994; 105:701–5
122. Bodenhamer J, Bergstrom R, Brown D, Gabow P, Marx JA, Lowenstein SR: Frequently nebulized beta-agonists for asthma: Effects on serum electrolytes. Ann Emerg Med 1992; 21:1337–42
123. Hirota K, Sato T, Hashimoto Y, Yoshioka H, Ohtomo N, Ishihara H, Matsuki A: Relaxant effect of magnesium and zinc on histamine-induced bronchoconstriction in dogs. Crit Care Med 1999; 27:1159–63
124. Rowe BH, Bretzlaff JA, Bourdon C, Bota GW, Camargo CA Jr.: Magnesium sulfate for treating exacerbations of acute asthma in the emergency department. Cochrane Database Syst Rev 2000; CD001490
125. Rowe BH, Camargo CA Jr.: The role of magnesium sulfate in the acute and chronic management of asthma. Curr Opin Pulm Med 2008; 14:70–6
126. Fogarty A, Lewis SA, Scrivener SL, Antoniak M, Pacey S, Pringle M, Britton J: Oral magnesium and vitamin C supplements in asthma: A parallel group randomized placebo-controlled trial. Clin Exp Allergy 2003; 33:1355–9
127. Schenk P, Vonbank K, Schnack B, Haber P, Lehr S, Smetana R: Intravenous magnesium sulfate for bronchial hyperreactivity: A randomized, controlled, double-blind study. Clin Pharmacol Ther 2001; 69:365–71
128. Mills R, Leadbeater M, Ravalia A: Intravenous magnesium sulphate in the management of refractory bronchospasm in a ventilated asthmatic. Anaesthesia 1997; 52:782–5
129. Blitz M, Blitz S, Beasely R, Diner BM, Hughes R, Knopp JA, Rowe BH: Inhaled magnesium sulfate in the treatment of acute asthma. Cochrane Database Syst Rev 2005; CD003898
130. Aggarwal P, Sharad S, Handa R, Dwiwedi SN, Irshad M: Comparison of nebulised magnesium sulphate and salbuta-

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mol combined with salbutamol alone in the treatment of acute bronchial asthma: A randomised study. Emerg Med J 2006; 23:358–62

131. Cheuk DK, Chau TC, Lee SL: A meta-analysis on intravenous magnesium sulphate for treating acute asthma. Arch Dis Child 2005; 90:74–7
132. Glover ML, Machado C, Totapally BR: Magnesium sulfate administered via continuous intravenous infusion in pediatric patients with refractory wheezing. J Crit Care 2002; 17:255–8
133. Skorodin MS, Tenholder MF, Yetter B, Owen KA, Waller RF, Khandelwahl S, Maki K, Rohail T, D'Alfonso N: Magnesium sulfate in exacerbations of chronic obstructive pulmonary disease. Arch Intern Med 1995; 155:496–500
134. do Amaral AF, Rodrigues-Junior AL, Terra FJ, Vannucchi H, Martinez JA: Effects of acute magnesium loading on pulmonary function of stable COPD patients. Med Sci Monit 2008; 14:524–9
135. McKee JA, Brewer RP, Macy GE, Borel CO, Reynolds JD, Warner DS: Magnesium neuroprotection is limited in humans with acute brain injury. Neurocrit Care 2005; 2:342–51
136. Turkyilmaz C, Turkyilmaz Z, Atalay Y, Soylemezoglu F, Celasun B: Magnesium pre-treatment reduces neuronal apoptosis in newborn rats in hypoxia-ischemia. Brain Res 2002; 955:133–7
137. Mami AG, Ballesteros JR, Fritz KI, Kubin J, Mishra OP, ivoria-Papadopoulos M: Effects of magnesium sulfate administration during hypoxia on CaM kinase IV and protein tyrosine kinase activities in the cerebral cortex of newborn piglets. Neurochem.Res 2006; 31:57–62
138. Lin JY, Chung SY, Lin MC, Cheng FC: Effects of magnesium sulfate on energy metabolites and glutamate in the cortex during focal cerebral ischemia and reperfusion in the gerbil monitored by a dual-probe microdialysis technique. Life Sci 2002; 71:803–11
139. Spandou E, Soubasi V, Papoutsopoulou S, ugoustides-Savvopoulou P, Loizidis T, Pazaiti A, Karkavelas G, Guiba-Tziampiri O: Neuroprotective effect of long-term MgSO4 administration after cerebral hypoxia-ischemia in newborn rats is related to the severity of brain damage. Reprod.Sci 2007; 14:667–77
140. van der Hel WS, van den Bergh WM, Nicolay K, Tulleken KA, Dijkhuizen RM: Suppression of cortical spreading depressions after magnesium treatment in the rat. Neuroreport 1998; 9:2179–82
141. Kemp PA, Gardiner SM, March JE, Rubin PC, Bennett T: Assessment of the effects of endothelin-1 and magnesium sulphate on regional blood flows in conscious rats, by the coloured microsphere reference technique. Br J Pharmacol 1999; 126:621–6
142. Marinov MB, Harbaugh KS, Hoopes PJ, Pikus HJ, Harbaugh RE: Neuroprotective effects of preischemia intraarterial magnesium sulfate in reversible focal cerebral ischemia. J Neurosurg 1996; 85:117–24
143. Yang Y, Li Q, Ahmad F, Shuaib A: Survival and histological evaluation of therapeutic window of post-ischemia treatment with magnesium sulfate in embolic stroke model of rat. Neurosci Lett 2000; 285:119–22
144. Lee EJ, Lee MY, Chang GL, Chen LH, Hu YL, Chen TY, Wu TS: Delayed treatment with magnesium: Reduction of brain infarction and improvement of electrophysiological recovery following transient focal cerebral ischemia in rats. J Neurosurg 2005; 102:1085–93
145. Vink R, O'Connor CA, Nimmo AJ, Heath DL: Magnesium attenuates persistent functional deficits following diffuse traumatic brain injury in rats. Neurosci Lett 2003; 336:41–4
146. Jellish WS, Zhang X, Langen KE, Spector MS, Scalfani MT, White FA: Intrathecal magnesium sulfate administration at the time of experimental ischemia improves neurological functioning by reducing acute and delayed loss of motor neurons in the spinal cord. Anesthesiology 2008; 108:78–86
147. Suzer T, Coskun E, Islekel H, Tahta K: Neuroprotective effect of magnesium on lipid peroxidation and axonal function after experimental spinal cord injury. Spinal Cord 1999; 37:480–4
148. Saeki H, Matsumoto M, Kaneko S, Tsuruta S, Cui YJ, Ohtake K, Ishida K, Sakabe T: Is intrathecal magnesium sulfate safe and protective against ischemic spinal cord injury in rabbits? Anesth Analg 2004; 99:1805–12
149. Muir KW, Lees KR, Ford I, Davis S: Magnesium for acute stroke (Intravenous Magnesium Efficacy in Stroke trial): Randomised controlled trial. Lancet 2004; 363:439–45
150. Saver JL, Kidwell C, Eckstein M, Starkman S: Prehospital neuroprotective therapy for acute stroke: Results of the Field Administration of Stroke Therapy-Magnesium (FAST-MAG) pilot trial. Stroke 2004; 35:106–8
151. Mack WJ, Kellner CP, Sahlein DH, Ducruet AF, Kim GH, Mocco J, Zurica J, Komotar RJ, Haque R, Sciacca R, Quest DO, Solomon RA, Connolly ES, Heyer EJ: Intraoperative magnesium infusion during carotid endarterectomy: A double-blind placebo-controlled trial. J Neurosurg 2009; 110:961–7
152. Chiu C, Heyer EJ, Rampersad AD, Zurica J, Ornstein E, Sahlein DH, Sciacca RR, Connolly ES Jr: High dose magnesium infusions are not associated with increased pressor requirements after carotid endarterectomy. Neurosurgery 2006; 58:71–7
153. van den Bergh WM, Algra A, van KF, Dirven CM, van GJ, Vermeulen M, Rinkel GJ: Magnesium sulfate in aneurysmal subarachnoid hemorrhage: A randomized controlled trial. Stroke 2005; 36:1011–5
154. Dorhout Mees SM, Rinkel GJ, Feigin VL, Algra A, van den Bergh WM, Vermeulen M, van GJ: Calcium antagonists for aneurysmal subarachnoid haemorrhage. Cochrane Database Syst Rev 2007; CD000277
155. Wong GK, Poon WS, Chan MT, Boet R, Gin T, Ng SC, Zee BC: Intravenous magnesium sulphate for aneurysmal subarachnoid hemorrhage (IMASH): a randomized, double-blinded, placebo-controlled, multicenter phase III trial. Stroke 2010; 41:921–6
156. Dorhout Mees SM: Magnesium in aneurysmal subarachnoid hemorrhage (MASH II) phase III clinical trial MASH-II study group. Int J Stroke 2008; 3:63–5
157. Sen AP, Gulati A: Use of magnesium in traumatic brain injury. Neurotherapeutics 2010; 7:91–9
158. Temkin NR, Anderson GD, Winn HR, Ellenbogen RG, Britz GW, Schuster J, Lucas T, Newell DW, Mansfield PN, Machamer JE, Barber J, Dikmen SS: Magnesium sulfate for neuroprotection after traumatic brain injury: A randomised controlled trial. Lancet Neurol 2007; 6:29–38
159. Dhandapani SS, Gupta A, Vivekanandhan S, Sharma S, Mahaptra AK: Randomized controlled trial of magnesium sulphate in severe closed traumatic brain injury. Indian J Neurotrauma 2008; 5:27–33
160. Hallak M, Berman RF, Irtenkauf SM, Evans MI, Cotton DB: Peripheral magnesium sulfate enters the brain and increases the threshold for hippocampal seizures in rats. Am J Obstet Gynecol 1992; 167:1605–10
161. Fuchs-Buder T, Tramer MR, Tassonyi E: Cerebrospinal fluid passage of intravenous magnesium sulfate in neurosurgical patients. J Neurosurg Anesthesiol 1997; 9:324–8
162. McKee JA, Brewer RP, Macy GE, Phillips-Bute B, Campbell KA, Borel CO, Reynolds JD, Warner DS: Analysis of the brain bioavailability of peripherally administered magnesium sulfate: A study in humans with acute brain injury undergoing prolonged induced hypermagnesemia. Crit Care Med. 2005; 33:661–6
163. Dohi K, Ohtaki H, Shioda S, Aruga T: Magnesium sulfate

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therapy in patients with acute neuronal damage: The problem of intravenous administration. Crit Care Med 2005; 33:698–9

164. Adams HP Jr, del ZG, Alberts MJ, Bhatt DL, Brass L, Furlan A, Grubb RL, Higashida RT, Jauch EC, Kidwell C, Lyden PD, Morgenstern LB, Qureshi AI, Rosenwasser RH, Scott PA, Wijdicks EF: Guidelines for the early management of adults with ischemic stroke: A guideline from the American Heart Association/American Stroke Association Stroke Council, Clinical Cardiology Council, Cardiovascular Radiology and Intervention Council, and the Atherosclerotic Peripheral Vascular Disease and Quality of Care Outcomes in Research Interdisciplinary Working Groups: The American Academy of Neurology affirms the value of this guideline as an educational tool for neurologists. Stroke 2007; 38:1655–711
165. Bederson JB, Connolly ES Jr, Batjer HH, Dacey RG, Dion JE, Diringer MN, Duldner JE Jr, Harbaugh RE, Patel AB, Rosenwasser RH: Guidelines for the management of aneurysmal subarachnoid hemorrhage: A statement for healthcare professionals from a special writing group of the Stroke Council, American Heart Association. Stroke 2009; 40:994–1025
166. Hennekens CH, Albert CM, Godfried SL, Gaziano JM, Buring JE: Adjunctive drug therapy of acute myocardial infarction–evidence from clinical trials. N Engl J Med 1996; 335:1660–7
167. Dube L, Granry JC: The therapeutic use of magnesium in anesthesiology, intensive care and emergency medicine: A review. Can J Anaesth 2003; 50:732–46
168. Turlapaty PD, Altura BM: Magnesium deficiency produces spasms of coronary arteries: Relationship to etiology of sudden death ischemic heart disease. Science 1980; 208:198–200
169. Christensen CW, Rieder MA, Silverstein EL, Gencheff NE: Magnesium sulfate reduces myocardial infarct size when administered before but not after coronary reperfusion in a canine model. Circulation 1995; 92:2617–21
170. Herzog WR, Schlossberg ML, MacMurdy KS, Edenbaum LR, Gerber MJ, Vogel RA, Serebruany VL: Timing of magnesium therapy affects experimental infarct size. Circulation 1995; 92:2622–6
171. Gyamlani G, Parikh C, Kulkarni AG: Benefits of magnesium in acute myocardial infarction: Timing is crucial. Am Heart J 2000; 139:703
172. Horner SM: Efficacy of intravenous magnesium in acute myocardial infarction in reducing arrhythmias and mortality. Meta-analysis of magnesium in acute myocardial infarction. Circulation 1992; 86:774–9
173. Herzog WR, Atar D, Mak IT, Alyono D, MacCord C, Weglicki WB: Magnesium deficiency prolongs myocardial stunning in an open-chest swine model. Int J Cardiol 1994; 47:105–15
174. Atar D, Serebruany V, Poulton J, Godard J, Schneider A, Herzog WR: Effects of magnesium supplementation in a porcine model of myocardial ischemia and reperfusion. J Cardiovasc Pharmacol 1994; 24:603–11
175. Dickens BF, Weglicki WB, Li YS, Mak IT: Magnesium deficiency in vitro enhances free radical-induced intracellular oxidation and cytotoxicity in endothelial cells. FEBS Lett 1992; 311:187–91
176. Bazargan M, Faghihi M, Chitsaz M: Importance of timing of magnesium administration in the isolated ischemic-reperfused rat heart: role of K(ATP) channels. Physiol Res 2008; 57:839–46
177. Ying SQ, Fang L, Xiang MX, Xu G, Shan J, Wang JA: Protective effects of magnesium against ischaemia-reperfusion injury through inhibition of P-selectin in rats. Clin Exp Pharmacol Physiol 2007; 34:1234–9
178. Barros LF, Chagas AC, da Luz PL, Pileggi F: Magnesium treatment of acute myocardial infarction: Effects on necrosis in an occlusion/reperfusion dog model. Int J Cardiol 1995; 48:3–9
179. England MR, Gordon G, Salem M, Chernow B: Magnesium administration and dysrhythmias after cardiac surgery. A placebo-controlled, double-blind, randomized trial. JAMA 1992; 268:2395–402
180. Rasmussen HS, McNair P, Norregard P, Backer V, Lindeneg O, Balslev S: Intravenous magnesium in acute myocardial infarction. Lancet 1986; 1:234–6
181. Woods KL, Fletcher S, Roffe C, Haider Y: Intravenous magnesium sulphate in suspected acute myocardial infarction: Results of the second Leicester Intravenous Magnesium Intervention Trial (LIMIT-2). Lancet 1992; 339:1553–8
182. ISIS-4: A randomised factorial trial assessing early oral captopril, oral mononitrate, and intravenous magnesium sulphate in 58,050 patients with suspected acute myocardial infarction. ISIS-4 (Fourth International Study of Infarct Survival) Collaborative Group. Lancet 1995; 345:669–85
183. Santoro GM, Antoniucci D, Bolognese L, Valenti R, Buonamici P, Trapani M, Santini A, Fazzini PF: A randomized study of intravenous magnesium in acute myocardial infarction treated with direct coronary angioplasty. Am Heart J 2000; 140:891–7
184. Antman EM: Magnesium in acute MI. Timing is critical. Circulation 1995; 92:2367–72
185. The Magnesium in Coronaries (MAGIC) Trial Investigators: Early administration of intravenous magnesium to high-risk patients with acute myocardial infarction in the Magnesium in Coronaries (MAGIC) Trial: A randomised controlled trial. Lancet 2002; 360:1189–96
186. Li J, Zhang Q, Zhang M, Egger M: Intravenous magnesium for acute myocardial infarction. Cochrane Database Syst Rev 2007; CD002755
187. Miller B, Craddock L, Hoffenberg S, Heinz S, Lefkowitz D, Callender ML, Battaglia C, Maines C, Masick D: Pilot study of intravenous magnesium sulfate in refractory cardiac arrest: Safety data and recommendations for future studies. Resuscitation 1995; 30:3–14
188. Baraka A, Ayoub C, Kawkabani N: Magnesium therapy for refractory ventricular fibrillation. J Cardiothorac Vasc Anesth 2000; 14:196–9
189. Zhang Y, Davies LR, Martin SM, Bawaney IM, Buettner GR, Kerber RE: Magnesium reduces free radical concentration and preserves left ventricular function after direct current shocks. Resuscitation 2003; 56:199–206
190. Hollmann MW, Strumper D, Salmons VA, Washington JM, Durieux ME: Effects of calcium and magnesium pretreatment on hyperkalaemic cardiac arrest in rats. Eur J Anaesthesiol 2003; 20:606–11
191. Cannon LA, Heiselman DE, Dougherty JM, Jones J: Magnesium levels in cardiac arrest victims: Relationship between magnesium levels and successful resuscitation. Ann Emerg Med 1987; 16:1195–9
192. Hassan TB, Jagger C, Barnett DB: A randomised trial to investigate the efficacy of magnesium sulphate for refractory ventricular fibrillation. Emerg Med J 2002; 19:57–62
193. Thel MC, Armstrong AL, McNulty SE, Califf RM, O'Connor CM: Randomised trial of magnesium in in-hospital cardiac arrest. Duke Internal Medicine Housestaff. Lancet 1997; 350:1272–6
194. Touyz RM: Magnesium in clinical medicine. Front Biosci 2004; 9:1278–93
195. Eichhorn EJ, Tandon PK, DiBianco R, Timmis GC, Fenster PE, Shannon J, Packer M: Clinical and prognostic significance of serum magnesium concentration in patients with severe chronic congestive heart failure: The PROMISE Study. J Am Coll Cardiol 1993; 21:634–40
196. Moran JL, Gallagher J, Peake SL, Cunningham DN, Salagaras M, Leppard P: Parenteral magnesium sulfate versus amioda-

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rone in the therapy of atrial tachyarrhythmias: A prospective, randomized study. Crit Care Med 1995; 23:1816–24

197. Coleman CI, Sood N, Chawla D, Talati R, Ghatak A, Kluger J: Intravenous magnesium sulfate enhances the ability of dofetilide to successfully cardiovert atrial fibrillation or flutter: Results of the Dofetilide and Intravenous Magnesium Evaluation. Europace 2009; 11:892–5
198. Lauer MS, Eagle KA, Buckley MJ, DeSanctis RW: Atrial fibrillation following coronary artery bypass surgery. Prog Cardiovasc Dis 1989; 31:367–78
199. Aranki SF, Shaw DP, Adams DH, Rizzo RJ, Couper GS, VanderVliet M, Collins JJ Jr, Cohn LH, Burstin HR: Predictors of atrial fibrillation after coronary artery surgery. Current trends and impact on hospital resources. Circulation 1996; 94:390–7
200. Mathew JP, Parks R, Savino JS, Friedman AS, Koch C, Mangano DT, Browner WS: Atrial fibrillation following coronary artery bypass graft surgery: predictors, outcomes, and resource utilization. Multi Center Study of Perioperative Ischemia Research Group. JAMA 1996; 276:300–6
201. Andrews TC, Reimold SC, Berlin JA, Antman EM: Prevention of supraventricular arrhythmias after coronary artery bypass surgery. A meta-analysis of randomized control trials. Circulation 1991; 84:236–44
202. Daoud EG, Strickberger SA, Man KC, Goyal R, Deeb GM, Bolling SF, Pagani FD, Bitar C, Meissner MD, Morady F: Preoperative amiodarone as prophylaxis against atrial fibrillation after heart surgery. N Engl J Med 1997; 337:1785–91
203. Leitch JW, Thomson D, Baird DK, Harris PJ: The importance of age as a predictor of atrial fibrillation and flutter after coronary artery bypass grafting. J Thorac Cardiovasc Surg 1990; 100:338–42
204. Toraman F, Karabulut EH, Alhan HC, Dagdelen S, Tarcan S: Magnesium infusion dramatically decreases the incidence of atrial fibrillation after coronary artery bypass grafting. Ann Thorac Surg. 2001; 72:1256–61
205. Alghamdi AA, Al-Radi OO, Latter DA: Intravenous magnesium for prevention of atrial fibrillation after coronary artery bypass surgery: A systematic review and meta-analysis. J Card Surg 2005; 20:293–9
206. Shepherd J, Jones J, Frampton GK, Tanajewski L, Turner D, Price A: Intravenous magnesium sulphate and sotalol for prevention of atrial fibrillation after coronary artery bypass surgery: A systematic review and economic evaluation. Health Technol Assess 2008; 12: iii-95
207. Burgess DC, Kilborn MJ, Keech AC: Interventions for prevention of post-operative atrial fibrillation and its complications after cardiac surgery: A meta-analysis. Eur Heart J 2006; 27:2846–57
208. Cook RC, Humphries KH, Gin K, Janusz MT, Slavik RS, Bernstein V, Tholin M, Lee MK: Prophylactic intravenous magnesium sulphate in addition to oral {beta}-blockade does not prevent atrial arrhythmias after coronary artery or valvular heart surgery: A randomized, controlled trial. Circulation 2009; 120:163–9
209. Ceremuzynski L, Gebalska J, Wolk R, Makowska E: Hypomagnesemia in heart failure with ventricular arrhythmias. Beneficial effects of magnesium supplementation. J Intern Med 2000; 247:78–86
210. Sueta CA, Clarke SW, Dunlap SH, Jensen L, Blauwet MB, Koch G, Patterson JH, Adams KF Jr.: Effect of acute magnesium administration on the frequency of ventricular arrhythmia in patients with heart failure. Circulation 1994; 89:660–6
211. Farouque HM, Sanders P, Young GD: Intravenous magnesium sulfate for acute termination of sustained monomorphic ventricular tachycardia associated with coronary artery disease. Am J Cardiol 2000; 86:1270–2
212. Kaye P, O'Sullivan I: The role of magnesium in the emergency department. Emerg Med J 2002; 19:288–91
213. Bailie DS, Inoue H, Kaseda S, Ben-David J, Zipes DP: Magnesium suppression of early afterdepolarizations and ventricular tachyarrhythmias induced by cesium in dogs. Circulation 1988; 77:1395–402
214. Banai S, Tzivoni D: Drug therapy for torsade de pointes. J Cardiovasc Electrophysiol 1993; 4:206–10
215. Tzivoni D, Banai S, Schuger C, Benhorin J, Keren A, Gottlieb S, Stern S: Treatment of torsade de pointes with magnesium sulfate. Circulation 1988; 77:392–7
216. 2005 American Heart Association Guidelines for Cardiopulmonary Resuscitation and Emergency Cardiovascular Care: Part 7.2: Management of Cardiac Arrest. Circulation 2005; 112: IV-58
217. Viskin S: Torsades de Pointes. Curr Treat Options Cardiovasc Med 1999; 1:187–95
218. Fazekas T, Scherlag BJ, Vos M, Wellens HJ, Lazzara R: Magnesium and the heart: Antiarrhythmic therapy with magnesium. Clin Cardiol 1993; 16:768–74
219. Zipes DP, Camm AJ, Borggrefe M, Buxton AE, Chaitman B, Fromer M, Gregoratos G, Klein G, Moss AJ, Myerburg RJ, Priori SG, Quinones MA, Roden DM, Silka MJ, Tracy C, Smith SC Jr, Jacobs AK, Adams CD, Antman EM, Anderson JL, Hunt SA, Halperin JL, Nishimura R, Ornato JP, Page RL, Riegel B, Priori SG, Blanc JJ, Budaj A, Camm AJ, Dean V, Deckers JW, Despres C, Dickstein K, Lekakis J, McGregor K, Metra M, Morais J, Osterspey A, Tamargo JL, Zamorano JL: ACC/AHA/ESC 2006 guidelines for management of patients with ventricular arrhythmias and the prevention of sudden cardiac death: A report of the American College of Cardiology/American Heart Association Task Force and the European Society of Cardiology Committee for Practice Guidelines (Writing Committee to Develop Guidelines for Management of Patients With Ventricular Arrhythmias and the Prevention of Sudden Cardiac Death). J Am Coll Cardiol 2006; 48:247–346
220. Fuster V, Ryden LE, Cannom DS, Crijns HJ, Curtis AB, Ellenbogen KA, Halperin JL, Le Heuzey JY, Kay GN, Lowe JE, Olsson SB, Prystowsky EN, Tamargo JL, Wann S, Smith SC Jr, Jacobs AK, Adams CD, Anderson JL, Antman EM, Halperin JL, Hunt SA, Nishimura R, Ornato JP, Page RL, Riegel B, Priori SG, Blanc JJ, Budaj A, Camm AJ, Dean V, Deckers JW, Despres C, Dickstein K, Lekakis J, McGregor K, Metra M, Morais J, Osterspey A, Tamargo JL, Zamorano JL: ACC/AHA/ESC 2006 Guidelines for the Management of Patients with Atrial Fibrillation: A report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines and the European Society of Cardiology Committee for Practice Guidelines (Writing Committee to Revise the 2001 Guidelines for the Management of Patients With Atrial Fibrillation): Developed in collaboration with the European Heart Rhythm Association and the Heart Rhythm Society. Circulation 2006; 114: e257–e354
221. Bradley D, Creswell LL, Hogue CW Jr, Epstein AE, Prystowsky EN, Daoud EG: Pharmacologic prophylaxis: American College of Chest Physicians guidelines for the prevention and management of postoperative atrial fibrillation after cardiac surgery. Chest 2005; 128:39–47
222. Dunning J, Treasure T, Versteegh M, Nashef SA: Guidelines on the prevention and management of de novo atrial fibrillation after cardiac and thoracic surgery. Eur J Cardiothorac Surg 2006; 30:852–72
223. Duley L: The global impact of pre-eclampsia and eclampsia. Semin Perinatol 2009; 33:130–7
224. Nassar AH, Sakhel K, Maarouf H, Naassan GR, Usta IM: Adverse maternal and neonatal outcome of prolonged course of magnesium sulfate tocolysis. Acta Obstet Gynecol Scand 2006; 85:1099–103
225. Buvanendran A, McCarthy RJ, Kroin JS, Leong W, Perry P, Tuman KJ: Intrathecal magnesium prolongs fentanyl anal-

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gesia: a prospective, randomized, controlled trial. Anesth Analg 2002; 95:661–6

226. Ko SH, Lim HR, Kim DC, Han YJ, Choe H, Song HS: Magnesium sulfate does not reduce postoperative analgesic requirements. Anesthesiology 2001; 95:640–6
227. Levaux C, Bonhomme V, Dewandre PY, Brichant JF, Hans P: Effect of intra-operative magnesium sulphate on pain relief and patient comfort after major lumbar orthopaedic surgery. Anaesthesia 2003; 58:131–5
228. O'Flaherty JE, Lin CX: Does ketamine or magnesium affect posttonsillectomy pain in children? Paediatr Anaesth 2003; 13:413–21
229. Seyhan TO, Tugrul M, Sungur MO, Kayacan S, Telci L, Pembeci K, Akpir K: Effects of three different dose regimens of magnesium on propofol requirements, haemodynamic variables and postoperative pain relief in gynaecological surgery. Br J Anaesth 2006; 96:247–52
230. Turan A, Memis D, Karamanlioglu B, Guler T, Pamukcu Z: Intravenous regional anesthesia using lidocaine and magnesium. Anesth Analg 2005; 100:1189–92
231. Tauzin-Fin P, Sesay M, ort-Laval S, Krol-Houdek MC, Maurette P: Intravenous magnesium sulphate decreases postoperative tramadol requirement after radical prostatectomy. Eur J Anaesthesiol 2006; 23:1055–9
232. Bilir A, Gulec S, Erkan A, Ozcelik A: Epidural magnesium reduces postoperative analgesic requirement. Br J Anaesth 2007; 98:519–23
233. Kaya S, Kararmaz A, Gedik R, Turhanoglu S: Magnesium sulfate reduces postoperative morphine requirement after remifentanil-based anesthesia. Med Sci Monit 2009; 15: I5–I9
234. Mentes O, Harlak A, Yigit T, Balkan A, Balkan M, Cosar A, Savaser A, Kozak O, Tufan T: Effect of intraoperative magnesium sulphate infusion on pain relief after laparoscopic cholecystectomy. Acta Anaesthesiol Scand 2008; 52:1353–9
235. Ozcan PE, Tugrul S, Senturk NM, Uludag E, Cakar N, Telci L, Esen F: Role of magnesium sulfate in postoperative pain management for patients undergoing thoracotomy. J Cardiothorac Vasc Anesth 2007; 21:827–31
236. Steinlechner B, Dworschak M, Birkenberg B, Grubhofer G, Weigl M, Schiferer A, Lang T, Rajek A: Magnesium moderately decreases remifentanil dosage required for pain management after cardiac surgery. Br J Anaesth 2006; 96:444–9
237. Tramer MR, Glynn CJ: An evaluation of a single dose of magnesium to supplement analgesia after ambulatory surgery: randomized controlled trial. Anesth Analg 2007; 104:1374–9

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