Treatment of severe persistent pulmonary hypertension of the newborn with magnesium sulphate

Yousef K Abu-Osba, Omar Galal, Khader Manasra, Abdellatif Rejjal

Abstract

Eight of nine newborn infants with severe persistent pulmonary hypertension of the newborn (PPHN), and a predicted mortality of 100%, and one infant with a predicted mortality >94% based on alveolar–arterial oxygen tension difference ((A–a)DO₂) were treated with magnesium sulphate (MgSO₄) as a life saving therapy after they failed to improve with conventional treatment. Magnesium at high serum concentrations decreases pulmonary pressures and is a muscle relaxant and sedative. Diluted MgSO₄·7H₂O solution (200 mg/kg) was given intravenously over 20–30 minutes. No changes in the treatment were made after MgSO₄. Mean serum magnesium concentration was maintained between 2.88 and 5.67 mmol/l by continuous intravenous infusion (six infants). Baseline arterial oxygen tension (PaO₂) and haemoglobin oxygen saturation had mean (SD) values of 4.66 (1.8) kPa and 60.4 (29.7)% respectively, which started to increase one hour after MgSO₄ infusion, and increased significantly at six hours to 12.04 (7.07) kPa and 91.8 (10.88)% respectively. Arterial carbon dioxide tension (PaCO₂) decreased and pH increased significantly after one hour compared with the baseline value. PaO₂ increases are probably secondary to a decrease in pulmonary vascular resistance and pressure, decrease in a right to left shunt, better ventilation:perfusion ratio, and PaCO₂ decrease and pH rise. Seven infants survived (77.8%). These results demonstrate the beneficial effect of magnesium in the management of PPHN when other accepted treatment fails, is contraindicated, or not available.

Persistent pulmonary hypertension of the newborn (PPHN) is characterised by a suprasystemic pulmonary vascular resistance and pressure causing a right to left shunt, and marked hypoxaemia and acidosis which may produce further pulmonary vasoconstriction. In severe cases mortality rate is changing with time and ranges from 10% to 60% despite aggressive management.^{1–5} Infants with an alveolar–arterial oxygen difference ((A–a)DO₂) more than 82.7 kPa (620 mm Hg) have been reported to have 100% mortality, and those with (A–a)DO₂ ≥81.3 kPa (610 mm Hg) for eight hours 80% mortality.^{4–6}

PPHN has a wide aetiological diversity which means that no single treatment may be uniformly effective.^{1–12} Mechanical hyperventilation, high frequency oscillatory ventilation, vasodilators

such as tolazoline and prostaglandins, muscle relaxants, and sedatives have all been advocated.^{1–12} Extracorporeal membrane oxygenation has been used to treat severe cases of PPHN with various success,^{3 6 7 11 12} but is not available in most neonatal centres. To date no controlled studies have been performed objectively to test the efficacy of the various treatments.

At high serum concentrations magnesium is a potent vasodilator, muscle relaxant, and sedative.^{13–16} Previous studies showed that magnesium can prevent and reduce hypoxia induced pulmonary hypertension.^{17–19} Eight infants with severe PPHN and a predicted mortality of 100% and one infant with a predicted mortality >94% based on (A–a)DO₂ criteria were treated with magnesium sulphate (MgSO₄) as a life saving therapy after they failed to improve with conventional treatment when extracorporeal oxygenation and oscillatory ventilation were not available.

Methods and subjects

In our unit, newborn infants with PPHN are treated by conventional methods.^{1–4 20} Nine infants with a clinical and laboratory picture consistent with PPHN^{1–3 20} failed to improve with conventional management after a period ranging from 15 to 92 hours (tables 1 and 2). Congenital heart disease was excluded in all infants by echocardiography. (A–a)DO₂ was greater than 84.3 kPa (630 mm Hg) in eight of nine infants, and was 82.1 kPa (616 mm Hg) in one infant (table 3). By published criteria all were considered candidates for extracorporeal membrane oxygenation.^{6 12} (A–a)DO₂ was calculated using the following formulas:

$$(A-a)DO_2 \text{ (kPa)} = 101.33 \times FIO_2 - PCO_2 + (PaO_2 + 6.27)$$

$$(A-a)DO_2 \text{ (mm Hg)} = 760 \times FIO_2 - (PCO_2 + PaO_2 + 47).^{2-6}$$

(Where FIO₂ is fractional inspiratory oxygen, PCO₂ is carbon dioxide tension, and PaO₂ is arterial oxygen tension.)

Clinical characteristics of these infants are described in table 1. All infants had normal serum magnesium, urea nitrogen, and creatinine values. Initial treatment is summarised in table 2, and the clinical and laboratory values for individual infants before MgSO₄ treatment (baseline) is presented in table 3.

Magnesium sulphate heptahydrate (MgSO₄·7H₂O from Abbott Laboratories) was given as compassionate treatment. Approved hospital procedures for compassionate treatment were

Perinatology/Neonatology
Section, Paediatric
Department, King Faisal
Specialist Hospital
and Research Centre,
PO Box 3354,
Riyadh 11211,
Kingdom of Saudi Arabia
Yousef K Abu-Osba
Omar Galal
Abdellatif Rejjal

Dhahran Health Centre,
Dhahran, Kingdom of
Saudi Arabia
Khader Manasra

Correspondence to:
Dr Abu-Osba.

Accepted 25 July 1991

Table 1 Clinical characteristics, diagnosis, and complications before MgSO₄ treatment

Patient No	Gestation (weeks)	Birth weight (g)	Outcome	Diagnosis and complications
1	40	2850	Survived	Diaphragmatic hernia, pulmonary haemorrhage, pneumothorax
2	42	3400	Survived	Perinatal asphyxia, MAS, cephalhematoma
3	42	2580	Survived	Perinatal asphyxia, MAS, SGA, sepsis, pulmonary haemorrhage, pneumothorax
4	40	3500	Survived	Perinatal asphyxia, MAS, sepsis
5	32	2240	Survived	Perinatal asphyxia, HMD, polycythaemia, probable sepsis
6	33	2400	Died	Perinatal asphyxia, probable sepsis, gastric and pulmonary haemorrhage
7	41	2880	Died	Perinatal asphyxia, MAS, pneumothorax
8	32	1770	Survived	Perinatal asphyxia, intracranial bleed, seizures, bilateral pneumothorax
9	38	2450	Survived	Diaphragmatic hernia, cleft lip and palate, SGA, pneumothorax

MAS, meconium aspiration syndrome; SGA, small for gestation; HMD, hyaline membrane disease.

followed. Each individual case was discussed by at least two neonatologists, approved by the chairman of the department, and informed consent from the parents was then obtained. Each gram of MgSO₄·7H₂O contains 4.06 mmol magnesium. MgSO₄ 50% was diluted to 8% concentration in 5% dextrose solution. An average bolus dose of MgSO₄, 200 mg/kg body weight, was given intravenously over 20–30 minutes; one infant received the bolus dose intramuscularly. A continuous intravenous drip of MgSO₄ 20–50 mg/kg/hour) was given with the same solution for six infants. Prostaglandin E₂ (PGE₂, tolazoline, and pancuronium were discontinued before MgSO₄ was given. No other medications or changes in the ventilator settings or FIO₂ were made after MgSO₄ was given except when PaO₂ rose to high values; FIO₂ and ventilator settings were then reduced. Blood gases, magnesium, calcium, electrolytes, and vital signs were measured before MgSO₄

was given and periodically thereafter. Arterial blood gases were measured from samples drawn from the umbilical artery (postductal) with a Corning blood gas analyser, and (A–a)Do₂ was calculated.

Results are given as mean (SD) for all infants unless indicated otherwise. One sample paired *t* test was used to compare values two hours before MgSO₄ infusion and at various intervals after infusion, with the baseline values measured directly before MgSO₄ infusion. Percentage change was calculated as the difference between the value at a certain interval and the baseline value, divided by the baseline value, and multiplied by 100. The χ^2 test with Yates' correction, Fisher's exact test, two tailed test and confidence intervals were used to compare rates. Kruskal-Wallis one way analysis by ranks was used when appropriate.

Results

Serum magnesium concentration increased significantly 1 hour after the supplement, giving values of mean (SD) from 0.7 (0.1) mmol/l to 4.0 (2.2) mmol/l (*p* < 0.01). Mean magnesium values during the first 8 hours varied from 2.88 to 5.67 mmol/l.

Umbilical arterial blood PaO₂ for the individual infants and the mean for all at the various intervals are shown in fig 1. For arterial blood gases, the mean percentage change from the baseline and 95% confidence intervals (CI) are shown in fig 2. The mean (SD) of the value for PaO₂ 2 hours before MgSO₄ infusion was similar to that at the baseline, being 5.47 (2.49) and 4.66 (1.80) kPa respectively (*p* < 0.459). PaO₂ started to increase within 1 hour after MgSO₄ to

Table 2 Summary of treatment, ventilator settings, and duration before MgSO₄ treatment

Patient No	Drugs				Mechanical ventilation				
	Tolazoline	PGE ₂	Pancuronium	Dopamine	Rate (per min)	PIP (cm H ₂ O)	PEEP (cm H ₂ O)	FIO ₂	Duration (hours)
1	Yes	No	Yes	Yes	110	35	3	1	50
2	No	No	Yes	No	60	35	5	1	46
3	Yes	No	Yes	Yes	90	50	5	1	92
4	No	Yes	No	No	80	30	3	0.95	52
5	No	No	No	No	70	30	3	1	30
6	Yes	No	No	Yes	100	35	3	1	21
7	Yes	No	No	Yes	101	30	4	1	15
8	Yes	No	No	Yes	80	28	4	1	48
9	No	No	No	Yes	80	38	2	1	32

PIP, positive inspiratory pressure; PEEP, positive end expiratory pressure, FIO₂, fractional inspiratory oxygen pressure.

Table 3 Initial clinical and laboratory values for individual infants before MgSO₄ treatment. Mean blood pressure values are shown

Patient No	Serum magnesium (mmol/l)	Heart rate (bpm)	Blood pressure (mm Hg)	pH	Paco ₂ (kPa)	PaO ₂ (kPa)	Oxygen saturation (%)	(A–a)Do ₂ (kPa)
1	0.64	154	46	7.47	5.87	4.27	67	84.93
2	0.68	141	60	7.35	5.2	3.73	49	86.13
3	0.64	136	78	7.56	3.33	6.93	92	84.80
4	0.94	150	72	7.15	6.27	1.87	12	82.13
5	0.68	147	64	7.38	4.53	6.0	81	84.53
6	0.8	171	46	7.08	7.33	2.27	13	85.47
7	0.58	120	52	7.42	2.8	4.67	71	87.60
8	0.68	148	29	7.19	4.93	6.4	75	83.73
9	0.65	134	41	7.51	4.40	5.73	84	84.93
Mean	0.7	144	54.2	7.35	4.90	4.66	60.4	84.97
SD	0.11	14.3	15.66	0.17	1.43	1.8	29.7	1.47

Figure 1 PaO₂ changes before and after MgSO₄ treatment for individual infants. Each line represents one infant, the mean for all the infants treated is shown as wide solid line with solid circles.

Figure 2 Mean and 95% confidence intervals of percentage change in the arterial blood gas values before and after MgSO₄ treatment for all infants.

11.29 (11.41) kPa ($p < 0.137$), mean percentage change was 181.4% and CI was -45.65 to 408.49. At 2 and 4 hours, PaO₂ showed a trend to be higher than baseline ($p < 0.12$ and $p < 0.06$ respectively). PaO₂ was significantly higher at 6 and 8 hours, with values at 12.04 (7.07) kPa ($p < 0.029$) and 16.47 (12.63) kPa ($p < 0.035$) respectively, and percentage mean change (and CI) from the baseline of 203% (26 to 379%) and 294% (6 to 582%) respectively. Kruskal-Wallis one way analysis by ranks showed that PaO₂ had changed significantly during the study period ($p < 0.004$).

Mean (SD) haemoglobin oxygen saturation at 2 hours before MgSO₄ infusion was similar to baseline (64 (27)% and 60 (30)% respectively; $p < 0.78$). Saturation increased significantly within 1 hour after MgSO₄ infusion to 84 (18)% ($p < 0.017$) and at 8 hours to 95 (6)% ($p < 0.02$). Percentage change (and CI) were 130% (-27 and 288%) and 119% (-87 to 325%) respectively.

Paco₂ means (SD) were similar at 2 hours before MgSO₄ and at the baseline (4.75 (0.89) and 4.9 (1.43) kPa respectively), and decreased to 4.07 (0.78) kPa ($p < 0.048$) and 3.29 (0.89) kPa ($p < 0.04$) at 1 and 8 hours respectively, mean percentage change and CI being shown in fig 2. Mean (SD) values of arterial pH at 2 hours before MgSO₄ infusion and the baseline were

7.37 (0.1) and 7.35 (0.17). Arterial blood pH showed a significant increase at 1, 2, and 4 hours after infusion ($p < 0.034$, $p < 0.046$ and $p < 0.045$) and showed a trend to be higher at 6 and 8 hours, $p < 0.066$ and $p < 0.08$ respectively, mean percentage change and CI being shown in fig 2. Comparing bicarbonate and base excess values during the study period and the baseline did not reveal significant changes. Means (SD) of arterial blood bicarbonate 2 hours before MgSO₄, at the baseline and after 8 hours were 20.5 (5.6), 20.1 (6.9), 20.4 (4.6).

(A-a)Do₂ started to decrease from the baseline (85 (1.5) kPa) within 1 hour after MgSO₄ (80 (11.1) kPa, $p < 0.89$) and was significantly lower after 8 hours 72.2 (13.2) kPa, $p < 0.025$, mean percentage change and CI being shown in fig 2. Seven infants (77.8%) survived while on treatment; in the two infants who died a small decrease in (A-a)do₂ was seen initially but it remained greater than 82.67 kPa (620 mm Hg) until they died. One infant died seven days after stopping MgSO₄ treatment. None of the infants who died responded to tolazoline and dopamine treatment.

Heart rate 2 hours before MgSO₄ was similar to the baseline value: means (SD) were 142 (22) and 145 (14) beats/minute (bpm) respectively. Heart rate showed a trend to decrease during the study period. After 1 and 8 hours the heart rate was 143 (12) bpm ($p < 0.66$) and 129 (14) bpm ($p < 0.089$), but not below 116 bpm in any surviving infant during the study period.

Baseline mean blood pressure for all infants was similar to that at 2 hours before MgSO₄ infusion, the values being 54.2 (15.7) and 54 (13.6) mm Hg respectively. Although mean blood pressure showed a trend to decrease at 2 hours after MgSO₄ infusion to 47.1 (15.1) mm Hg ($p < 0.08$), it did not show any significant change during the 8 hour period. At 8 hours blood pressure was 51.4 (11.8) mm Hg. No significant changes were observed during the study period in the serum electrolytes and calcium.

Ultrasound scans were taken of the head in all infants and none developed intracranial haemorrhage during treatment. Patient 8 who had had severe perinatal asphyxia and had been successfully resuscitated from a cardiac arrest at 2 days of age, before MgSO₄ treatment, had an intraventricular haemorrhage and subsequently developed hydrocephalus. Patient 4 had normal head scans before and at two and seven days after treatment but showed an old infarct lesion in the left frontal lobe in a follow up computed tomographic scan of the brain one month after the treatment. Patient 3 subsequently developed bronchopulmonary dysplasia. No infant had any bleeding from gastrointestinal and urinary tract or through the endotracheal tube during the study period.

Discussion

Drugs that are specific pulmonary vasodilators and reduce pulmonary hypertension are not available yet for clinical use. Pulmonary vasoconstriction depends on the availability of calcium to the affected cells,^{21 22} and therefore

calcium channel blockers have been tried to induce pulmonary vasodilatation. Magnesium is nature's calcium antagonist: it is a muscle relaxant, vasodilator, sedative, and anti-thrombotic.^{13 14 23-29} Cropp showed in dogs that increase in blood magnesium to 5–6 mmol/l will block hypoxic pulmonary vasoconstriction without causing deleterious changes in haemodynamics or pulmonary ventilation.¹⁷ Paidas showed that continuous infusion of ATP and magnesium chloride produced a significant decrease in mean pulmonary artery pressure after induced hypoxia, but magnesium chloride had no effect when infused alone¹⁸; but the doses given were very small and magnesium chloride values in the blood were not measured. Abu-Osba *et al* showed in anaesthetised sheep that a sharp increase in the mean pulmonary artery pressure occurred by breathing 10% oxygen, but during hypoxia it fell suddenly to the baseline after MgSO₄ infusion.¹⁹ No significant change in the cardiac output was observed, and the heart rate decreased transiently. In contrast, no change was observed after placebo infusion. Magnesium aspartate hydrochloride oral therapy has been shown by Mathew *et al* to attenuate monocrotaline induced pulmonary hypertension, right ventricular hypertrophy and pathological changes in the pulmonary vasculature in rats.³⁰ Howel and Carrier showed that in rabbit, magnesium reduces the contractile responses of the pulmonary artery to noradrenaline and histamine and alters the sensitivity to histamine.³¹ These studies demonstrate the beneficial effect of magnesium in reducing pulmonary hypertension.

MgSO₄ has been used for several decades to treat toxemia of pregnancy. During treatment maternal serum magnesium concentration is 2–3.5 mmol/l and magnesium ions cross the placenta promptly to achieve equilibrium between the mother and the fetus.²⁶ Side effects of hypermagnesaemia, which has beneficial therapeutic applications in infants with PPHN, include: central sedation, muscle relaxation, hyporeflexia, and decreased excitability.^{27 28 32 33} Possible undesirable side effects include calcium and potassium disturbances.^{27 28 34} Frequent monitoring of blood concentrations and appropriate supplementations will prevent these complications. Abdominal distension may occur, with absence of bowel sounds. Infants with PPHN usually have a gastric tube inserted and connected to low pressure suction or free drainage and usually they are not fed enterally. High serum concentrations of magnesium may produce respiratory depression, a non-consequential effect in these mechanically ventilated infants. The MgSO₄ dose we used and the serum values were similar to that used in toxemia of pregnancy which has been proved to be safe for both the fetus and the newborn infant.^{26-28 32}

Ideally, a controlled double blind study should have been done to test the efficacy and safety of this treatment. Our study was not controlled and our justification was that all the infants were treated with MgSO₄ on a compassionate basis after all other available treatment had failed to relieve the severe hypoxaemia and

they were expected to die (according to the accepted criteria of (A–a)Do₂ used in various studies). There are no pilot studies in humans showing that MgSO₄ can treat PPHN, although there is good theoretical and experimental evidence to support this. As the incidence of PPHN is very low it will require a long period to conduct a randomised controlled study unless a multicentre study is organised.

Carter *et al* reported 22 of 25 patients survived (88%) with (A–a)Do₂ ≥ 80 kPa (600 mm Hg): they required extracorporeal membrane oxygenation treatment after failure of high frequency oscillatory ventilation and conventional therapy.³ Dworetz *et al* reported survival rates in patients eligible for extracorporeal membrane oxygenation based on (A–a)Do₂ ≥ 81.33 kPa (610 mm Hg) for eight hours with a predicted mortality 80%.² In 1980–1 survival rate was 0% (0/5) and 1986–8 survival rate was 89% (8/9). Although our patients were more severely ill, with (A–a)Do₂ > 82.67 kPa (620 mm Hg) in eight (predicted mortality 100%) and 82.13 kPa (616 mm Hg) in one patient (predicted mortality 94%), the survival rate in our study was 77.8% (7/9), which is comparable with Carter *et al* and Dworetz *et al*.²

Though we did not measure the pulmonary pressure, we suggest that the observed increase in PaO₂ and haemoglobin oxygen saturation is probably secondary to the vasodilator effect of magnesium on the pulmonary vessels. The relief of hypoxaemia, the continuing effect of magnesium, muscle paralysis, and the expected improvement in ventilation: perfusion ratio, could be reasons for PaCO₂ decreases and pH increases which then lead to further improvement in oxygenation.

Several prostaglandins have been used to decrease pulmonary hypertension.⁸⁻¹⁰ MgSO₄ has a powerful effect on the production and release of several prostaglandins, especially PGI₂ and its metabolite 6-keto-PGF_{1α}. Nadler and Rude have shown in normal human subjects that MgSO₄ infusion increases significantly the excretion of the stable PGI₂ metabolite 6-keto-PGF_{1α}.³⁵ Watson *et al* have reported that MgSO₄ increases the release of PGI₂ by cultured human umbilical vein endothelial cells (HUVEC); PGI₂ production was two to five times greater when HUVEC were incubated with plasma from preeclamptic patients undergoing MgSO₄ therapy than when HUVEC were incubated with pretherapy plasma.³⁶ Also, MgSO₄ enhances by 20–36% the prostacyclin liberation from the umbilical cord vascular wall.²⁹ Furthermore, magnesium increases production of prostacyclin or its metabolite 6-keto PGF_{1α} in other organs, for example cardiac muscle³⁷ and antrum and duodenum.³⁸ Magnesium increases PGI₂ production, decreases PGD₂ production,³⁸ and depresses the vascular contractions induced by PGF₂.³⁹ There is evidence that magnesium acts directly on the PGF₂ (vasodilator) receptor site.⁴⁰

The therapeutic effect observed in the infants with PPHN is possibly due to one or a combination of effects of magnesium on production, release, metabolism and receptor

sites of prostaglandins. Some reports describe a beneficial magnesium vasodilator effect and reduction of complications after ischaemic hypoxia in the central nervous system, in ischaemic heart disease, and in kidney and liver conditions^{16 35 41-43} which frequently coexist with PPHN in the severely hypoxaemic neonate. This study and others suggest the possible benefits of magnesium treatment in PPHN when conventional therapy fails and alternative modes of therapy, for example, extracorporeal membrane oxygenation and high frequency oscillatory ventilation are not available or are contraindicated. A controlled multicentre study is required before recommending magnesium as primary treatment and further work is needed to clarify its mechanism of action in PPHN. Close monitoring of blood pressure, kidney function, electrolytes, glucose, and calcium should be observed and long term follow up is needed.

We thank Professor RDG Milner for his critical review of the manuscript.

- 1 Fox WW, Duara S. Persistent pulmonary hypertension of the neonate: diagnosis and clinical management. *J Pediatr* 1983;103:505-8.
- 2 Dworetz AR, Moya FR, Sabo B, Gladstone I, Gross I. Survival of infants with persistent pulmonary hypertension without extracorporeal membrane oxygenation. *Pediatrics* 1989;84:1-6.
- 3 Carter JM, Gerstmann DR, Clark RH, et al. High-frequency oscillatory ventilation and extracorporeal membrane oxygenation for the treatment of acute neonatal respiratory failure. *Pediatrics* 1990;85:159-64.
- 4 Davis JM, Spitzer AR, Cox C, Fox WW. Predicting survival in infants with persistent pulmonary hypertension of the newborn. *Pediatr Pulmonol* 1988;5:6-9.
- 5 Hageman JR, Dusik J, Keuler H, Bregman J, Gardner TH. Outcome of persistent pulmonary hypertension in relation to severity of presentation. *Am J Dis Child* 1988;142:293-6.
- 6 Krummel TM, Greenfield LJ, Kirkpatrick BV, et al. Alveolar-arterial oxygen gradients versus the neonatal pulmonary insufficiency index for prediction of mortality in ECMO candidates. *J Pediatr Surg* 1984;19:380-4.
- 7 Short BL, Miller MK, Anderson KD. Extracorporeal membrane oxygenation in the management of respiratory failure in the newborn. *Clin Perinatol* 1987;14:737-48.
- 8 Kaapa P, Koivisto M, Ylikorkala O, Kouvainen K. Prostacyclin in the treatment of neonatal pulmonary hypertension. *J Pediatr* 1985;107:951-3.
- 9 Philips III JB, Lyrene RK, McDevitt M, et al. Prostaglandin D₂ inhibits hypoxic pulmonary vasoconstriction in neonatal lambs. *J Appl Physiol* 1983;54:1585-9.
- 10 Roberts RJ. Cardiovascular drugs. In: *Drug therapy in infants, pharmacologic principles and clinical experience*. Philadelphia: W B Saunders, 1984:192.
- 11 Anonymous. Persistent fetal circulation and extracorporeal membrane oxygenation. *Lancet* 1988;ii:1289-91.
- 12 Bartlett RH, Roloff DW, Cornell RG, et al. Extracorporeal circulation in neonatal respiratory failure: a prospective randomized study. *Pediatrics* 1985;76:479-87.
- 13 Altura BM, Altura BT. Role of magnesium ions in contractility of blood vessels and skeletal muscle. *Magnesium Bull* 1981;3:102-14.
- 14 Ebel H, Gunther T. Magnesium metabolism: a review. *J Clin Chem Clin Biochem* 1980;18:257-70.
- 15 Turplapay PD, Altura BM. Extracellular magnesium ions control calcium exchange and content of vascular smooth muscle. *Eur J Pharmacol* 1978;52:421-3.
- 16 White BC, Winegar CD, Wilson RF, Krause GS. Calcium blockers in cerebral resuscitation. *J Trauma* 1983;23:788-94.
- 17 Cropp GJA. Reduction of hypoxic pulmonary vasoconstriction by magnesium chloride. *J Appl Physiol* 1968;24:755-60.
- 18 Paidas CN, Dudgeon DL, Haller JA Jr, Clemens MG. Adenosine triphosphate: a potential therapy for hypoxic pulmonary hypertension. *J Pediatr Surg* 1988;23:1154-60.
- 19 Abu-Osba YK, Rhydderch D, Balasundaram S, et al. Reduction of hypoxia-induced pulmonary hypertension (HIPH) by MgSO₄ in sheep. *Pediatr Res* 1990;27:351A.
- 20 Wung JT, James LS, Kilchevsky E, et al. Management of infants with severe respiratory failure and persistence of the fetal circulation, without hyperventilation. *Pediatrics* 1985;76:488-94.
- 21 Bohr DF. The pulmonary hypoxic response. *Chest* 1977;71 (suppl):244-6.
- 22 Dickstein PJ, Trindate O, Goldberg RN, Bancalari E. The effect of calcium antagonists on hypoxic pulmonary hypertension in the piglet. *Pediatr Res* 1984;18:1262-5.
- 23 Vacanti FX, Ames A. Mild hypotension and Mg protect against irreversible damage during CNS ischemia. *Stroke* 1984;15:695-8.
- 24 Mroczek WJ, Lee WR, Davidov ME. Effect of magnesium sulfate on cardiovascular hemodynamics. *Angiology* 1977;28:720-4.
- 25 Abu-Osba YK. Treatment of persistent pulmonary hypertension of the newborn: update. *Arch Dis Child* 1991;66:74-7.
- 26 Pritchard JA, MacDonald PC, Gant NF, eds. Hypertensive disorders in pregnancy. In: Pritchard JA, MacDonald PC, Gant NF, eds. *Williams' obstetrics*, 7th Ed. Norwalk: Appleton-Century-Crofts, 1985:525-60.
- 27 Stone SR, Pritchard JA. Effect of maternally administered magnesium sulfate on the neonate. *Obstet Gynecol* 1970;35:574-7.
- 28 Lipsitz PJ. The clinical and biochemical effects of excess magnesium in the newborn. *Pediatrics* 1971;47:501-8.
- 29 Briel RC, Lippert TH, Zahradnik HP. Changes in blood coagulation, thrombocyte function and vascular prostacyclin synthesis caused by magnesium sulfate. *Geburtshilfe Frauenheilkd* 1987;47:332-6.
- 30 Mathew R, Altura BT, Altura BM. Strain differences in pulmonary hypertensive response to monocitraline alkaloid and the beneficial effect of oral magnesium treatment. *Magnesium* 1989;8:110-6.
- 31 Howell RE, Carrier GO. Influence of magnesium on norepinephrine- and histamine-induced contractions of pulmonary vascular smooth muscle. *Pharmacology* 1986;33:27-33.
- 32 Ayromloo J, Desiderio DM, Tobias M, Berg P. Effect of magnesium sulfate on maternal and fetal hemodynamics and fetal brain function and metabolism. *Pediatric Pharmacology (New York)* 1982;2:305-15.
- 33 Raash DK, Huber PA, Richardson CJ, L'Hommedieu CS, Nelson TE, Reddi R. Neurobehavioral effects of neonatal hypermagnesium. *J Pediatr* 1982;100:272-6.
- 34 Durlach J, Durlach V. Speculations on hormonal controls of magnesium homeostasis: a hypothesis. *Magnesium* 1984;3:109-31.
- 35 Nadler JL, Goodson S, Rude RK. Evidence that prostacyclin mediates the vascular action of magnesium in humans. *Hypertension* 1987;9:379-83.
- 36 Watson KV, Moldow CF, Ogburn PL, Jacob HS. Magnesium sulfate: rationale for its use in preeclampsia. *Proc Natl Acad Sci USA* 1986;83:1075-8.
- 37 Weis MT, Malik KU. The influence of mono- and divalent cations on the cardiac metabolism of arachidonic acid. *Prostaglandins* 1989;37:707-23.
- 38 Precilik G, Stange EF, Gerber K, Fetzer G, Horn H, Ditschuneit H. Alimentary tract and pancreas: stimulation of mucosal prostaglandin synthesis in human stomach and duodenum by antacid treatment. *Gut* 1989;30:148-51.
- 39 Miura K. Changes in Mg²⁺ concentrations of CSF after subarachnoid hemorrhage and Mg²⁺ effects on the contractions of bovine cerebral artery. *No Shinkei Geka* 1988;16:1251-9.
- 40 Wisner A, Bommelaer-Bayet MC, Tiberghien C, Renard CA, David F, Dray FAF. Hypothalamic prostaglandin E₂ receptors coupled to an adenyl cyclase. *J Pharmacol* 1989;162:89-100.
- 41 Altura BT, Altura BM. Interactions of Mg and K on cerebral vessels—aspects in view of stroke: review of present status and new findings. *Magnesium* 1984;3:195-211.
- 42 Chaudry IH. Cellular mechanisms in shock and ischemia and their correction. *Am J Physiol* 1983;245:R117-R34.
- 43 Clemens JG, McDonagh PF, Chaudry IH, et al. Hepatic microcirculatory failure following ischemia and reperfusion: improvement with ATP-MgCl₂ treatment. *Am J Physiol* 1985;248:H804-11.