Invasive Warming of Intravenous Fluids: Overheating of the Toroid Heating Element during Rapid Infusion

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REFRIGERATION of stored packed erythrocytes at 1°–6°C prolongs the shelf life up to 42 days. 1 In an attempt to avoid transfusion-related hypothermia, conductive, convective, radiant, and inductive fluid warming techniques have been used with varying success. We report a unique observation in which an inductive fluid warming device overheated during rapid infusion.

Case Report

A 42-yr-old, 80-kg male with chondrosarcoma of the left pelvis was scheduled to undergo elective left internal hemipelvectomy. His medical and physical examination results were unremarkable. After placing standard American Society of Anesthesiologists monitors, general anesthesia was induced and maintained without incident. Based on historic precedent, large fluid shifts were anticipated, which prompted placement of a right radial arterial catheter as well as 8.5-French and 14-gauge antecubital intravenous catheters. Central venous pressure was continuously monitored via the distal port of a right internal jugular 9-French multilumen cordis. A Belmont FMS 2000 Rapid Infusion Device (Belmont Instrument Corporation, Billerica, MA) was connected to the 8.5-French antecubital catheter to deliver warmed fluids throughout the procedure.

The case proceeded uneventfully through the first 9.5 h of the operation. Despite receiving 12 units packed erythrocytes, 11 l crystalloid, 12 units fresh frozen plasma, 6 units platelets, and 2.5 l albumin, 5%, the patient remained warm (36.9°C at the conclusion of pelvic resection) and hemodynamically stable. During fascial closure of the wound, the surgeon observed a “dusky” left leg. Doppler examination disclosed absence of a femoral pulse, necessitating emergent femoral artery exploration and bypass.

Despite having just completed a highly invasive orthopedic surgical procedure, 5,000 units intravenous heparin was administered, as requested by the vascular surgeon, resulting in an activated clotting time of 200 s. Ten minutes after heparin administration, hemostasis became increasingly difficult, and hemorrhage was evident in the surgical field. Despite fulminant hemorrhage, central venous and systemic arterial blood pressures were maintained within 20% of baseline using the Belmont FMS 2000 to deliver an additional 8 units of packed erythrocytes and 3 l saline, 0.9% (flow rate ranged from 100 to 500 ml/min). However, near the conclusion of the resuscitative effort (and after the surgeons had regained hemostasis), we noted an acrid smell reminiscent of burning plastic that coincided with an abrupt profound hemodynamic change. The overhear alarm sounded and automatically shut off the Belmont warming unit. The disposable tubing insert was removed, was noted to be disfigured, and seemed to have charred material in one half of the heating coil (figs. 1A and B). The warming unit itself appeared grossly undamaged, but it was promptly replaced with another Belmont FMS 2000 with a new disposable insert.

Subsequent fluid warming proceeded uneventfully, and the patient remained hemodynamically stable and warm (esophageal temperature 37.0°C at the time of discharge from the operating room). He was transferred to the intensive care unit, where serum electrolytes and urine output remained within normal limits. He was extubated on the second postoperative day and discharged to a rehabilitation facility on postoperative day 8, without adverse sequelae.

Discussion

Rapid resuscitation with large volumes of unwarmed intravenous fluid and blood products may result in life-threatening hypothermia. In response to this concern, the medical equipment industry has developed several fluid warming devices that are capable of delivering large volumes of temperature-specific intravenous fluids at high rates of infusion. Unlike conductive warming, which requires physical contact between the intravenous fluid and the warming device, inductive warming occurs in the absence of physical contact between the intravenous fluid and warming element. The Belmont FMS2000 is an inductive fluid warmer capable of heating intravenous fluids to 37.5°C at flow rates ranging from 60 to 500 ml/min and to 39°C at rates of less than 60 ml/min. 2 With this device, intravenous fluid passes through a toroidal-shaped (donut-shaped) heat exchanger by a built-in peristaltic pump. 2 A magnetic field is created by a coil at the center of the heat exchanger. 2 Energy from the magnetic field is transferred to the steel rings of the heat exchanger and then to the intravenous fluid. 2 Infrared temperature sensors are located on both the input and output ports of the heat exchanger. 2 If the output sensor detects a fluid temperature of 42°C or greater, the system is designed to—and did so in our case—shut down and alarm, thereby preventing thermal-related injury. 2

Malfunction of fluid warming devices has previously been reported. 3–6 However, regional overheating of the toroid is a unique observation. In hope of elucidating the etiology of malfunction, we sent the disposable warming
were administered through an alternate
alternative of this potential pitfall, procoagulant solutions
administered through their device. However, being cog-
calcium, clotting factors, cryoprecipitate, or platelets) were
that the melting point of the plastic housing was 100 °C.

In extraordinary testing conditions, the manufacturer determined
from clot formation or improper use. Also, under extreme testing conditions, the manufacturer determined
the melting point of the plastic housing was 100 °C. Aside from providing this information, the manufacturer
was unable to clearly identify the cause of overheating in
our case.

Because the damaged portion of the toroid was likely
exposed to temperatures of 100 °C or greater (i.e., at or
beyond the melting point of the toroid), another consid-
eration for the source of toroidal discoloration was ther-
mal injury to formed elements in transfused blood. In
regard to the latter, human erythrocytes are capable of
withstanding temperatures near 45 °C (i.e., a value signif-
ificantly greater than the maximal output temperature of
commercially available fluid warmers) for prolonged pe-
riods of time with little effect on cellular integrity.7
Denaturation of erythrocyte membrane proteins is re-
ponsible for increased osmotic fragility and hemolysis
after exposure to temperatures exceeding 45 °C.8–13 The
percentage of hemolyzed blood cells increases linearly as
a function of exposure duration and temperature mag-
nitude.8,10,12 Of interest, on review of the patient’s lab-
oratory studies, two arterial blood gas samples were
noted to be hemolyzed during and soon after the period
of hemodynamic instability. Ironically, all other samples
drawn from the same arterial line either before or there-
after were not reported as hemolyzed specimens.

Unless leukocyte filtration is performed before or dur-
ing transfusion, leukocytes are also present in units of
packed erythrocytes. To our knowledge, the tempera-
ture of leukocyte lysis has not been reported. However,
in research of thermal-mediated leukocyte free-
radical production, complement activation, and release
of vasoactive mediators (e.g., prostaglandins, leukotri-
enes, interleukins, bradykinins, tumor necrosis factor,
oxygen free radicals, and cytokines) from thermally
lysed or degranulated leukocytes may contribute to
physiologic perturbations such as hypotension.14

As stated above, when the output sensor detects tem-
peratures of 42 °C or greater, the device shuts down,
thereby preventing thermal injury. However, tempera-
ture within the toroid itself is not monitored. Therefore,
it is plausible that formed elements in blood exposed to
nonphysiologic extreme temperatures (i.e., ≥ 100 °C in
malfuctioning half of the warming element) lyed, re-
leasing vasoactive mediators. We speculate this may
have been the cause of the brief, but profound hypoten-
sive episode rather than an abrupt change in preload, as
the central venous pressure was maintained within 20%
of baseline and surgical control of hemorrhage had al-
ready been achieved. We envision that prevention of this
vasoactive mediator exposure was not possible because
the output sensor detects temperature of fluid mixed
from both halves of the toroid. That is, admixture of fluid
within the distal toroid resulted in effluent temperatures
of less than 42 °C until the temperature within the mal-
fuctioning half of the toroid was so extreme that
"cooler" fluid (from the normal functioning region of the
toroid) was no longer able to moderate outgoing fluid
temperature. Accordingly, up to this endpoint, flow

Fig. 1. Anterior (A) and oblique (B) views of the Belmont FMS 2000 disposable tubing insert (Belmont Instrument Corpora-
portion, Billerica, MA). Charred, deformed toroidal shaped heating
element suggests exposure to temperatures exceeding 100 °C
(i.e., the melting point of the plastic used to manufacture this
device).

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through the toroid may have flushed vasoactive media-
tors into the patient’s circulation, resulting in hemody-
namic instability.

In summary, we report a unique observation in which
the heating element of an inductive fluid-warming de-
vice experienced overheating (i.e., temperature ≥
100°C) during rapid infusion. Without prompt inter-
tervention, such an occurrence could result in patient injury.

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In Reply—The case report by Husser et al. describes a situation
involving massive transfusion of crystalloid, packed erythrocytes,
and platelets in a crisis situation. During the case, our rapid infusion/
warmer, the FMS 2000 (Belmont Instrument Corporation, Billericá,
MA), detected an overtemperature situation, alarmed, and stopped
the infusion. A portion of the heat exchanger appeared to have become
very hot, and a portion of the housing seemed to have softened. The authors
attribute a brief episode of hypotension, and tachycardia, to the
incident.

The FMS 2000 monitors the true temperature of the infusate (not
that of a water bath or plate) and alarms whenever the fluid Exiting
the heat exchanger reaches 42°C, well below the temperature at which
blood can be damaged. When the alarm occurs, the system immedi-
ately closes the line to the patient and stops the pump and heater,
and an alarm message instructs the user to discard the disposable set.
There is a substantial volume (~5 ml) in our disposable set downstream of
the heat exchanger, at lower temperature, so that it is impossible for any
fluid above 42°C to reach the patient. When the system involved in
the incident was returned to us for evaluation, it was thoroughly tested,
and it performed according to specification. The disposable set
was returned to us, and the heat exchanger was found to be partially
occluded with what seemed to be clotted blood. There was no charred
plastic. Blood clots had become trapped in the fine channels of the
heat exchanger, preventing blood from flowing through them, and also
preventing much of the clot material from being infused into the
patient. When sufficient clot material is trapped in the heat exchanger,
a portion of the heater can be occluded, trapping infusate fluid, which
can get very hot. However, the trapped fluid cannot reach the patient.
As soon as any fluid at 42°C or higher exits the heat exchanger, the
over-temperature alarm activates, closing off flow to the patient as
described above.

The heat exchanger in our system consists of a series of specially
coated stainless steel annular rings that are heated indirectly by mag-
netic induction and are enclosed in plastic housing. The system has
been tested multiple times by an independent, university-affiliated labora-
tory using packed human erythrocytes from a blood bank. Hemolysis and
erythrocyte osmotic fragility have been measured both for test samples at
all flow rates and for control samples that did not pass through the system.
In all measurements, which were repeated on several occasions using
different blood samples, no difference between the test samples and
controls was ever found. As to the origin of the clots, we know that they
were formed downstream of the reservoir filter of our disposable set,
which removes all gross particulate matter, suggesting the involvement
of a soluble factor. The pore size of the reservoir filter is 160 μm (0.16 mm),
which is much smaller than the heat exchanger channel spacing, 760 μm
(0.76 mm). At some institutions, lactated Ringer’s solution (containing
Ca2+ ions) has been infused with citrated blood products, which, in a few
cases, has led to clotting within the disposable set. However, in this case
report, the authors state that lactated Ringer’s solution was never added
to the FMS.

The only way in which we are able to reproduce such high heat as
to soften the heat exchanger housing is to completely occlude a
section of the heat exchanger with epoxy cement. This causes no flow
to occur in the blocked section, which leads to dramatic overheating.
(The annular rings of the heat exchanger divide the flow into a series
of parallel fine channels. Occluding approximately two thirds of the
fluid path for all 17 channels in the heat exchanger and monitoring the
fluid temperature just downstream of the blockage with a small ther-
mocouple probe showed only a small increase in temperature to
between 42° and 46°C, which does not damage stored erythrocytes.1
This makes the scenario in the second to last paragraph of the case
report, regarding vasoactive mediators, very unlikely. It is only when
several channels were completely blocked that dramatic overheating
occurred. This was due to a region of trapped, stagnant fluid being
continually heated by the rings. The temperature in the adjacent
unblocked channels stayed near normothermic temperature.) If the
flow path changes slightly, and some of the overheated fluid can reach
the output temperature probe, the system alarms as soon as the output
temperature reaches 42°C. In the disposable set returned to us, the
occlusion was located very close to the output of the heat exchanger,
so that the response would have been very quick.

The authors speculate that the hypotensive incident could have
been caused by damage to the small amount of leukocytes contained
in the packed erythrocytes. However, the high temperature in the
heat exchanger results from complete lack of flow in an area of occlusion.
Furthermore, leukocytes in packed erythrocyte suspensions stored
under standard conditions are already degraded and are known to
release numerous cytokines.2–4 In this case report, no laboratory mea-
surements were made relating to leukocytes or cytokines, and no
conclusion regarding the involvement of these factors can be made. As

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Vasopressin for Hemodynamic Rescue in Catecholamine-resistant Vasoplegic Shock after Resection of Massive Pheochromocytoma

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PERIOPERATIVE management of pheochromocytoma remains an anesthetic challenge.1,2 Acute variations in serum catecholamine levels may present as hypertensive or hypotensive crises, depending on tumor type and stage of the procedure. Major advances in perioperative management included preoperative catecholamine blockade and adequate preoperative volume resuscitation.2

We present a case of massive pheochromocytoma that required urgent surgical resection. The urgency of the case and tumor mass precluded complete preoperative catecholamine blockade. The major perioperative challenge was profound vasoplastic shock after tumor resection.

The unusual feature in this case was that vasopressin therapy was required to reverse the catecholamine-resistant vasoplastic shock that persisted after tumor resection. Although this application of vasopressin has recently been reported, it was in a case of pheochromocytoma that was complicated by massive blood loss.3 Our case is unique because it illustrates the successful application of vasopressin in pheochromocytoma resection, complicated not by hypovolemia but by severe acute catecholamine deficiency resulting from the resection of a giant tumor.

Case Report

Preoperative Presentation

A 47-yr-old man presented to the emergency room in respiratory distress. His vital signs included heart rate of 166 beats/min, blood pressure of 212/153 mmHg, respiratory rate of 45 breaths/min, and a systemic oxygen saturation of 75% on room air. Chest auscultation revealed bilateral rales. The electrocardiogram was remarkable for sinus tachycardia and widespread ST-segment depression. His chest radiograph revealed pulmonary edema.

The patient was placed on mechanical ventilation, and vasodilator therapy with nitroprusside was instituted. He was transferred to cardiac catheterization laboratory for emergent angiography that revealed normal coronary and renal arterial anatomy. Transthoracic echocardiography revealed an ejection fraction of 20%, global left ventricular hypokinesis, and no significant valvular disease.

The patient was admitted to the intensive care unit. His hemoglobin was 19 g/dl, and his creatinine was 3.7 mg/dl. His blood pressure was gradually controlled with both nitroprusside and labetalol. Plasma free normetanephrine was 88.1 nM (range, 0.49–33 nM), and plasma free metanephrine was 35.3 nM (range, 0.49–9 nM). A computed tomographic scan of the abdomen revealed a 10 cm left adrenal mass. He was referred to our institution with a diagnosis of left adrenal pheochromocytoma.

In the intensive care unit there was complete resolution of his cardiomyopathy and acute renal failure. Mechanical ventilation was successfully withdrawn. Repeat transthoracic echocardiography re-

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vealed normal left ventricular size and function with no regional wall abnormalities.

The patient was volume resuscitated and commenced on oral phenoxybenzamine. Oral labetalol and nifedipine were then added to achieve a blood pressure of 100/60–120/80 mmHg, complicated by breakthrough hypertensive spells. The hemoglobin was 11.5 g/dl, and serum creatinine was 1.2 mg/dl. Despite breakthrough hypertension, surgery was scheduled because complete preoperative catecholamine blockade was unlikely given the tumor mass and the extreme catecholamine production.

### Intraoperative Management

After placement of routine monitors (as recommended by the American Society of Anesthesiologists) and adequate intravenous sedation, a thoracic epidural (T10-T11) was placed without hemodynamic consequence. General anesthesia was induced with propofol 2 mg/kg and fentanyl 10 μg/kg. Vecuronium 0.1 mg/kg was added for neuromuscular blockade (goal train-of-four ratio was less than 25%). The hemodynamic response to tracheal intubation was attenuated with esmolol 1 mg/kg (maximum blood pressure, 128/75 mmHg; maximum heart rate, 100 beats/min). Anesthesia was maintained with isoflurane in oxygen and titrated fentanyl. There was no epidural drug administration.

Invasive hemodynamic monitoring consisted of a left radial arterial line and a pulmonary arterial catheter (via the right internal jugular vein). The baseline hemodynamic profile was as follows: blood pressure 95/65 mmHg, heart rate 70 beats/min (sinus rhythm), central venous pressure 15 mmHg, pulmonary arterial pressure 25/16 mmHg, cardiac index 2.2 l/min/m², systemic vascular resistance 900–1000 dynes-cm⁻⁵, and mixed venous saturation 70% (FiO₂, 1.0).

Incision, dissection, and tumor manipulation were continuously associated with baseline mean arterial pressure and systemic vascular resistance. Close communication with the surgical team was maintained during the entire procedure. Intravascular volume expansion with crystalloid was titrated to the following goals: central venous pressure of 12–15 mmHg and urine output of at least 1 ml/kg⁻¹-h⁻¹. Blood loss was 0.2 l and crystalloid replacement was 6.0 l in total.

Systemic vascular resistance was maintained at 900–1200 dynes-s-cm⁻⁵ with the following agents: isoflurane (1.5–2.5%, end-tidal concentration), fentanyl (intraoperative total of 40 μg/kg), nicardipine infusion (2–4 mg/h), and labetalol (total 400 mg).

After tumor mobilization, all vasodilators were terminated in anticipation of tumor venous ligation. The patient was mechanically ventilated with pure oxygen, and scopolamine (0.4 mg) was administered for amnesia. Immediately after tumor venous ligation, profound vasoplegic shock developed. The blood pressure was 55/30 mmHg, and the systemic vascular resistance was 300–400 dynes-cm⁻⁵.

Despite aggressive intravascular volume expansion, norepinephrine (bolus of 50–100 μg; infusion of 10–30 μg/min) and epinephrine (bolus of 50–100 μg; infusion of 10–20 μg/min), the blood pressure only rose to 65/45 mmHg. The profound vasoplegia responded to bolus vasopressin in doses of 10–20 units. The blood pressure steadily increased to 90/60 mmHg, and the systemic vascular resistance increased to the low normal range of 800–900 dynes-cm⁻⁵. A vasopressin infusion at 0.1 units/min was added to maintain systemic vascular resistance.

After skin closure, the patient followed simple commands and had no focal neurologic deficit. His extremities were warm and his urine output greater than 1 ml/kg⁻¹-h⁻¹. The following infusions maintained his blood pressure of 90/55 mmHg and a systemic vascular resistance of 800–900 dynes-cm⁻⁵: norepinephrine 15 μg/min, epinephrine 4 μg/min, and vasopressin 0.1 units/min. The central venous pressure was 12 mmHg, and his cardiac index was 2.0–2.5 l/min/m².

### Postoperative Management

The patient was admitted to the intensive care unit. Tracheal extubation was performed 16 h later. The vasopressor infusions were gradually withdrawn over 24 h: epinephrine first, norepinephrine second, and vasopressin last. Patient-controlled epidural analgesia was begun thereafter. The patient was discharged from the intensive care unit within 48 h. The rest of the hospital stay was uneventful.

### Discussion

This case of massive pheochromocytoma illustrates a clinical approach to catecholamine blockade and catecholamine replacement at the appropriate stages of the procedure. An unusual feature of this case is the application of vasopressin to complete the pharmacologic support of vasomotor tone after tumor resection. Tan et al. recently described vasopressin in the treatment of catecholamine-resistant hypotension after resection of a pheochromocytoma that was complicated by significant intraoperative blood loss. The unique feature of our case is that vasopressin restored vascular tone after pheochromocytoma resection that was uncomplicated by hypovolemia. There was no significant blood loss in this case. Euvolemia was always maintained, as evidenced by a high normal central venous pressure and brisk urine output.

The main etiology of the catecholamine-resistant vasoplegia was the severe abrupt catecholamine deficiency induced on tumor removal. This was exaggerated because of the massive tumor catecholamine secretion. Aggressive exogenous catecholamine replacement did not restore vascular tone. Vasopressin provides an alternative pharmacologic route to reverse catecholamine-resistant vasoplegia. Vasopressin should be readily available as an adjunctive agent for vascular rescue, given that there is almost always a degree of catecholamine-tolerance after resection of a pheochromocytoma.

The ability of vasopressin to reverse catecholamine-resistant vasoplegia has also been described in vasodilatory shock associated with sepsis, insertion of ventilator-assist devices, cardiopulmonary bypass, and organ donation. Vasopressin levels in these types of vasodilatory shock are low. The mechanism of this deficiency is unclear, although several hypotheses have been proposed. The proposals include central depletion of neurohypophyseal stores, decreased stimulation of vasopressin release, and inhibition of vasopressin release. A possible explanation for vasopressin deficiency in our case may be the excessive circulating norepinephrine levels that are known to inhibit vasopressin release. Chronic increase of circulating norepinephrine would thus chronically inhibit vasopressin release and ultimately down-regulate neurohypophyseal vasopressin synthesis. Thus, after tumor removal, the neurohypophysis is unable to acutely release high levels of vasopressin.
of vasopressin to restore adequate vasopressin levels and restore vascular tone. This hypothesis requires further investigation, including serum vasopressin assays during the perioperative management of pheochromocytoma.

A limiting factor in this case was the persistent α-blockade because of phenoxybenzamine. Although phenoxybenzamine is the standard for preoperative α-blockade, its effects persist for 48 h postoperatively. Doxazosin may be a superior alternative to phenoxybenzamine because it is a specific alpha1-blocker with a shorter half-life: its effects disappear within 12 h postoperatively.15 Prys-Roberts and Farndon concluded that doxazosin was a safe and effective alternative to perioperative phenoxybenzamine.13 As experience with doxazosin increases, nonspecific long-acting α-blockade with phenoxybenzamine may no longer be the standard for preoperative preparation of pheochromocytoma.

A second limiting factor in this case was the lack of preoperative blockade of catecholamine synthesis with methyl-para-tyrosine, the competitive inhibitor of tyrosine hydroxylase.14 Tyrosine hydroxylase is the rate-limiting enzymatic step in endogenous catecholamine production. Synergistic preoperative therapy with methyl-para-tyrosine and α-blockade results in superior perioperative hemodynamic management.15 Although our preoperative protocol for pheochromocytoma typically includes this synergistic combination, this patient was better served with prompt tumor removal. The symptomatic profile of this giant tumor mandated urgent resection, allowing insufficient time to achieve perfect preoperative catecholamine blockade.

A third limiting factor in this case was the choice of labetalol for catecholamine blockade because its half-life of 4–6 h complicates the vasoplegia after tumor removal. Labetalol was chosen because it was part of the preoperative regimen that had achieved near adequate catecholamine blockade. The advantage of this choice was that intraoperative catecholamine excess was asymptomatic. Given that the postoperative vasoplegia lasted 24 h (four times the half-life of labetalol), labetalol was not a major factor in the profound vasoplegia after tumor removal.

In summary, this case highlights vasopressin for hemodynamic rescue in the management of vasoplegic shock after complicated resection of symptomatic pheochromocytoma. The anesthesiologist should have a low threshold to initiating therapy with vasopressin in this setting, especially when the vasoplegia is catecholamine-resistant and hypovolemia has been corrected.

References

ANAPHYLAXIS is one of the few remaining causes of mortality that is directly due to general anesthesia. It is particularly tragic when death occurs in American Society of Anesthesiologists class I and II patients undergoing elective procedures—despite all available treatment. The most important requirements in the treatment of anaphylaxis are prompt diagnosis and the maintenance of coronary and cerebral perfusion, but these can be difficult or even impossible to accomplish. In the case described, rapid diagnosis was made easier by the invasive monitoring and transesophageal echocardiography. Evidence has recently emerged for the use of vasopressin in cardiopulmonary resuscitation.1 In septic shock, the application of vasopressin in varying concentrations and combinations with other inotropic or vasoactive agents has resulted in conflicting conclusions.2–4 To our knowledge, we are the first to report the successful treatment of anaphylactic shock with vasopressin.

Case Report

A 59-yr-old woman with coronary artery disease was scheduled for minimally invasive direct coronary artery bypass grafting for her anterior descending artery stenosis (80%). Her arterial hypertension was well controlled with 2 × 40 mg propanolol, and she was taking 10 mg atorvastatin daily. She had undergone appendectomy as a child, hystereectomy in 1986, and adenectomy in 1993. Otherwise, her medical history was unremarkable, with no reports of drug or food allergies, hay fever, or bronchial asthma.

One hour before surgery, 40 mg propanolol and 7.5 mg midazolam were administered orally for premedication. General anesthesia was induced using 100 µg sufentanil, 10 mg midazolam, and 8 mg pancuronium and was maintained with 25 µg/h sufentanil. After intubation with a Univent endotracheal tube (Fuji Systems Corp., Tokyo, Japan), the patient was ventilated with sevoflurane in oxygen-air (inspiratory oxygen fraction, 0.5; tidal volume, 550 ml; 12 breaths/min; positive end-expiratory pressure, 5 cm H2O). Continuous monitoring included electrocardiography; monitoring of pulse, oxygen saturation, end-tidal carbon dioxide, invasive arterial blood pressure, and central venous pressure; and transesophageal echocardiography.

After induction, vital signs were stable, with a blood pressure of 130/70 mmHg, a heart rate of 70 beats/min, a central venous pressure of 11 mmHg, a pulse oxygen saturation of 99% and an end-tidal carbon dioxide of 32 mmHg.

After starting one-lung ventilation, the inspiratory oxygen fraction was increased to 0.7, and vital signs remained stable while the surgeon prepared the left internal mammary artery. To optimize cardiac preload, an infusion of succinylated gelatin solution (Gelifus®); molecular weight, 30,000 Da; Serumwerk Bernburg AG, Bernburg, Germany) was started. Less than 50 ml had been given when the patient’s blood pressure decreased suddenly to 50/25 mmHg, with a heart rate of 90 beats/min, an oxygen saturation of 96%, and an end-tidal carbon dioxide of 28 mmHg. Anaphylaxis was immediately suspected. Transesophageal echocardiography of transgastric mid short axis view showed a hyperkinetic empty left ventricle with a decrease in end-diastolic area without any signs of dyskinesia and without mechanical disturbance due to a surgical compression system. The diagnosis of distributive shock caused by anaphylaxis was made after excluding significant bleeding. There was neither an increase in airway pressure nor evidence of wheezing, urticaria, or erythema.

The gelatin solution was thought to be the trigger agent, and its infusion was stopped. Inspiratory oxygen fraction was increased to 1.0. Resuscitation included intravenous administration of 1000 ml hydroxyethyl starch, 10% (HAES-steril®; molecular weight, 200,000 Da; Fresenius Kabi, Bad Homburg, Germany), as well as repeated doses of 100 µg epinephrine (totalling 1.5 mg), norepinephrine with a maximum rate of 1 µg · kg⁻¹ · min⁻¹, and 1 g methylprednisolone via the central venous catheter. Twenty minutes after the beginning of the anaphylactic reaction, the patient’s blood pressure was 80/40 mmHg, her heart rate was 116 beats/min, and she still required increasing doses of vasopressor support. The decision was made to add a bolus of 2 U vasopressin (Pitressin®; Monarch Pharmaceuticals, Bristol, United Kingdom) via the central venous catheter. Within 5 min, the patient stabilized; after an additional 10 min, blood pressure and heart rate returned to normal (100/60 mmHg and 80 beats/min, respectively), while epinephrine and norepinephrine were discontinued (fig. 1). The patient was successfully extubated in the intensive care unit 2 h after completion of the minimally invasive direct coronary artery bypass grafting. Medical progress was uneventful, and the patient was discharged from the hospital 6 days later. During follow-up, skin testing for gelatin solution was performed: 1 ml of the gelatin solution was diluted in 100 ml normal saline. A positive response was produced in less than 15 min by 0.05 ml of this solution injected intracutaneously. The wheal was greater than 1 cm in diameter, and the flare approximated 2 cm.

The temporal sequence of events during anesthesia and the positive skin test later confirmed that the gelatin infusion caused the anaphylactic shock.

Discussion

The predominant reasons for acute cardiovascular collapse in anaphylaxis are vasodilatation and leakage of plasma from capillaries due to increased permeability. Although multiple mediators such as prostanoids, leukotrienes, and kinins can all promote vasodilatation, histamine seems to play a major role in the pathomechanism.5 The heart is not typically the primary target organ in most cases of anaphylaxis, and cardiac dysfunction is
usually related to underlying disease. The heart has histamine receptors and contains drug-specific immunoglobulin E. Cardiac abnormalities in anaphylaxis mediated by immunoglobulin E are more often due to underlying cardiac disease or the arrhythmogenic effects of epinephrine than the anaphylaxis itself. Stimulation of endothelial H1 receptors releases nitric oxide and prostacyclin. Blockade of the target enzyme of the nitric oxide pathway, guanylate cyclase with methylene blue, or use of vasopressin may represent additional therapeutic options in the treatment of anaphylactic shock.

Although questioned by some, standard therapy to reverse the vascular collapse in anaphylaxis is epinephrine, a catecholamine with both \( \alpha \)- and \( \beta \)-adrenergic effects. Epinephrine inhibits further vasodilating mediator release from basophils and mast cells, reduces bronchoconstriction, increases vascular tone, and improves cardiac output. Nevertheless, human studies on the utility of epinephrine in improving hemodynamic recovery from anaphylactic or anaphylactoid reactions have not been totally supportive. Furthermore, prospective studies to determine the best possible therapy to reverse the vascular collapse are nearly impossible because the occurrence of anaphylactic reactions is rare and unpredictable. Therefore, therapy with epinephrine remains empirical and may not always effectively reverse the vasodilation. Patients with ischemic heart disease are especially vulnerable to the undesired effects associated with epinephrine, e.g., increased myocardial oxygen consumption, ventricular arrhythmia, and myocardial dysfunction during the period after resuscitation. Individuals who use \( \beta \) blockers—as was the case in the current patient (and possibly angiotensin-converting-enzyme inhibitors, although such evidence is incomplete)—may not respond completely to epinephrine. This is in accordance with the observations from a retrospective survey on anaphylaxis during anesthesia in France. Of eight cases involving long-term treatment with \( \beta \) blockers, seven had a grade III anaphylactic reaction, and one had grade IV with cardiac arrest.

The current patient did not respond adequately to volume expansion and epinephrine infusions. To maintain cerebral and coronary perfusion pressure, we added norepinephrine at an increasing dosage (fig. 1). The use of vasopressin to treat shock is well established, and the use of vasopressin for resuscitation of septic and vasodilatory shock is not new and has been well studied. Anaphylaxis is one form of vasodilatory shock. Therefore, the application of vasopressin in such a situation seems to be logical. Vasopressin plays an important role in cardiovascular homeostasis through both its vasoactive and antidiuretic actions. In vitro studies have shown that epinephrine only partially reverses histamine-induced vasodilation in human internal mammary arteries, whereas vasopressin, methylene blue, and drugs involved in the inhibition of nitric oxide and prostaglandin generation lead to a complete reversal of the vascular relaxation. Vasopressin is also known to reduce heart rate, whereas epinephrine induces tachycardia that might be deleterious in patients with ischemic heart disease or aortic stenosis.

Our case report suggests that adding vasopressin to standard therapy should be considered as a potential therapeutic approach for mediator-induced vasodilatory shock, such as in anaphylactic/anaphylactoid reactions, especially when catecholamines do not restore vascular tone.

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Intraneural Injection during Anterior Approach for Sciatic Nerve Block

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DESPITE the technological advances in nerve approach and neurostimulation techniques, the percentage of nerve block procedure associated neuropathies has not decreased significantly. It is still between 1.7% and 1.9%.1,2 Use of nerve stimulation techniques do not guarantee avoidance of nerve puncture.3,4 Bearing these questions in mind, we devised a research protocol, which was approved by the Ethical Committee of our Hospital, in which we included a computerized tomographic (CT) scan examination with the aim of having better chances of avoiding vulnerable structures in the path of the needle from the skin to the nerve when using the anterior approach for sciatic nerve block. We describe two cases in which, after localizing the nerve with nerve stimulation, CT scanning revealed that the needle has been placed intraepineurally.

Case Report

A 75-year-old woman, 75 kg, 158 cm, American Society of Anesthesiologists physical status III having a history of noninsulin-dependent diabetes mellitus treated with oral hypoglycemic agents was scheduled for transmetatarsal amputation of the right foot because of a severe vasculopathy. The patient gave her written informed consent to perform a continuous sciatic nerve block using the anterior approach.3 A CT image confirmed possible access to the sciatic nerve along an anatomical path that avoided contact with other significant structures (fig. 1). After setting up a peripheral blood access line, administering oxygen at a rate of 4 l/min, sedating the patient with 1 mg of midazolam, and anesthetizing the injection site with 3 ml of 1% mepivacaine we inserted the 100 mm stimulation needle (Plexolong®; Pajunk GmbH, Geisingen, Germany). Final position of the needle tip was determined by nerve stimulation. Nerve stimulation (Stimuplex® HNS 11; B Braun Melsungen AG, Melsungen, Germany) performed at a frequency of 2 Hz and pulse duration of 300 μs. The initial stimulation current intensity was set at 1.5 mA, and the needle was advanced until we observed a plantar response. At this time, the initial stimulation current was set at 1.5 mA, and the needle was advanced until we observed a plantar response. At this time, the initial stimulation current was set at 1.5 mA, and the needle was advanced until we observed a plantar response.

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small bubble of entrapped air intraepineurally (fig. 2). Contrast medium showed along the entire 9.5-cm length of nerve explored (fig. 3). Normal flat nerve morphology before needle puncture changed to circular morphology after the injection (fig. 2). A catheter was inserted through the needle to a depth of 3 cm. A further dose of 10 ml of 1.5% mepivacaine mixed with 0.5 ml of iodine contrast medium was administered. Further scan sequences showed the catheter inside the epineurium (fig. 4). The catheter was left in place for 3 days after the surgical procedure to administer a continuous infusion of 0.2% ropi-
cases, stimulus duration of 300 μs was used and current intensity was varied. Minimal current intensities to produce motor responses in our patients were 0.3 mA (90 nC) and 0.56 mA (168 nC), which, according to the literature, are in the range of intensities used for infusion of the anesthetic near the nerve. Finally, a disappearance of muscular twitch with 2 ml of local anesthetic without inducing paresthesia or discomfort and the reappearance with increased voltage (negative Raj test) indicates correct performance of the technique. However, several tests confirmed that the nerve was punctured and that the anesthetic was actually administered intraepineurally in both patients. CT images showed contrast medium inside the nerve. The contrast occupied the interfascicular space, and the catheter inserted through the stimulator needle was positioned inside the nerve.

The fact that these two patients were diabetic should be taken into account. However, diabetic polyneuropathy would affect the excitability of distal more than proximal parts of the nerve. Therefore, a proximal approach to the sciatic nerve in a diabetic patient might not be expected to theoretically significantly alter the response to stimulation.

Nerve stimulation can induce specific motor responses. Nevertheless, because of the random distribution of nerve fibers into fascicles, the specific muscle group activated may vary among patients. Induction of specific movements may also be the consequence of selective stimulation of nerve fascicles if the needle has been placed intraneurally through the epineurium.

The structure of the sciatic nerve is different from other nerves. It has a thick, well-formed epineurium that covers two main nerve branches, the tibial and the peroneal nerves. These two nerves are functionally and structurally separate but share a common epineurium. These structural characteristics may explain why, for this specific nerve, to achieve nerve stimulation at the usual clinical intensities, the needle may have to go through the epineurium. As Vloka et al., injecting the anesthetic within the epineural adventitia causes the contrast medium to spread into the epineurium around the perineurium that surrounds the fascicles. This procedure is different from an “intrafascicular” injection, which could indeed induce nerve damage. Vloka et al. performed their studies in embalmed cadavers, in which the neural fascia might have suffered structural changes. This intraepineural adventitial administration explains the diffusion of the contrast medium observed in our two patients. The study by Reina et al. suggested that by inserting the needle into the epineurium of the sciatic nerve, nerve damage may occur because the fascicles can be "easily touched." However, the strong sheath of the perineurium is different from the loose tissue framework of the interfascicular epineurium. After puncture of the epineural adventitia the needle probably enters the nerve but separates the fascicles rather than punctures them. CT images showed that the local anesthetic diffused within the intraneural space as well as

Discussion

Several factors may contribute to postoperative nerve damage after performing peripheral nerve block anesthesia. Modern current nerve stimulators, such as those used in our case studies, allow for the more precise positioning of the needle electrodes and minimize the risk of errors resulting from a possible malfunction of the equipment during nerve stimulation. The electrical current applied to the nerve (electrical charge = nC) will depend on two settings controlled by the nerve stimulator: current intensity and duration of the stimulus (measured in mA and μs, respectively). In the above cases, stimulus duration of 300 μs was used and current intensity was varied. Minimal current intensities to produce motor responses in our patients were 0.3 mA

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outside the epineurum. This may be the result of a partial administration of the anesthetic inside and outside because of needle displacement or of the retrograde flow from intraneural space.

The two cases described here demonstrate that, when using a nerve stimulation guided approach, puncture of the sciatic nerve can occur and the local anesthetic can be injected intraneurally (inside the epineurium). Although such procedure did not induce any noticeable nerve damage in the reported patients, intraneural administration of local anesthetic should be avoided. More extensive studies on the sciatic nerve as well as other peripheral nerves are indicated to improve our understanding of this phenomenon.

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