proved by optimization of such factors as temperature and carrier gas.

Along with the capillary column, many packed columns were tested under turbulent conditions; most were "inert" (nonretentive) glass-bead columns designed to help unravel the underlying phenomena. They included, however, three "active" gas-solid columns. Fig. 3 shows three relevant curves, all passing through a maximum; the top two apply to an "active" 50-foot (15.2-m) column packed with NaI-coated alumina particles of diameter $d_p = 0.38$ mm; the top curve, involving the retained peak propane, lies well above the middle plot for unretained methane.

This finding and the weakness of the maximum suggest that adsorption-desorption processes here limit efficiency of the column, thus masking the advantages of turbulence. The true potential of turbulent flow in packed columns is perhaps best illustrated by the bottom curve, applying to 0.51-mm glass beads in a 15.2-m column; h reaches a maximum of only 2.2 and then falls to 0.9; at 145 atm at the inlet, methane is eluted in 4.8 seconds with 18,000 plates, thus giving 3800 plates per second.

Theoretical interpretation of turbulence in packed columns is complicated by the fact that the coupling phenomenon (*4, 9*) (a consequence of flow-diffusion interactions) also reduces plate height at high velocities; both act gradually—not discontinuously as in capillaries. The two effects have not yet been unscrambled, but undoubtedly both are beneficial. The magnitude of their combined influence is shown in Fig. 3 by comparison with the shaded area representing the performance range of columns when one assumes classical theory—that is, without turbulence or coupling. The classical range pertains very roughly to all three systems shown. The reduction in plate height, caused by turbulent and coupling effects, is clearly significant.

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8 August 1966

Silicone Rubber: A New Diffusion Property Useful for General Anesthesia

Abstract. *Ether, nitrous oxide, halothane, and cyclopropane diffuse through silicone rubber. General anesthesia can be produced in dogs by passing the vapors of any of these anesthetic agents through a coil of silicone rubber tubing, each end of which is placed in an artery and vein. Potential applications include a new method for general anesthesia and a simple accurate vaporizer for halothane.*

We have found that the four most commonly used anesthetic agents, ether, nitrous oxide, halothane and cyclopropane, diffuse through silicone rubber. This observation was made after several kinds of tubing used for perfusion of organs were flushed with ether. Only the silicone rubber tubing continued to smell of ether 1 hour after it was dry. This indicated that ether had diffused across the wall of the tube. One milliliter of ether was then placed in a silicone rubber tube and sealed at each end with a paper clip. When the tube was placed on a Mettler balance, weight was lost from the tube at a constant rate because of vaporization of ether from the surface. When the supply of ether was depleted the tube collapsed, an indication that the diffusion of air into the tube was much slower than the diffusion of ether out of it. The tube did not re-expand until over an hour later.

When tubes of varying thickness and length were filled with ether and occluded at both ends, the rate of transfer of ether through silicone rubber was directly proportional to surface area, and inversely proportional to thickness. Moreover, increasing the wall thickness introduced a latent period of diffusion (Fig. 1). Weight loss did not occur until ether had reached the outside surface. Thus, for a tube with a 0.5 mm wall, weight loss began almost immediately, and peak diffusion rate reached 4.1 mg/cm^2 per minute. For a tube 1.5 mm thick, the weight loss did not begin for approximately 5 minutes and then the diffusion rate reached a peak of only 0.85 mg of ether/cm^2 per minute.

Silicone rubber tubing is inert when implanted in the body. Such tubes have been permanently inserted from the radial artery to a suitable vein in the same arm in patients with renal failure (*1*). This bypass is then opened whenever the patient requires hemodialysis from an artificial kidney to enable his blood to flow through a dialysis coil. We placed such a shunt from the femoral artery to the femoral vein in heparinized dogs (30 kg). To allow catheterization of the femoral vessels, the dogs were anesthetized briefly with pentothal and then allowed to wake up gradually so that the ether anesthesia could be tested. The silicone rubber tubing used was 12 cm long. When the tubing was dipped into ether, ether vapor was expired in the alveolar air after 6 minutes; this caused hemolysis. Therefore, ether vapor alone was passed over the tube, and ether appeared in the expired air in 6 minutes; there was no hemolysis. This short length of tubing did not admit enough ether to produce general anesthesia. However, by increasing the length of the tubing through which the blood flowed, deeper levels of anesthesia were reached. When tubing of 5.0 mm outside diameter (OD) and 1.0 mm wall thickness was exposed to ether vapor, a small coil (Fig. 2) made from 450 cm of tubing produced deep surgical anesthesia in these large dogs. (Shorter lengths of tubing could be substituted when thinner tubing was used.) Any level of anesthesia could be obtained simply by exposing more or less of the coil to 100 percent ether or by exposing

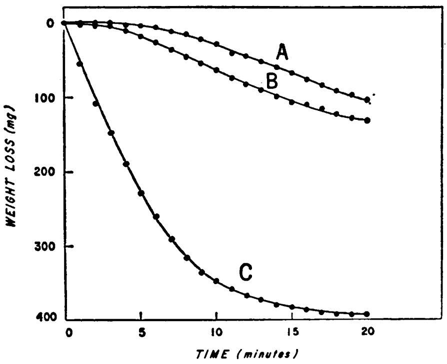

Fig. 1. Effect of wall thickness on diffusion rate of ether through silicone rubber tubes. Approximately 0.5 ml of ether was added to each tube. The surface area of each tube was 9.42 cm^2. Temperature was 20 C°. Weight loss from the thickest tube did not begin for approximately 5 minutes, an indication of the time necessary for ether to diffuse to the outer surface. *A*, 1.5 mm thick; *B*, 1.0 mm thick; *C*, 0.5 mm thick.

the entire coil to varying concentrations of ether vapor. There was no hemolysis or other abnormality even after 8 hours of anesthesia. Halothane vapor and cyclopropane gas also entered the blood when passed over the coil, and surgical anesthesia was then produced. Nitrous oxide also diffused into the blood through the silicone rubber coil, producing only light anesthesia. If an endotracheal tube was inserted and a re-breathing system was used, shorter lengths of coil with shorter exposures to the anesthetic vapor could be used.

A silicone rubber tube, 4.0 mm OD and 2.0 mm ID, was sealed at one end with silicone-rubber cement. It was then pierced with multiple holes, 0.1 mm in diameter. The tube was coated with a silicone rubber membrane approximately 0.002 inch thick. This tube was inserted into the femoral vein of the dogs for a distance of 30 cm, in the same manner that an intravenous catheter is inserted into the anticubital vein of a patient to record venous pressure. (The tube was rigid enough to prevent collapse.) At the other end of the tube was a syringe with a three-way stopcock attached to an aneroid manometer and to a tube leading to a tank of cyclopropane (Fig. 3). Air was aspirated from the tube and replaced with a flow of 100 percent cyclopropane. As the pressure approached 20 to 40 mm-Hg, cyclopropane diffused from the tube and was carried away by the venous blood. If the cyclopropane was turned off at this point, the pressure fell until a vacuum registered on the manometer, indicating that air could not replace the cyclopropane which had diffused from the tube. Although this tube permitted the continuous diffusion of cyclopropane into the blood stream, we could not obtain anesthesia that was deep enough for surgery.

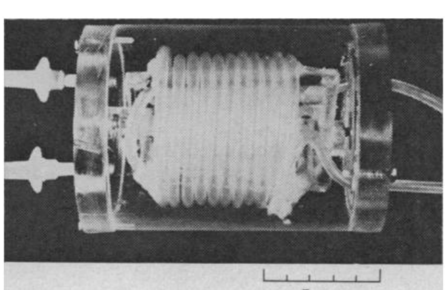

Fig. 2. Silicone rubber coil in plexiglass cylinder. Blood enters the coil on the right and anesthetic gases are introduced into the cylinder on the left.

We have previously reported (*2*) that triiodothyronine, isoproterenol, and digitoxin will pass through implanted silicone rubber capsules. Since then, others have shown that histamine and atropine, (*3*) antimalarial agents, (*4*) and steroids and alcohol (*5*) will pass through silicone rubber. However, nothing has yet been reported on the use of silicone rubber tubing to transmit anesthetic vapors and gases. This phenomenon suggests some new directions in the science of anesthesia in that any of the anesthetic gases or vapors may in the future be given by vein. Modern anesthesia techniques require that the concentration of anesthetic be limited to allow space for oxygen, as both must be administered together through the lungs. It is conceivable that with two separate ports one may in the future administer 100 percent anesthetic gas through the blood stream, and up to 100 percent oxygen through the lungs.

The arteriovenous shunt method might be useful for a burned patient. One could use an arteriovenous silicone bypass in the arm, with a three-way stopcock to keep a route open for plasma administration. Anesthesia for dressings or skin grafts could be given at any time during the succeeding weeks by inserting a suitable coil or a miniature silicone membrane prosthesis into the shunt. This could then be exposed to any of the anesthetic vapors. For sedation and caloric intake, one might conceivably expose the shunt to ethyl alcohol.

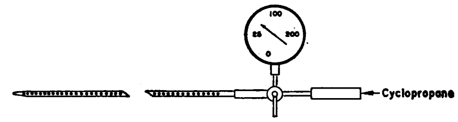

Fig. 3. Silicone rubber tubing for diffusion of cyclopropane into a vein. The tube is 40 cm long and the holes extend for a distance of 30 cm from the occluded end.

At the moment, the single intravenous tube will not allow enough diffusion to reach deep levels of anesthesia. If a tube that will allow sufficient diffusion can be perfected, more potent anesthetic gases might be administered more safely through the vein. This might be very useful in pediatric and thoracic cases, and under military conditions. Clotting would not be a problem with the single intravenous catheter. It might even be avoided in the arteriovenous coil by coating the inner wall of the silicone rubber tubing with anticoagulants (*6*).

Another possible application of this new diffusion property would be in the vaporization of halothane. A simple and accurate halothane vaporizer could be made from a coil of silicone rubber tubing. When oxygen is blown through the lumen it will pick up increasing concentrations of halothane vapor as the coil is dipped deeper into liquid halothane.

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