The Safety of Hydrogen in Shunt Detection

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General Considerations

Numerous reports confirm the unequivocally superior sensitivity of hydrogen gas as used electrometrically for the detection of both left-to-right and right-to-left circulatory shunts when the aberrant flow is not clearly definable by oxygen studies.\textsuperscript{1–8} When used according to any one of the several described methods, in addition to superior sensitivity and immediate recognition of a shunt, it offers reduced complexity of procedure and interpretation and much greater economy than other agents and methods. No special equipment is needed beyond a platinum-tipped or coated electrode catheter, a conventional anesthesia mask-bag-valve, and a $6.00 tank of industrial hydrogen with reducing valve. This quantity of gas is sufficient to permit the recording of several thousand diagnostic curves. For the identification of right-to-left shunts, instead of the anesthetic mask-bag-valve, we have utilized hydrogenated ascorbic acid\textsuperscript{9} and measured its arrival time in the arterial periphery by means of a platinized tip within an artery to which a second electrocardiographic preamplifier is attached.

Wider acceptance of the manifold advantages of hydrogen technics, especially when combined with oximetry for the purpose of quantitation, has been delayed by an understandable reluctance to introduce an explosive gas into the diagnostic laboratory. In an excellent review of the method and results of one facet of its use, Hugenholtz et al. stated, "The danger of explosion inherent in the handling of hydrogen and the hazards of an intracardiac electrode may have precluded its general acceptance thus far."\textsuperscript{6}

The danger in using an intracardiac electrode for hydrogen sensing is certainly no greater than that inherent in the utilization of ascorbic acid for shunt detection. Such risk is considered extremely remote, if indeed it does actually exist, provided the patient and all apparatus to which he is connected are attached to a common ground\textsuperscript{5, 8–11} and provided a good quality conventional electrocardiographic preamplifier with capacitance-coupled input stage is attached to the intracardiac electrode. It is of course basic that all equipment be provided with an isolation transformer.

The risk in using an explosive gas, however, is less readily dismissed. Since hydrogen and air mixtures ranging from 4.1 to 74.2 per cent hydrogen are explosive,\textsuperscript{12} its use in a hospital carries the implied requirement of conformity to The Code for Use of Flammable Anesthetics.\textsuperscript{13} This would mean, in addition to multiple other requirements, that for greatest safety all electrical apparatus used in cardiac catheterization should be explosion-proof. Usually, this is quite impracticable. Yet those who have been experienced in the use of hydrogen have stated that when hydrogen is used, the same precautions should be observed as with any flammable anesthetic gas.\textsuperscript{5, 14} Perhaps they, as we, were impressed with the recommendation of The National Fire Protection Association that when hydrogen is used within a closed building, there should be no ordinary electrical equipment within 25 feet of the gas and it should be at least 50 feet away from any air-conditioning equipment.\textsuperscript{15} Elsewhere emphasis has been

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placed on the necessity for allowing sufficient time to elapse between hydrogen inhalations to permit its dispersion. Others have discussed its use without reference to a potential danger.\textsuperscript{3,4} It was therefore decided further to delineate the exact nature of the hydrogen hazard involved when this gas is employed in the cardiac catheterization laboratory for the detection of shunts and to define more clearly the extent of danger.

**Materials and Methods**

Initial tests were conducted during routine cardiac catheterizations and are cited as clinical observations. Subsequent determinations were made in an artificial setting deliberately aimed at testing the relative safety in using hydrogen under extremely adverse circumstances. These findings are cited as experimental studies.

**Clinical Observations**

Twenty patients, 10 children and 10 adults, ranging from 2 to 28 years of age were given repeated single inhalations of hydrogen from a 5-liter rubber anesthetic bag in the catheterization laboratory. The gas was transferred from a standard 173-ft.\textsuperscript{3} cylinder of industrial hydrogen. This larger tank was preferred over smaller tanks because in its portable stand it is more secure against falling or slipping when its valves are opened and closed. The mask was applied to the patient’s face and at a given recorded manual signal, the integral 2-way valve was opened. This exchanged hydrogen for air at the beginning of inspiration. The valve was closed at the height of inspiration. At least eight different samples of the resultant hydrogen-air mixture were taken at 2-inch distances laterally and above each patient’s mouth during initial and subsequent exhalations until only trace concentrations were recorded. Samples were trapped in an inverted plastic cup having a volume of 35 in.\textsuperscript{3}. This in turn was attached to a conventional Hydrogen Explosimeter, Model 3* (fig. 1). This is the instrument used to evaluate the risk imposed by the generation of hydrogen in the charging of submarine batteries.

The MSA Explosimeter is basically a Wheatstone bridge, one leg of which is a platinum filament. An aspirator bulb draws the sample of hydrogen-air into a detection chamber where it is burned on the platinum filament. The additional heat that is generated alters the resistance of this leg of the bridge and the degree of imbalance that results is proportional to the concentration of hydrogen in the air specimen tested. This value is read on an indicating meter as 0 to 4.1 per cent, the latter figure being the lower explosive limit of hydrogen in air.\textsuperscript{12}

For the clinical observations, an ordinary breath of hydrogen was used. This was adequate to cause a prominent change in the baseline of the intracavity electrocardiogram as recorded in the wedge position of the lung and right pulmonary artery of a normal patient (fig. 2). On 18 occasions, a sedated but cooperative patient was asked to “take a deep breath” after the hydrogen valve had been opened, especially if previous breathing had been erratic. The results in these instances were included in the 288 expiratory concentrations measured. Usually three consecutive meter readings were taken at 5- to 10-second intervals but occasionally only two were recorded.

Patients were studied in a fasting state and

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under mild premedication from which they could be readily aroused. With an occasional child who would not tolerate the physical contact of the face mask, it was held as close as possible to the face and the hydrogen bag was compressed during a normal inspiration as signaled by the respiratory tracing. This procedure also permitted the recording of satisfactory curves. In these instances, aspiration bulbs were used to draw in samples below the level of the mouth.

**Experimental Studies**

Repeated hydrogen inhalations were performed by 12 cooperative subjects in a carefully closed and unventilated 1,400-ft.\(^3\) room with a ceiling 10 feet high. The subjects' inspiratory volumes were purposely varied from "normal" to 5,000 ml. of hydrogen, the latter by trained divers. At least six serial samples of the resultant hydrogen-air mixture were taken at 2-inch distances above, lateral, and below the mouth of each patient during the initial and each subsequent exhalation until trace concentrations were recorded. Samples of hydrogen were also tested in the vicinity of each patient's mouth after forceful compression of the gas from the bag in the manner described by Hugenholtz et al.\(^6\) The tank of hydrogen with which the breathing bag was filled was kept in the same room in order to avoid dispersive drafts. In this room, because of a nonconductive floor, the assistant handling the hydrogen bag touched the skin of the patient each time prior to the inhalation of hydrogen in order to neutralize any possible static charge. The mean room temperature was 75 degrees; the humidity was 72 per cent.

Subsequently, to evaluate the relative concentration of hydrogen at upper room levels, 150 liters of hydrogen were released in 5-liter increments from the patient level into the atmosphere during a 4-minute period, and samples were tested for an explosive concentration at 6-inch levels from the 10-foot ceiling downward. Thereafter, 200 liters of hydrogen
were released during a 5-minute period under the same circumstances after the room had been aired. Finally, after 5-liter ejections of hydrogen directed toward the ceiling, the nature and extent of the resultant explosion zone were actually tested with an acetylene igniter (sparking device).

Results

Clinical Observations in the Catheterization Laboratory

The average hydrogen concentrations in air as measured at variable distances and times following the onset of hydrogen-air expiration are recorded in Table 1 and a graphic representation of the maximal zone of risk induced is shown in Figure 3. It is thus apparent that the zone of risk did not extend more than 12 inches above the patient's mouth or exceed 4 inches in any lateral direction from his mouth.

These maximal measurements were taken with adult patients. The variations encountered from one patient to another were understandably dependent on the quantity of gas inhaled and the force of the air-hydrogen exhalations. In general, contracted explosion zones were found in children which correlated well with their lesser tidal volumes. When, under the most extreme circumstances, hydrogen was forcibly expressed downward from the anesthetic bag without touching the face of the patient after the manner of Hugenholz et al., an explosive concentration was never encountered at a depth greater than 4 inches below the level of the patient's mouth, more than 6 inches in any lateral direction and more than 10 inches directly above the point of release.

Experimental Studies in 1,400-ft.³ Unventilated Room

Under conditions of normal consciousness and normal breathing, the duration and ex-

Table 1

Mean Percentage Concentrations of Hydrogen in Air After an Ordinary Breath of Hydrogen

<table>
<thead>
<tr>
<th>Distance above mouth in inches</th>
<th>Time in seconds beginning with onset of exhalation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>Expl</td>
</tr>
<tr>
<td>6</td>
<td>Expl</td>
</tr>
<tr>
<td>10</td>
<td>Expl</td>
</tr>
<tr>
<td>12</td>
<td>3.4 ± 0.6</td>
</tr>
<tr>
<td>14</td>
<td>2.4 ± 0.6</td>
</tr>
<tr>
<td>20</td>
<td>1.3 ± 0.7</td>
</tr>
</tbody>
</table>

Samples were collected and tested at points directly over the mouths of 10 adult patients at distances and time intervals as indicated. Expl, explosive hydrogen in air concentrations; Tr, trace only of hydrogen in air.
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tent of the explosion zone did not differ significantly from that observed in the cardiac catheterization laboratory. Therefore, in an attempt to define the maximal possible limits of an explosive zone in terms of duration and extent, six cooperative, robust, adult underwater divers repeatedly inhaled the full 5-liter bagful of hydrogen in a single breath and, again, serial determinations of the concentrations of the exhaled mixtures were recorded. The difference between the potential explosion zone in the catheterization laboratory under resting conditions in adults and in an artificial setting under extreme conditions with 5,000-ml. inhalations of hydrogen is depicted in figure 4. Even with forceful exhalation and with the subject turning his head to the side, explosive concentrations could be recorded for only 25 seconds at distances not exceeding 18 inches laterally and 30 inches directly over the mouth.

When checked with an acetylene igniter, hydrogen, which was forcefully ejected toward the ceiling, ignited in a flame that returned to the anesthetic bag at distances up to 30 inches but not beyond. Between 30 and 36 inches, occasionally a pale transient flame was produced which did not return to the source of hydrogen ejection.

Five liters of hydrogen released from a 40-inch level in an upward direction arrived at the ceiling after 3 seconds where it registered 0.7 per cent. A measurable concentration persisted for approximately 6 seconds. Following the direct release of 150 liters of hydrogen in 4 minutes the maximum hydrogen concentration reached at the ceiling was 1.6 per cent directly overhead. The corresponding value after the release of 200 liters of hydrogen in 5 minutes was 1.8 per cent. Therefore overhead conventional electrical apparatus (incandescent lights) did not constitute an explosive hazard under the extreme conditions imposed in the small, unventilated room used.

**Discussion**

It came as a distinct surprise that the zones of flammability of exhaled hydrogen both in the cardiac catheterization laboratory and in a small, unventilated room with 5-liter inhalations of the gas were so limited in extent and duration. Although the potential explosion hazard of exhaled hydrogen is definite in the zones defined, it is transient, lasting no longer than 25 seconds following inhalation. When compared with the heavier combustible anesthetic gases, the hazard involved in this type of use is relatively small because hydrogen is a hypobaric gas which rapidly rises in air like a cork in water. At no time, however, because of its diffusion, was a dangerous concentration reached at ceiling level. Taking the density of air as one, the density of hydrogen is 0.07. The next lightest anesthetic gas, ethylene, has a density of 0.97 while all other explosive anesthetic gases and mixtures are considerably heavier than air. Ether vapor, for example, has a density of 2.41. Thus, an oxygen-ether mixture tends to become concentrated and to remain for long periods in every concavity or level below which the ether is vaporized. By contrast, hydrogen because of its small molecular size and lightness, diffuses and rises with extreme rapidity into the surrounding atmosphere. Even in an “air tight” rubber-topped container, it is difficult to keep

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**Figure 4**

Zone A: Maximum danger zone in patients studied following an ordinary breath of hydrogen. Zone B: Maximum danger zone induced after inspiring 5,000 ml. of hydrogen followed by forcible upward exhalation.

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hydrogenated ascorbic acid under a positive pressure of hydrogen. On the other hand, explosive gases which are heavier than air will remain for long periods within concave enclosures which are semipermeable to air.16

Summary

The hazards of hydrogen as used for the detection of shunts has been studied under clinical conditions with the Standard Mine Safety Appliance Explosimeter and under additional simulated circumstances far more extreme than would ever be encountered in a catheterization laboratory. Because of the lightness of the gas and its ready diffusibility, explosive concentrations were transiently identified in small zones that were grossly different from those reportedly associated with "heavier than air" explosive gases. With its use in single inhalations for the identification of an intracardiac shunt and with allowances for a liberal safety factor, no explosive risk exists outside a conical envelope, which may be considered to extend 3 feet above, 6 inches below, and 12 inches laterally in all directions from the patient's mouth. Ordinary electronic apparatus, motor-driven syringes, and x-ray equipment, provided they are commonly grounded and outside this zone, require no explosive safety precautions in their use when hydrogen is used in this manner for shunt detection. Room ventilation is desirable for personal comfort but should not be considered a safety requirement. Release of large quantities of hydrogen has shown that there is no reason to specify a time interval between inhalations for the dispersion of hydrogen.

These conclusions are not intended to be mean those measures that are routinely followed to avoid the generation of static electricity.16 But were a spark generated, it would be of no significance unless it occurred in the restricted zone described.

References


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