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Fetal and maternal bubbles detected noninvasively in sheep and goats following hyperbaric decompression

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Powell MR, Smith MT. Fetal and maternal bubbles detected noninvasively in sheep and goats following hyperbaric decompression. Undersea Biomed Res 1985; 12(1):59–67.—Pregnant sheep and goats were compressed with air to an equivalent depth of 49 msw (160 fsw) for bottom times ranging from 5 to 15 min. Maternal (precordial) and fetal (umbilical artery) circulation were monitored transcutaneously with a Doppler ultrasound flowmeter to determine the presence of decompression gas bubbles. It was found that the number of bubbles detected precordially in the maternal circulation exceeded the number detected in the fetal umbilical artery for any given bottom line. Additionally, bubbles were found in the fetal circulation even when the mother did not display signs of decompression sickness. Thus, avoidance of symptoms of pain-only decompression sickness in the mother is not sufficient to preclude gas phase formation in the fetus.

Doppler ultrasound — decompression sickness
goats — sheep
bubbles — fetus
pregnancy

In the last decade, it has become increasingly important to investigate problems of physiology particular to women since many are now occupying jobs and partaking of activities once occupied mainly by men. Regrettably, little is known about the effects of decompression and hyperbaric stress upon women. It is apparent that these factors should be investigated to determine any precautions that need to be made for women who are preganant.

Increasing numbers of women are entering the labor force as professional divers in addition to sport divers and those who dive for research purposes. Pregnant airline passengers and the effect of rapid cabin decompression are also of concern; what should be an appropriate course of action?

In the fetus, the pulmonary filter is not functioning, and bubbles, generated by either fetal tissue or placental tissue, will pass through the foramen ovale into the fetal arterial circulation from whence they can proceed to embolize organs, the cord, and the brain.

Despite recent interest in the effects of hyperbaric stress on women, few studies have been done. Bangasser (1) and Bolton (2) have made statistical studies of women who dive while pregnant, but their samples were relatively small and the studies were retrospective. Bolton's study indicated an increased number of congenital malformations among divers compared to her nondiving controls. The problems reported included mutiple hemivertebrae, congenital absence of a hand, hairy birthmark, hypertrophic pyloric stenosis, ventricular septal defect, and possible coarctation of the aorta. Although high, the occurrence rate of these problems was within the normal range for the population as a whole.

Boycott et al. (3) conducted the earliest study on the effects of diving during pregnancy and published the results of their observations with pregnant ewes. They noted that intravascular bubbles were present at autopsy after dives to 52 meters of sea water (msw) with bottom times ranging from 15 to 240 min. When the fetus was young and less than 4 inches in length, they concluded that it had too active a circulation and too small a bulk to develop bubbles. They also found that there were no bubbles at autopsy even in an advanced fetus if the exposure lasted for 15 min or less at this depth. Within these time and depth restrictions, they concluded that there was no more risk to the fetus than to the mother. If only a limited number of fetal bubbles were present shortly after decompression, however, these could easily be missed at autopsy (typically conducted 0.5 to 1 h later). Because women were not engaged in diving until relatively recently, further research in the first half of the century was not conducted.

A study by Bolton and Alamo (4) indicated that exposing pregnant rats to decompression does not affect fetal health or survival. In the fixed fetuses, minor visceral abnormalities were noted in 16.3%, but this was not significantly different from the controls. There was no correlation between decompression stress (bends score) in the mother and such variables as number of absorptions, number of dead fetuses, mean fetal weight, and malformation, when compared to the nondived controls. The mothers made only one dive and decompression.

McIver (5) exposed 28 pregnant dogs to a simulated depth of 51 msw. At autospy, all 28 of the adult dogs presented numerous disseminated intravascular bubbles. Bubbles were seen in the coronary arteries of 2 of the 94 fetuses of the first group (1 h at pressure) and 2 of 99 fetuses of the second group (2 h at pressure); however, no bubbles were seen in the other vessels. All fetuses survived the dives, although bubbles were found in the amniotic fluid surrounding them. In another dive series, McIver (5) exposed 28 newborn pups to the same simulated depth of 51 msw for 60 min and noted that 8 showed numerous bubbles throughout the vascular system.

Chen (6) reported another instance of apparent fetal resistance to decompression sickness in that the fetuses of anesthetized pregnant rats did not show intravascular bubbles, even in cases where the mother developed fatal decompression sickness. Thus, both these studies suggested the fetus was more resistant than the mother to decompression sickness, which has evoked the conclusion among many that the fetus is not at risk as long as the mother herself does not develop problems of decompression sickness.

Fife et al. (7) instrumented 7 pregnant sheep by means of Doppler cuff-type transducers around one maternal jugular vein and around one fetal umbilical artery. The conclusion from 17 simulated air dives was that the fetus is at more risk than the mother in terms of decompression bubble formation.

Two problems in Fife's procedure lead to reservations concerning the results of his study. First, it is our experience that monitoring the maternal circulation by means of a Doppler probe placed only on the jugular vein gives a poor indication of the gross, whole body bubble formation in sheep. A better indicator is a precordial ultrasonic probe placed over the pulmonary artery. The second problem is that Doppler probes were surgically placed around the umbilical cord and this seems to have induced artifacts.

Stock et al. (8) performed simulated no-decompression dives to 18.5 and 31 msw using 12 near-term sheep carrrying 16 fetuses. Of the 6 *surgically prepared* fetuses that were dived to

31 msw, 5 died within 20 min of ascent and severe cardiac arrhythmias were found in the 6th. Considerable numbers of gas bubbles in the arterial system and heart were noted at autopsy in all fetuses. Five mothers and fetuses were dived to 100 ft *without surgical manipulation,* 2 were alive 3 h later and no bubbles were present at autopsy (note, however, the 3-h time delay between autospy and the dive). Three were born alive at term.

In the 18.5 msw dive series, 3 fetuses were subjected to *surgery* and all suffered massive cavitation postdecompression. Two fetuses were dived to the same depth *without surgery;* 1 was alive 3 h later (then subjected to autopsy) and another was born alive at term. On the basis of these experiments, it was concluded that surgery for Doppler ultrasound probe placement resulted in the formation of postdive decompression bubbles that would otherwise not have appeared.

Although surgical intervention and its possible provocative effects on bubble formation were eliminated, observation at autopsy, *3 h later,* was considerably too late for easy detection of decompression-generated bubbles.

We wanted the ultrasound monitoring to answer two questions:

1. Did the fetus produce bubbles in dives that did not result in decompression sickness for the mother?
2. If fetal bubbles were produced, were there more or less than for the mother?

METHODS

Domestic goats and sheep purchased locally were used as subjects; a total of 20 dives were made. Two goats (one at approximately the middle of the second trimester, the second in the early third trimester) were used extensively and dived on a series of titrated profiles. In the entire series, a total of 6 young were born.

All simulated dives were conducted in a chamber using air as the compression gas. All compressions and decompressions were made at the standard rate employed by divers, i.e., 0.31 m/s (1 ft/s). The time spent at maximum pressure (bottom time) is indicated in Table 1. All dives were made to a simulated depth of 49 msw.

All subjects were unanesthetized and free-standing during the measurements to allow for the assessment of decompression sickness. In quadrupeds, this manifests itself first as rocking from side to side indicating discomfort in the limbs (Type I decompression sickness). More severe forms (Type II) are evidenced by the inability of the animal to stand or by frank convulsions (indicative of cerebral gas embolism).

Noninvasive Doppler ultrasonic techniques were employed to monitor the mother and fetus for postdecompression gas bubble formation. A 5 cm focusing, 5 MHz continuous wave Doppler ultrasound bubble detector was used and measurements were made at the maternal precordial region and from the umbilical artery and vein of the fetus and analyzed visually by means of bidirectional on-line spectral analysis. This sytem displays (Fig. 1) in video format the frequency spectrum of bidirectional Doppler flow signals utilizing a microprocessor single-board computer and fast Fourier transform with a 5 ms updating time (SONACOLOR, Carolina Medical Electronics). This system allows an easy differentiation of maternal and fetal blood flow signals. Maternal blood flow signals were confirmed by comparison with the maternal ECG. Fetal aortic flow signals could rarely be detected; umbilical signals were used exclusively for this study and were confirmed by wave form (9). Monitoring was done for 1 h postdecompression.

TABLE 1
SUMMARY OF SIMULATED DIVE EXPOSURES

Dive	Gestation Fraction	Dive, msw/min	Maternal Grade	Result or Comment	Fetal Grade
	"Marguette" (sheep)				
1	0.94	49/10	IV	treat @ 49 msw O_2	N.A.
2	0.96	49/10	IV	O.K.	N.A.
3	0.96	49/12.5	IVb	O.K.	N.A.
	1.00	Delivered normal lamb, #3 + 5 d*			
	"Bandet" (sheep)				
4	0.96	49/12.5	II	O.K.	(F)I
5	0.98	49//12.5	III	O.K.	(F)II
6	0.99	49/15	IVb	treat @ 18.5 msw on O_2	(F)V
	1.00	Delivered lamb with mild hind leg paralysis, #6 + 2 d			
	"Nanny" (goat)				
7	0.57	49/5	0	O.K.	0
8	0.61	49/7.5	I	O.K.	0
9	0.62	49/10	IV	O.K.	(F)IV
10	0.63	49/7.5	0	O.K.	(F)I
11	0.64	49/10	III	O.K.	(F)I
12	0.64	49/12.5	IV	O.K.	(F)II
13	0.67	49/12.5	III–IV	O.K. (twins detected)	(F)I; 0
14	0.68	49/15	IV	treat @ 18.5 msw on O_2	(F)III
15	0.69	49/10	III	O.K.	(F)I
16	0.69	49/12	IV	O.K.	
	1.00	Delivered 3 kids (a, b, c)		a. normal b. normal c. weak front & hind limbs; died after 2 d, apparent respiratory condition	
	"Ninny" (goat)				
17	0.71	49/5	0	O.K.	0
18	0.71	49/7.5	I	O.K.	0
19	0.72	49/10	III	O.K.	(F)I–II
20	0.74	49/12.5	III	O.K.	(F)II
	1.00	Delivered normal kid			

*#3 + 5 d is 5 days after dive #3

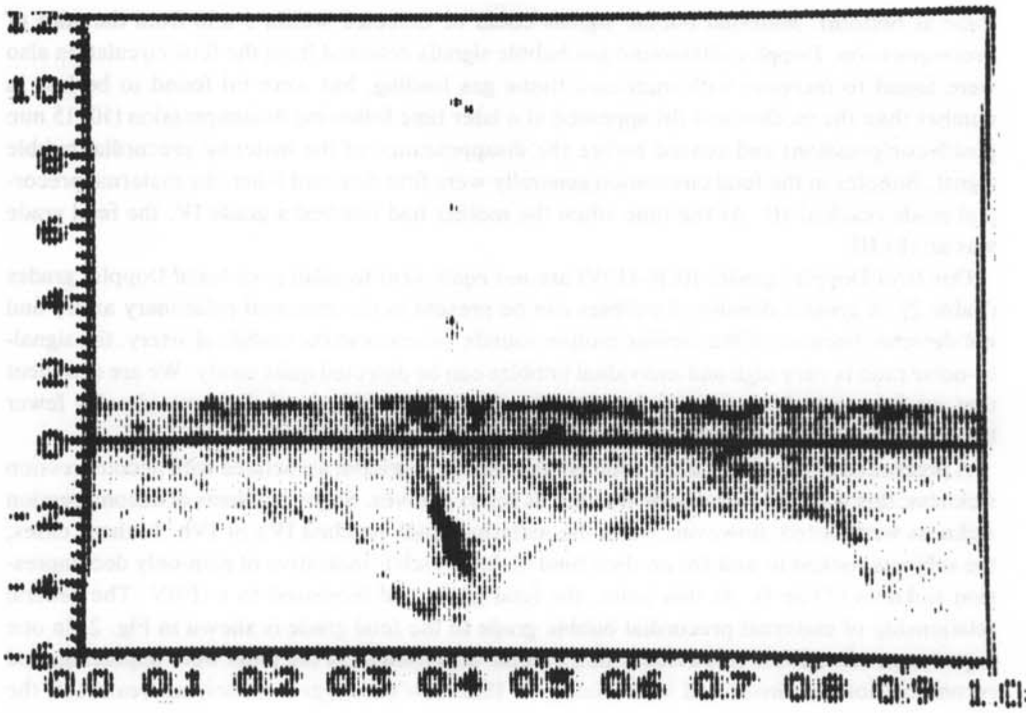

Fig. 1. Doppler spectrum of chord flow. Area above the spectral zero line represents flow in the umbilical vein, area below represents flow in the umbilical artery. Dark area near center of arterial signal represents a single decompression bubble.

TABLE 2
DOPPLER ULTRASOUND GRADING SYSTEM FOR ANIMAL SUBJECTS

Precordial Grading Scheme	
Grade	Characteristics
0	No bubbles can be detected
I	Bubbles/cardiac cycle <1
II	Bubbles/cardiac cycle = 1
III	Bubbles/cardiac cycle >1
	Bubbles heard throughout cycle, and
IVa	—numerous but discrete, or
IVb	—numerous but not discrete
V	Individual bubbles not discernible; flow sound louder than cardiac motion sounds

RESULTS

Following decompression, maternal precordial Doppler ultrasound gas bubble signals increased in a predictable manner in that precordial grade (Table 2) increased with tissue gas loading (time at bottom). Maternal bubble signals could be detected within 5 min from the start of decompression. Doppler ultrasound gas bubble signals detected from the fetal circulation also were found to increase with increased tissue gas loading, but were (a) found to be less in number than the mother and (b) appeared at a later time following decompression (10–15 min postdecompression) and ceased before the disappearance of the maternal precordial bubble signal. Bubbles in the fetal circulation generally were first detected when the maternal precordial grade reached III. At the time when the mother had reached a grade IV, the fetal grade was an (F) III.

Our *fetal* Doppler grades [(F)I–(F)V] are *not equivalent* to *adult precordial* Doppler grades (Table 2). A greater density of bubbles can be present in the maternal pulmonary artery and not detected because of the cardiac motion sounds, whereas in the umbilical artery, the signal-to-noise ratio is very high and individual bubbles can be detected quite easily. We are confident that we have a high sensitivity for detecting fetal gas bubbles and that *considerably* fewer bubbles were present when compared to the maternal venous return.

A precordial grade of 0 to III in adult goats or sheep is seldom associated with decompression sickness; this was also found to be true in this series of dives. Slight problems of decompression sickness were noted, however, when the maternal grade reached IVa or IVb. In these cases, the subjects rocked to-and-fro on their hind limbs, which is indicative of pain-only decompression sickness (Type I). At this point, the fetal grade had increased to a (F)IV. The general relationship of maternal precordial bubble grade to the fetal grade is shown in Fig. 2. In one experiment (dive 14) it was evident that cardiac arrhythmias in the fetus were appearing, and recompression was instituted immediately to 18.5 msw on oxygen. Following treatment, the

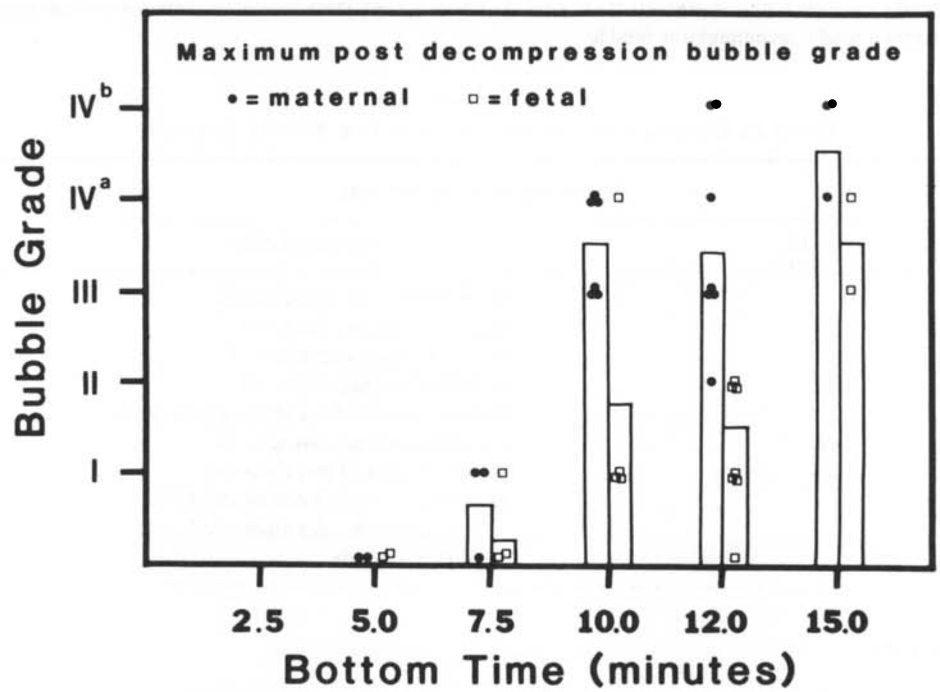

Fig. 2. Maternal and fetal Doppler ultrasound bubble grade, detected transcutaneously, as a function of bottom time at 49 msw (160 fsw).

mother recovered uneventfully. The lamb was born 4 d later with weakness in its hind legs, and subsequently died. Another pain-only case occurred in the mother who was treated at 49 msw on a 50%–50% oxygen-nitrogen mixture. In this case, the lamb was born 8 d later; it was normal and was subsequently released to a farm.

In the series with the 2 goats exposed on the titrated profiles, triplets were born to one and a singleton to the other. The singleton was normal, but triplets appeared weak though normal at birth; however, one triplet died 2 d later of apparent respiratory failure. Because they were triplets, which is somewhat unusual for this species, their postpartum survival was in jeopardy, and the fact that one died cannot be directly attributed to the effects of the decompression and bubble formation per se.

DISCUSSION

Although decompression bubbles have been shown to develop in "pure, isolated" biological systems (10) (hens' eggs), at the outset of this study we had reservations regarding the potential for bubble formation in the fetus. Some of the mechanisms thought to aid bubble formation are present within the fetal system, but the system as a whole was considered to be isolated. We initially speculated that this isolated condition might preclude fetal gas bubble formation altogether.

It is clear from this study however that a gas phase can form in the sheep and goat fetus following hyperbaric decompression, even on exposures that do not give evidence of even mild decompression sickness. This supports our earlier work (11) although is somewhat at variance with a report by Nemiroff et al. (12). Their subjects exceeded the limits of the U.S. Navy dive tables for the given time/depth relationship (165 ft for 20 min), although they did not observe signs of decompression sickness in their subjects and fetal bubbles were not detected by a transcutaneous Doppler flow meter.

In our study, fetal gas bubbles were detected following decompression when the bottom time was as short as 10 min. This is approximately within the limits of the U.S. Navy decompression table as being a safe dive for humans. In one fetal subject (#9), the number of detectable bubbles was large. This is within the commonly noted variability for gas phase formation in a dive even when suitable decompression tables are followed.

The work of Willson et al. (13) has shown that fetal abnormalities can be found when the mother has been subjected to dives that resulted in signs of decompression sickness. Our study indicates that, in these cases, there should have been considerable numbers of gas bubbles present in the fetal circulation.

All gas bubbles in the fetal circulatory system are potential arterial emobolizing agents. Consequently, no "safe bubble limits" can be determined for fetal decompression. In general, human divers suffer few problems when the precordially measured bubble grade is less than III. This reflects both minimal gas phase formation (avoidance of "the bends" because of insignificant gas phase formation in joint tissue) and the integrity of the pulmonary filter (avoidance of arterial gas embolism).

CONCLUSION

On the basis of these 20 dives with 4 subjects and their 6 young, we can make the following tentative conclusions: (a) Gas bubble formation does occur following decompression in both second and third trimester fetuses. (b) Fetal gas bubble formation occurs following a dive which is easily tolerated by the maternal sheep and the goat. (c) The detectable level of gas bubble formation in the fetus is considerably less than that which can be determined precordially in the maternal venous return because of the favorable signal-to-noise ratio. (d) Fetal gas bubble formation occurs at a later time than it does in the mother postdecompression and does not persist as long as gas bubbles in the maternal venous return. (e) The absence of the pulmonary filter makes the fetal system far less tolerant of gas bubbles than is the maternal system. (f) Fetal problems appear earliest as fetal cardiac arrhythmias. (g) In cases where the mother is displaying obvious signs of decompression sickness (in the sheep and goat at least), the fetus is usually experiencing cardiac arrhythmia.

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Powell MR, Smith MT. Bulles foetales et maternelles détectées indirectement chez des brebis et des chèvres à la suite d'une décompression hyperbare. Undersea Biomed Res 1985; 12(1):59–67.—Des brebis et chèvres enceintes furent comprimées avec de l'air à une profondeur équivalente à 49 msw (160 fsw) pour des temps de séjour au fond variant de 5 à 15 min. Les circulations maternelle (précordiale) et foetale (artère ombilicale) furent observées de façon trans-cutanée avec un débitmètre á ultrason à effet Doppler afin de déterminer la présence de bulles gazeuses de décompression. Il fut trouvé que le nombre de bulles détectées précordialement dans la circulation maternelle surpassait le nombre détecté dans l'artère ombilicale foetale pour n'importe quel temps de séjour au fond. De plus, des bulles furent trouvées dans la circulation foetale même quand la mère ne montra aucun signe de maladie de décompression. Ainsi, le manque de symptômes de douleur seulement de la maladie de décompression chez la mère, n'est pas suffisant pour prévenir la formation de la phase gazeuse chez le foetus.

ultrason à effet Doppler	bulles
maladie de décompression	foetus
brebis, chèvre	grossesse

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