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Oscillating Gas Bubbles as the Origin of Bowel Sounds: A Combined Acoustic and Imaging Study

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Abstract

Bowel sounds have been speculated to stem from the movement of gas or a mixture in the bowel lumen, with gas as the major component. The exact role and the mechanism through which gas participates have not been elucidated. Video images of actively moving bubbles under either real-time ultrasonography (RU, n = 4) or videofluoroscopy (VF, n = 4) with synchronous sound recording were studied and a total of 24 bubbling bowel sounds (BBS's) were obtained. The physical dimensions and acoustic parameters of bubbles were analyzed. Freely oscillating bubbles were demonstrated clearly in both groups. Bubble radii ranged from 1.5 to 7.2 mm and frequencies from 258.3 to 1,078 Hz. The bubble frequency correlated inversely with the radius (*P* < 0.01). The relevant acoustic features and parameters of bubble dynamics further supported the identification of gas bubbles. Although the acoustic features seemed to be of minor clinical significance, increased number of clustering or fixed, repetitive pattern of occurrences might suggest a poorer prognosis. In summary, oscillating gas bubbles are capable of producing BBS's and may play a central role in this newly recognized model of bowel sound genesis. The patterns of BBS's may be of prognostic value in clinical application, underlining the need for further study.

Key Words: bowel sound, bubble, bubble frequency, bubble acoustics, real-time ultrasonography, videofluoroscopy

Introduction

Bowel sound auscultation is a physical examination that can be carried out easily, painlessly, and at low costs. However, the mechanisms underlying the genesis of bowel sounds are poorly understood (34). Bowel sounds have been proposed to stem from movement of a mixture of gas, liquid and semisolid materials in the bowel lumen, with gas as the major component (8). Factors governing the quality of bowel sounds have been speculated to include dimensions of bowel segments, contents of the lumen and thickness of the intestinal wall (35). Nevertheless, because of the lack of knowledge on how they work or interact, these speculations have not been validated (18).

Although gas has been postulated to play a crucial role in the genesis of bowel sound (8, 29, 34, 35), the mechanisms remain elusive. We have observed in human gastrointestinal tract moving gas bubbles that gave rise to clear sounds. We therefore turned our attention to the possible role of gas bubbles in bowel sound formation.

The adult intestinal tract contains 100-200 ml of gas (28). The intraluminal gas, in the form of bubbles or bubble clusters, is a frequent finding in our daily practice on ultrasonography (US), described as the

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ring-down artifact or the dirty shadowing (2, 22, 37). Gas bubbles responsible for these findings were found to be 1-7 mm in diameter (2). Moreover, intraluminal bubbles throughout the small bowel have been considered the major obstacle for clear visualization during capsule endoscopic examinations (13, 36). A recent article confirmed the presence of vertically rising bubbles in human gastrointestinal tract on multidetector computed tomography (MDCT) scan (17). The accumulated evidence suggests that bubbles are constantly and actively present in the human gastrointestinal tract.

Bowel sounds exhibit instantaneous and rapidly changing characteristics. Attempts aiming at visualizing the generation of sound *in situ* have been difficult. Farrar (7) discovered under fluoroscopy a “to-and-fro” shifting of gaseous contents in the intestinal loops responsible for the staccato pops. However, the ability of this method to detect the so-called “finely dispersed gas”, a synonym of “air bubble” to our interpretation, was questioned by the author himself (7). In addition, the use of barium meals in such a study was later shown to affect bowel contraction (26). The use of imaging modalities aided by barium meal in bowel sound study was, therefore, limited.

In contrast, technology of US has progressed rapidly during recent years and has provided another alternative. Patterns of accumulation of gas under US, ranging from single free bubble, clusters of bubbles, to gas pocket have been well described by Wilson *et al*. (37). In contrast to the probe-limited view of US, fluoroscopic examination has the advantage of making observation over a wider range but with poorer resolution (7). In this context, the combination of both modalities may work complementarily and synergistically in defining the possible role of bubbles.

Owing to its extensive application in many fields of sciences and industries, bubble acoustics has been an active subject of research ushered by the studies of Minnaert on the sound of running water (20). The sound produced by air bubbles has been attributed primarily to volume pulsations of the bubble in which the bubble behaves as a simple oscillating system with damping (14, 32). Bubbles are excited to give rise to acoustic signals on formation and deformation (13, 19). Thanks to modern knowledge on bubble dynamics, we are now able to recognize the presence of bubbles by their oscillation frequencies, so-called “passive acoustics” method which is a highly reliable tool in measuring the size of a pulsating bubble (1). The relationship between the natural frequency and bubble radius has been described as (20):

$$f_0 = 1/R_0 2\pi \cdot (3\kappa P_0/\rho)^{1/2} \qquad \text{(Equation 1)}$$

where f_0 is the oscillation frequency in Hz, R_0 is the bubble radius, κ is the ratio of specific heats for the gas, ρ is the liquid density and P_0 the absolute liquid pressure. In the case of air-filled bubble in water at atmospheric pressure, the equation may be reduced to $f_0 \cdot R_0 \fallingdotseq 3000$ Hz · mm (9, 12). We were able to apply this algorithm in identifying bubbles as the origin of specific sounds audible in human body.

The purposes of the present study were to demonstrate the mechanism of bowel sounds by obtaining synchronized imaging and acoustic signals, with emphasis on the role of bubbles, and to investigate possible clinical significance of the bubbling bowel sounds (BBS’s).

Materials and Methods

Patients

Patients underwent routine US or fluoroscopic examinations were opportunistically recruited. Most had been fasting when the examination took place. Indications and contraindications for the use of routine abdominal US and fluoroscopy were followed. The study protocol was approved by the Institutional Review Board of the hospital and an informed consent was obtained prior to enrollment.

Real-Time Ultrasonography (RU)

Patients were examined in a quiet room with M2410A Ultrasound System (Hewlett-Packard, Andover, MA, USA) equipped with a curvilinear 3.5 MHz and a linear 7.5 MHz transducers, or SSA-510A (Toshiba Corp., Tochigi, Japan) with a curvilinear 3.75 MHz transducer. The video images were recorded on a videocassette recorder AG-7350 (Panasonic Corp., Osaka, Japan) at 30 frames per second with simultaneous bowel sound recording (see below). The recordings were carried out for at least 20 min in most instances and no water or food was given throughout the procedures.

Videofluoroscopy (VF)

A XUD 150L-30F Fluorograph (Shimadzu Corp., Kyoto, Japan) or a PHF-15XVC2 (TU-51, Hitachi Ltd., Tokyo, Japan) was used. Patients, on their supine position, were viewed under fluoroscopy without contrast agents. Images were recorded and analyzed in the same way as described in the RU section. To minimize irradiation exposure, the accumulated time under fluoroscopy in each patient was strictly restricted to ≤10 min.

The sizes of the bubbles were calculated by comparing to the diameter of the electronic stethoscope (see below) which is 4.7 cm. Since the stethoscope reference was placed closer to the X-ray focus than

Table 1. Patients' profile, clinical diagnoses and outcomes

Patient No.	Age	Sex	Clinical Diagnosis	Recovery
RU1	78	M	Senility, Paralytic ileus	Yes
2	48	M	Quadriplegia, Paralytic ileus	Yes
3	48	F	Cirrhosis, Paralytic ileus	Yes
4	56	F	Bed-ridden, Paralytic ileus	Yes
VF1	69	M	Carcinomatosis, Paralytic ileus	Yes
2	56	M	Acute gastroenteritis and diarrhea	Yes
3	70	F	Small bowel obstruction	No (Mortality)
4	75	M	Laxatives-induced diarrhea	Yes

RU, real-time ultrasonography; VF, videofluoroscopy; M, male; F, female.

the bubble targets, the calculated bubble sizes might be underestimated from 0 to -10% depending on the distance of the bubbles.

Analysis of Audio and Video Signals

The video recordings received an audio input from an electronic stethoscope (SPE-120, Jac Instrument Co., Van Nuys, CA, USA). The audio signals were relayed in parallell to a hand-held digital recorder (Dragon NaturallyMobile, The Dragon Systems, Inc., Newton, MA, USA). This system allows digital recording with a sampling rate of 8 KHz (4). The gain on the stethoscope was set empirically between 3 and 4 and the frequency range at 20-2,000 Hz. Synchronization of the sound and video tracks was accomplished by the addition of clicking sound markers.

After recording, the videotape was screened carefully for possible acoustico-image linkage. A bubble-like image would not be taken as such unless shown to travel a certain distance with an unequivocal image. Every identified BBS and the relevant footage were downloaded for further confirmation. The obtained acoustic signals were analyzed using Adobe Audition (ver1.5 Adobe Systems Inc., San Jose, CA, USA) for frequency, waveform and spectral analyses in which Fast Fourier Transform (FFT) applying a Hanning method and a window width of 512 was adopted. Waveform and power spectral analysis were also performed on EnteroTach® (Western Research Co., Inc., Tucson, AZ, USA) for data exporting and graphing.

Statistical Analysis

Quantitative data are expressed as means ± standard deviation (SD) unless stated otherwise. The relationship between bubble radii and oscillation frequencies was analyzed using the Spearman rank-order correlation method. By correlating the reciprocals of the bubble radii with their frequencies, a correlation coefficient r_s and *P* value were obtained. A *P* value less than 0.05 was considered statistically significant. In addition, for a further description of our data, functional approximation by the use of the least squares analysis was performed and R^2 calculated.

Results

A total of 8 patients (4 RU and 4 VF) out of an original pool of nearly 150 were found to display BBS's. They consisted of 5 men and 3 women, aged 48 to 78 year-old with a mean of 62.5. Table 1 summarizes the patient profiles, clinical diagnoses and outcomes. All in the RU group had a diagnosis of paralytic ileus in common. The co-morbidities are listed. The VF group, in contrast, had varying clinical conditions and different severities. All patients recovered from their bowel disorders except one (VF3) who died of bowel obstruction later.

A total of 32 bowel sounds with poor tracings, overlapping signals or un-measurable images were excluded. Table 2 lists the detailed characteristics of the final 24 BBS's eligible for study. Sequential bowel sounds found to originate from the same locus were labeled under the same Arabic numeral with sequential lowercase letters, *e.g.* VF1-1a and 1b. Bubble radii were measured under both RU and VF. Non-spherical or ellipsoidal bubbles were expressed as spheres with the same volume according to Strasberg (31). The results showed the mean of bubble radii was 4.4 mm, ranging 1.5-7.2 mm, and bubble sound durations 20.0 msec, ranging 11-38 msec.

The bubbling may be single or multiple in occurrences as revealed by the bubbling rate in Hz. Successions of bubbles were observed in most of VF but only one in the RU group (RU2). Repetitive occurrences of clusters of BBS over a fixed point were noted in two cases (VF3 and VF4). In others, the bubbling episodes seemed to be transient phenomena, at least within the observed period. The significance

Table 2. Characteristics of the 24 BBS's

Patient No	BBS No	Equivalent Bubble radius (mm)	Frequency spectrum (Hz) Dominant	2nd	3rd	Duration (msec)	Clustered no. (Bubbling rate in Hz)
RU1	1	3.0	562.5	–	–	13	Single
RU2	1	2.0	812	–	–	14	3 (2.8 Hz)
RU3	1	1.8	344.5	1012*	–	38	Single
	2	4.0	258.3	495.2*	–	24	Single
RU4	1	1.5	1078	–	–	13	Single
VF1	1a	6.0	468.7	593.7	296.8*	18	7 (2.3 Hz)
	1b	7.0	296.8	–	–	19	7 (2.3 Hz)
	2	5.0	531.2	–	–	23	2 (3.2 Hz)
VF2	1a	4.0	401.9	–	–	33	2 (2.2 Hz)
	1b	4.5	387.5	–	–	37	2 (2.2 Hz)
VF3	1	4.0	473.3	–	–	11	Single
	2a	4.0	452.0	–	–	17	Single
	2b	4.0	430.6	–	–	18	Single
	3	6.5	387.5	–	–	15	3 (2.6 Hz)
	4a	7.2	531.2	–	–	17	9 (3.5 Hz)
	4b	6.6	546.8	–	–	15	9 (3.5 Hz)
	4c	5.7	312.5	–	–	18	9 (3.5 Hz)
	4d	6.0	312.5	–	–	11	9 (3.5 Hz)
VF4	1a	6.0	453.1	515.6	–	26	2 (1.8 Hz)
	1b	5.0	1100	437.5*	–	28	2 (1.8 Hz)
	2a	3.5	546.8	–	–	24	4 (2.8 Hz)
	2b	3.0	578.1	–	–	17	4 (2.8 Hz)
	2c	3.0	609.3	843.7	–	16	4 (2.8 Hz)
	2d	3.0	500	890.6	–	14	4 (2.8 Hz)

Bubble radii were expressed as the radii of spheres with the equivalent volume. BBS, bubbling bowel sound; RU, real-time ultrasonography; VF, videofluoroscopy; M, male; F, female; a, b, c and d, sequential subgroup of bowel sounds originated from the same locus as labeled under the same Arabic numeral. *Frequencies chosen as the true bubble frequencies without being the dominant ones (see text for explanation)

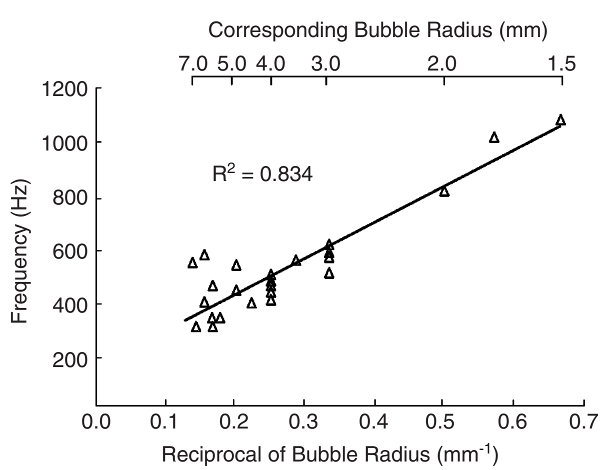

Fig. 1. Graphic representation of frequency versus reciprocal bubble radius for the 24 BBS's listed in Table 2. By the use of the least squares approximation, a trend line with high R^2 value was obtained which implied an inverse relationship between bubble radius and its frequency. Reference scale for corresponding bubble radius in mm is given in the figure.

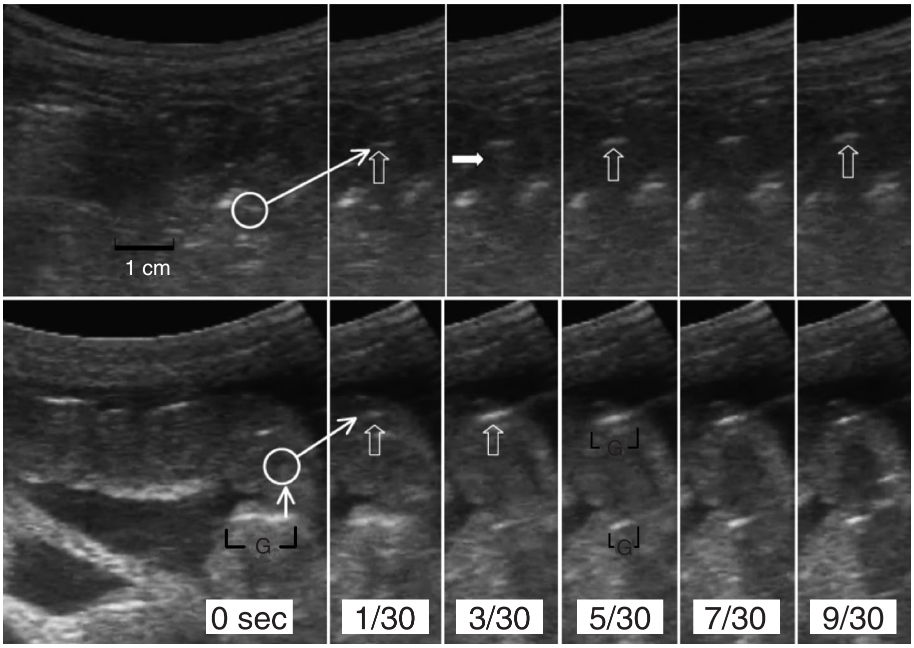

Fig. 2. Two rising bubbles (open arrows), 6 mm (upper panel) and 8 mm in radius (lower panel), were obtained in RU1-1 and RU3-2, respectively. Reverberation lines were observed distal to the echo (filled arrow, upper panel). The thin arrows denote the paths and circles indicate the origins of the bubbles. The bubbling process proceeded in such a way that the size of the bigger G roughly equaled the sum of the smaller G's. Note that maximal rising velocity was attained at the first frame (33 msec) in both cases. The reference bar is 1 cm.

of this clustering phenomenon will be discussed below.

As stated earlier, bubbles make sounds on formation and deformation. Four major applications were introduced (32): (a) bubble formation at a nozzle, (b) bubble coalescence or splitting, (c) flow past constrictions, and (d) erratically rising bubbles. In our study, owing to the absence of observable bubble coalescence or splitting as stated in (b) and, because the rising paths were uniformly smooth enough to rule out (d), only (a) and (c) remained as the possible mechanisms. The excitation mechanism in the former was found to be associated with the collapse of the bubble neck, defined as the narrowest point connecting the bubble to its reservoir (6), while the latter, the transient distortion when the change in pressure is of sufficient brevity and magnitude (33). Note that in both situations, bubbles oscillate at the same frequency as predicted by the early study of Minnaert (20).

Power spectral analyses disclosing the relative energy level of individual peaks are given in Table 2. The dominant frequency (Fd) refers to the frequency at which the power is maximum, followed by second and third peaks in decreasing order, if present. The Fd's corresponded to the bubble frequencies in all except four, as asterisked in Table 2. In these four cases, the second or the third peaks were chosen instead. The reasons are as follows: In RU3-1 and RU3-2, the dominant peaks (344.5 and 258.3 Hz, respectively) were believed to have stemmed from the low-frequency vibration of the intestinal wall itself on bubble impaction, as was evident in videos, and were, thus, excluded. VF1-1a, sharing the same origin, size and moving path with VF1-1b, was believed to have the same 296.8 Hz component despite being its third peak. Likewise, in VF4-1b, the dominant 1,100 Hz peak can be excluded due not only to its rarity in the spectra of bowel sounds but also because of the absence of such a high frequency component in the homologous VF4-1a.

Bubble radii were plotted against the bubble frequencies and showed an inverse dependency (Fig. 1). A Spearman rank-order correlation coefficient was obtained with $r_s = 0.693$ and $P < 0.01$. Bubbles in the RU group were obviously smaller than those in VF. The cause for this is intrinsic to the methodology itself in that VF preferentially tracked larger bubbles while RU tracked smaller bubbles.

Under US (Fig. 2), the rising bubbles appeared as well-defined and slightly curved echoes which have enabled a precise tracing. Reverberation lines were observed distal to the echo, the presence of which further supported the evidence of gas bubble (30). Upon bubbling, the original gas reservoirs reduced their sizes to an extent that roughly equaled the detached bubbles. With a frame-to-frame approach, the rising velocities of bubbles in RU1, RU2

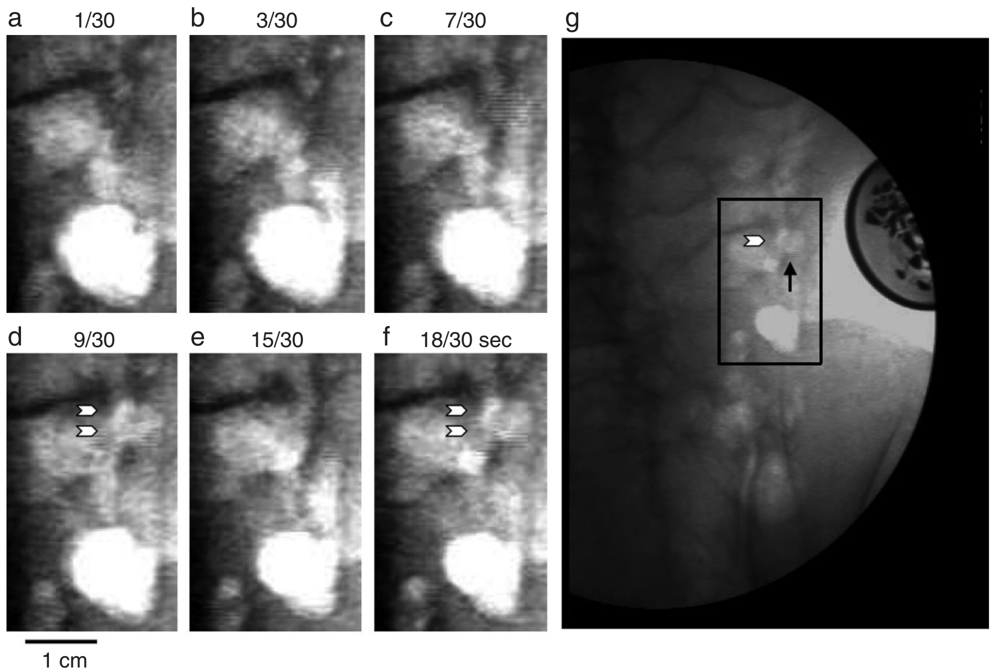

Fig. 3. Series of VF images acquired at 30 frames per second in VF4-2a and VF4-2b. Two consecutive bubbles (double arrowheads) appeared at d (9/30 sec) and f (18/30 sec) with estimated diameters of 7 and 6 mm, respectively. The thin arrow (right panel) indicates the path of the moving bubble (single arrowhead). The reference bar is 1 cm.

and RU3-2 were found to be 330, 150 and 300 mm/sec (with an error range of ±30 mm/sec), respectively.

Under VF imaging, a complete course of bubble formation could be demonstrated even clearer, as shown in Fig. 3. Initially, a protruding globule was formed near the bottom (Figs. 3a and b), growing upward (Figs. 3c and e), detached from the parent gas body and culminated in the formation of spherical bubbles (Figs. 3d and f). The bubble proceeded smoothly upward until it merged with the next gas pocket. Two successive bubbles, 7 and 6 mm in diameters, gave rise to two short bubbling sounds (VF4-2a and b); the respective waveforms, power spectra and the spectral displays are shown in Fig. 4. Both signals appeared as exponentially decaying, slightly perturbed sinusoid waves typical of oscillating bubbles with durations 24 and 17 msec, respectively. Narrow peaks displayed on power spectra are consistent with an underlying monopole acoustic excitation mechanism (Figs. 4a and b). These findings supported the existence of true oscillating bubbles rather than noises from other sources.

Discussion

Basically, the BBS waveforms are found to be spindle-shaped sinusoidal waves characteristic of bubbles as reported previously (1). The BBS durations ranged from 11 to 38 msec which overlapped with a reported range of 15 to 50 msec seen in a common, short, solitary bowel sound known as “short clicks” (10, 16). The rare BBS’s may, thus, be difficult to tell from the ordinary bowel sounds except being louder, softer and more or less “bubbly” to experienced ears. Under spectral analysis, most BBS’s showed a single dominant frequency, but occasionally multiple peaks were generated. In lieu of the relatively nonspecific features mentioned above, more specific evidence for bubbles is needed.

The bubble rise velocity has been considered one of the most fundamental properties in bubble dynamics and is regarded as providing strong evidence for the presence of bubbles (24). For air bubbles in water with diameters from 3 to 14 mm as in our BBS’s, a terminal rise velocity was narrowly confined between 160 and 300 mm/s, irrespective of the presence or absence of surfactant (24). Owing to the limited rising height in our BBS’s, maximal rising velocity (Umax) was adopted instead. Umax of single bubbles was also reported to be 160 to 370 mm/s for bubbles up to 2.7 mm in diameter (24). In BBS’s, our data of 330, 150 and 300 mm/s are well within the above ranges. Furthermore, the acceleration to Umax was reported as less than 50 msec in this recent article (24) and was comparable to an estimate of 33 msec in ours. The accumulated information supported air bubbles as the origin of the BBS’s in our patients.

In our study, the products of radii and frequencies

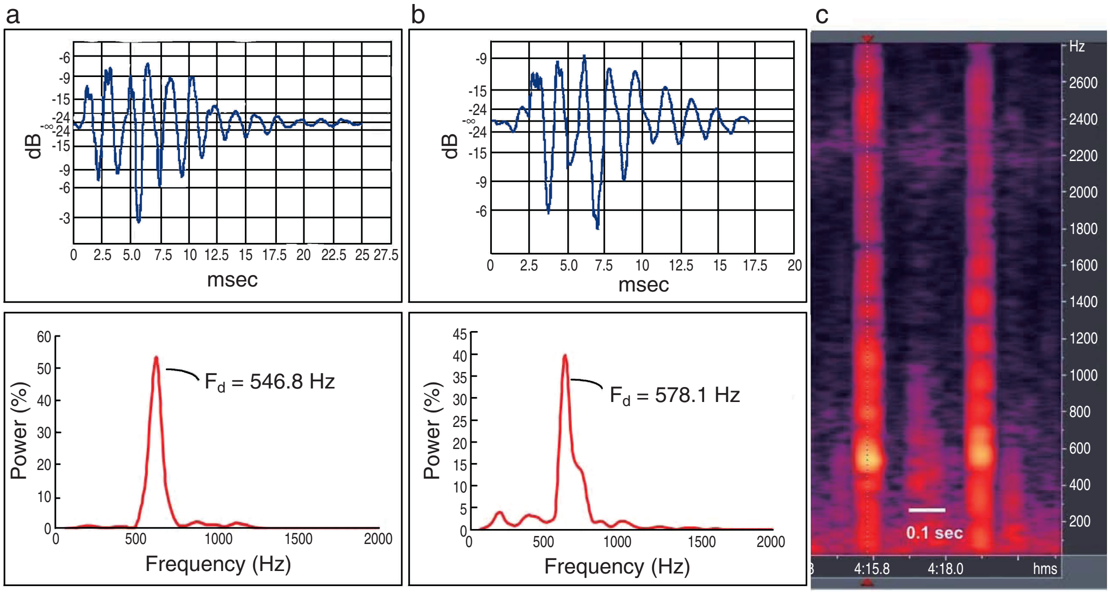

Fig. 4. The acoustic signals obtained in VF4-2a (a) and VF4-2b (b), from Fig. 3. Upper panels show waveforms and lower panels power spectra. Inset (c) gives the spectrographic display enabling readily identification of the dominant frequencies, where the x-axis represents time and y-axis measures frequency in Hz. Colors are used to display the amplitudes: dark blue for low, red for medium and bright yellow for high amplitudes. Note the temporal relationship and the strikingly similar spectra of the two signals. A time scale is shown as a bar in panel (c).

from the 24 BBS's yielded a value of 2060.8 ± 602.1 Hz·mm, which was 31% lower than predicted by Eq. 1 and was still around 22% to 30% after correction with the aforementioned underestimate of bubble sizing under VF. Lower oscillating frequencies are thought to account for this deviation. The cause may lie in the limited diameter and finite-length encountered in the bowel milieu.

Bubble oscillations in confined, closed or semi-closed tubes have been studied as opposed to infinite settings under which the theoretical equation was derived. Bubbles in a tube closed over one end or both ends, a reasonable approximation of the tortuous digestive tract, were reported to have a 20% to 80% reduction in their frequencies (21). Bubbles assumed a lower frequency if the bubble-to-lumen ratio was high or when occupying a lower position in the column. For example, when the former ratio was 0.5 and bubble centered at a higher 90% axial position from the bottom of a tube, the frequency reduction would be around 20% to 50% (21). The given 90% axial position possibly reflected what was true in BBS's because in our BBSs, as shown in Fig. 3, a long neck and late pinch-off had allowed the bubbles to ascend to a higher axial position before detachment. Similarly, in a study carried out in human vascular system, Sassaroli and Hynynen (25) reported a 30% reduction in the measured frequencies of the intravascular micro-bubbles. Consequently, a frequency shift of -30% exhibited by bubbles in BBS's is in agreement with other observations. Nevertheless, as a preliminary study on bubbles formed under a largely unexplored intestinal environment, our data may be the end result of complex interactions of multiple intra- or extra-luminal factors (12). Further studies are required for future investigation.

Considering the pathogenesis of BBS, it is evident from our observations that three components are considered necessary though by no means sufficient: an upstream gas accumulation, a downstream fluid-filled loop and an interposed narrowing in between.

Gas accumulation is essential but not sufficient for the generation of BBS's. The amount of gas may increase as a disease progresses, as is true in the case of bowel obstruction. In cases where bubble sizes are within a narrow range, greater number of bubbling sounds in succession means higher gas flow rates and longer discharge periods, both implying greater gas accumulation and possibly more advanced illness, especially when patients of the same disease are compared.

BBS's appeared as single or multiple short, soft, bubbling sounds with varying pitches. The tendency of clustering has made it a specific category of bowel sounds distinct from others. BBS's having clusters from single to as many as 9 in number are listed in Table 2. The clustering numbers were 4, 7 and 9 in VF4 (diarrhea), VF1 (carcinomatosis) and VF3 (bowel obstruction), respectively. In contrast, single bubbling is always observed in RU cases (paralytic ileus). Of note is that VF3, the only mortality case, has the highest number of clustering. We, therefore, hypothesized that the number of clustering may be of prognostic significance, although more studies are needed.

Luminal fluid accumulation is one of the major pathogenic processes in patients with bowel obstruction and laxatives-related diarrhea (23). The bowel segments that are distended with fluid may assume less tortuous configuration and, subsequently, foster the formation of erected and dilated intestinal loops (27). The presence of such downstream fluid-filled loops may provide the height and space necessary for observation of uninterrupted bubble rise.

The last component, also the central theme of BBS formation, is an interposed narrowing that allows accumulation of gas proximally and provides the site of acoustic activation.

When bubbles formed at a submerged orifice, their sizes are determined primarily by the orifice widths as predicted by the Tate's law (10). However, as the physical properties of the intestinal morphology are unknown, an accurate prediction is not possible for BBS. Nevertheless, prior to pinch-off, a bubble grows to several times the orifice width (14). Under a low flow-rate regime, the bubble-to-orifice ratio was found to be around 3 (3). Jamialahmadi and coworkers obtained a ratio of 6 for 3.0 mm-, 4 for 4.0 mm-, and around 1.7 for 5.0 mm-sized bubbles (11). Given that bubble diameters in our study were from 3.0 to 14.4 mm, the speculative orifice sizes would be no greater than 8.5 mm, a significantly narrowed lumen in contrast to the dilated upstream and downstream loops.

In our observation, BBS's occurred in either fixed or transient patterns. The former was defined as a visualization of at least two discrete clusters of BBS's over the same focus, either under VF or RU, which was observed in all four VF cases and was suspected to be the result of structural abnormalities. However, in milder cases as in the RU group, none of these repetitive events over a fixed point occurred even on later follow-up (in 3 out of 4, data not shown). Transient spasticity or temporary spatial configuration rather than structural abnormality are thought to be responsible.

Concerning factors affecting the properties of bowel sounds, the frequency of BBS's in our study bore no relationship with the physical dimensions of the bowel segments or contents of the lumen. The major determinant of BBS's seemed to be the bubbles themselves. Both luminal and intraluminal factors were necessary for BBS generation but neither was sufficient nor able to modify their properties beyond this point. As a result, the acoustic features such as frequency and duration seemed to play minor roles in clinical application although they may help in identifying BBS from other sounds.

In summary, with the help of the knowledge of bubble acoustics and dynamics, we have demonstrated in this combined imaging and acoustic study that oscillating gas bubbles may give rise to BBS. If interpreted properly, the pattern and frequency of BBS may shed light on the structure and topology of the intestine of interest and be of prognostic value. These results suggest that the role of bubbles in other bowel sounds is worth further exploration.

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