Letter to the Editor

Gas micronuclei that underlie decompression bubbles and decompression sickness have most probably been identified – in response to the Letter to the Editor from Dr David Doolette

In the March 2019 issue of *Diving and Hyperbaric Medicine*, Dr David Doolette expressed a degree of skepticism when he defined as speculation my assertion that nanobubbles formed on a hydrophobic surface are the source of decompression bubbles.[1] He catalogued my previously published paper,[2] which is based on a series of experimental studies, as a 'hypothesis article'.

There remains much that is uncertain about nanobubble physics, but central to our 'hypothesis' that pre-existing nanobubbles may be the precursors to decompression bubbles is the fact that nanobubbles are formed on many hydrophobic surfaces submerged in water from dissolved gas, and in some experiments where only aqueous solution was used, nanobubbles formed without supersaturation.[3]

Dr Doolette was deeply concerned about the Young-Laplace equation. A large number of studies published over the past two decades have shown that this equation and the subsequent exchange of gas is not applicable in the nano-world of bubbles. Nanobubbles (r = 50 nm) were injected into pure water and remained there for more than two weeks. The pressure within the nanobubble, twice that calculated from the surface tension, was ascribed to the strong hydrogen bond between the water molecules.[4] Numerous studies of hydrophobic surface nanobubbles have demonstrated their incompatibility with the Young-Laplace equation, inducing a similar number of attempts to explain this phenomenon. A recent study,[5] which noted that nanobubbles are stable and have low gas density, summarised the situation thus: "*We therefore suggest that current theories may lack the essential ingredient necessary for the formation and stabilization of the observed LCGM*" (layer of condensed gas molecules) from which nanobubbles bud.

The study[6] (also his reference 6), which Dr Doolette cites as a demonstration of nanobubble stability, to a great degree supports our suggested mechanism. In this study, 30 s of ultrasound irradiation resulted in the growth of surface nanobubbles. The authors related this to the well-known mechanism of rectified diffusion, where in one acoustic cycle the amount of gas that diffuses into the bubble (during the expansion phase) is greater than the amount that diffuses out (during the compression phase). This finding reinforces the notion that the nanobubbles expanded due to differences in gas tension and may thus also expand on decompression. In our experiments with silicon wafers,[2] degassing of the water ensured the elimination of any accidental gas micronuclei. Decompression bubbles then developed on hydrophobic but not hydrophilic wafers. The only reasonable explanation we could find was that surface nanobubbles were the precursors of these decompression bubbles. Dr Doolette expresses his disagreement with this, but fails to provide an alternative explanation.

The idea that surface nanobubbles develop on any other hydrophobic surface tested, but not on a hydrophobic surface within the body, is questionable. Because it is more than likely that our decompression bubbles had their origin in nanobubbles on the hydrophobic surface of the silicon wafers, it is likewise more than probable that the bubbles which developed at the active hydrophobic spots on the blood vessels of sheep originated in the same way. As far as we can interpret the wealth of experimental data, it is indeed a tenable proposition that decompression bubbles develop from pre-existing nanobubbles on hydrophobic surfaces within our body. Strong support for this hypothesis may be seen in the explanation it can provide for the numerous and varied features of decompression illness (timing, acclimation, risk on a second dive, endothelial injury, microparticles, taravana, local white matter lesions, spinal and vestibular DCS and joint pain, among others), as we found in our investigations of active hydrophobic spots summarised in the recent overview article.[2]

References

1 Doolette DJ. Gas micronuclei that underlie decompression bubbles and decompression sickness have not been identified. Diving Hyperb Med. 2019;49:64. doi: 10.28920/dhm49.1.64. PMID: 30856670.

2 Arieli R. Nanobubbles form at active hydrophobic spots on the luminal aspect of blood vessels: consequences for decompression illness in diving and possible implications for autoimmune disease – an overview. Front Physiol. 2017;8:591. doi: 10.3389/fphys.2017.00591. PMID: 28861003. PMCID: PMC5559548.

3 van Limbeek MAJ, Seddon JRT. Surface nanobubbles as a function of gas type. Langmuir. 2011;27:8694–9. doi: 10.1021/la2005387.

4 Ohgaki K, Khanh NQ, Joden Y, Tsuji A, Nakagawa T. Physicochemical approach to nanobubble solutions. Chem Eng Sci. 2010;65:1296–300. doi: 10.1016/j.ces.2009.10.003.

5 Schlesinger I, Sivan U. Three-dimensional characterization of layers of condensed gas molecules forming universally on hydrophobic surfaces. J Am Chem Soc. 2018;140:10473–81. doi: 10.1021/jacs.8b04815. PMID: 30040878.

6 Brotchie A, Zhang XH. Response of interfacial nanobubbles to ultrasound irradiation. Soft Matter. 2011;7:265–9. doi: 10.1039/c0sm00731e.

Submitted: 11 April 2019
Accepted after revision: 02 October 2019

Ran Arieli, The Israel Naval Medical Institute, Israel Defence Forces Medical Corps, Haifa, Israel; Eliachar Research Laboratory, Western Galilee Medical Centre, Nahariya, Israel

Address for correspondence: *12 Klil-Hakhoresh, Rakefet, D.N. Misgav 2017500, Israel*
arieli1940@gmail.com

Key words
Nanobubbles; Gas micronuclei; Decompression bubbles; Hydrophobicity; Letter to the Editor

doi: 10.28920/dhm49.4.311-312. PMID: 31828752.