The Varying Permeability Model

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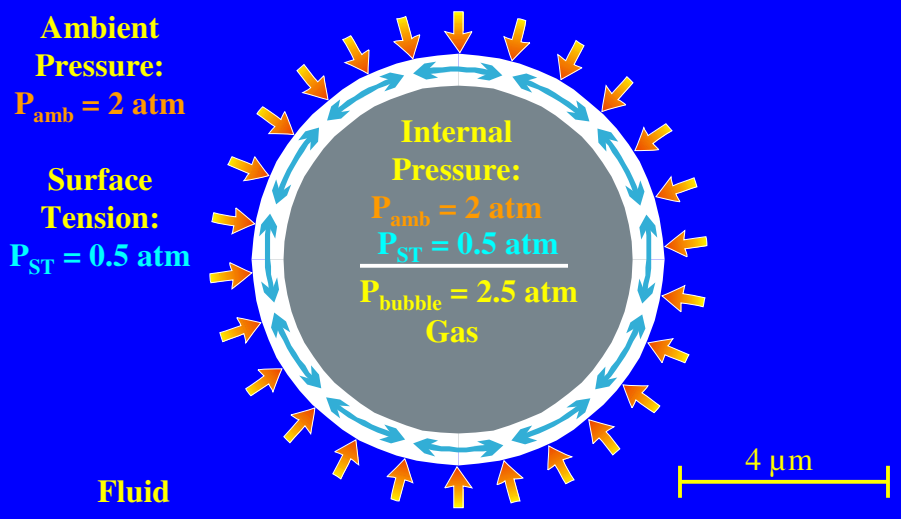
(with additional graphics and animations by Richard Pyle)

An easy explanation for the mathematically disinclined

First an Introduction to bubbles:

- The pressure of gas in a bubble is equal to the surrounding hydrostatic pressure, plus a contribution from the surface tension caused by water molecules "pulling" together at the bubble surface.
- The contribution from surface tension is found by the following formula: **$P_{ST} = 2\gamma_b/radius$**
- A bubble about the size of a red blood cell (4 um radius) has its pressure raised by up to 0.5 atmospheres.
- **The smaller the bubble, the greater the surface tension effect.**

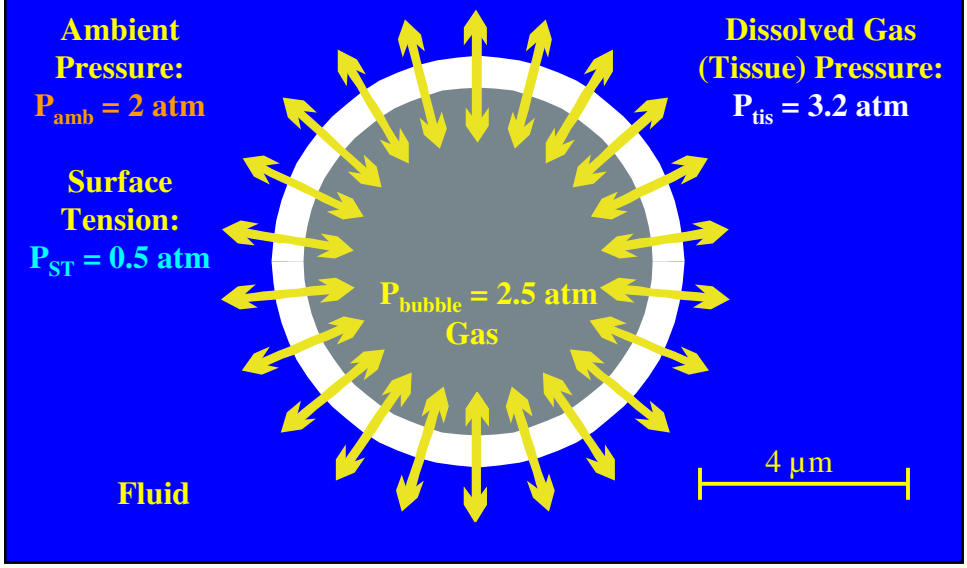
Effect of Surface Tension



Gas diffuses from bubbles

- If the pressure inside a bubble is greater than the pressure of the DISSOLVED gas in the surrounding tissue, the bubble will shrink.
- Conversely if the pressure in the bubble is less than the tissue dissolved gas pressure the bubble will grow.

Gas Diffusion Gradients



Implications

- Except for during decompression, all bubbles should eventually dissolve, because surface tension makes the bubble pressure higher than the surrounding dissolved gas pressure.
- A person who has not been diving recently should not have any bubbles.

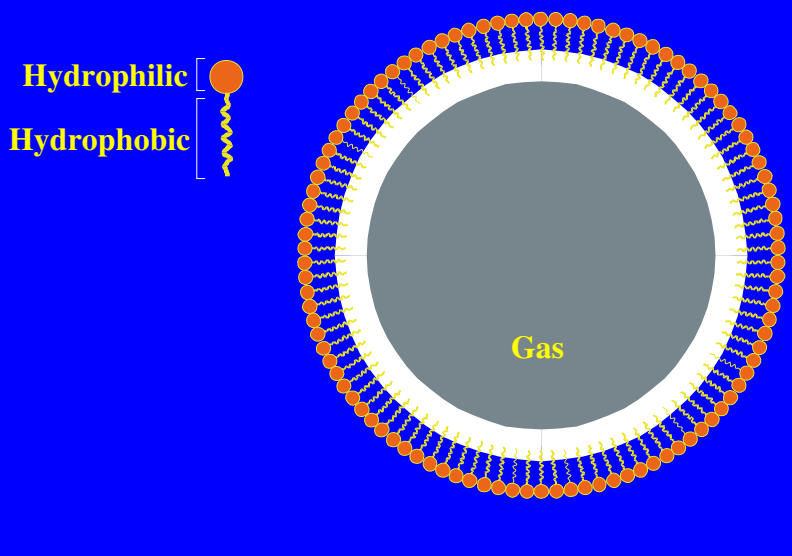
- **In reality, bubbles don't always dissolve.**

Enter the Varying Permeability Model!

- To explain why bubbles don't always dissolve, a lot of ideas have been suggested.
- The best explanation so far is that the tiny bubbles become stabilized by "surface active molecules"
- These are molecules that have both a ***hydrophobic*** component and a ***hydrophilic*** component, and embed themselves in the gas-water interface.

Hydrophobic molecules repel water, while hydrophilic molecules are attracted to it. Therefore molecules with both ends will go to the gas-water interface, with the hydrophobic end inside the gas and the hydrophilic end in the water.

Surface Active Molecules

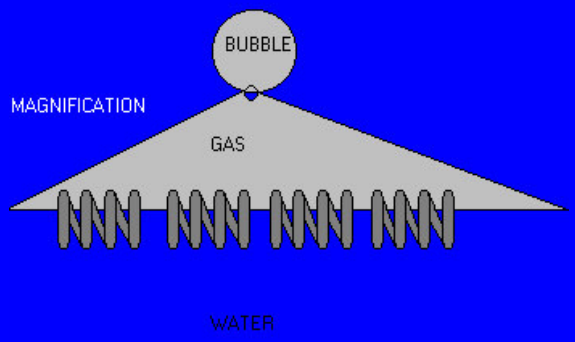


How do "surfactants" stabilize bubbles?

- Just as the water molecules "pull" towards each other in surface tension, the surface active molecules "push" against each other.
- This counteracts the effect of surface tension, and therefore eliminates the loss of gas by diffusion.
- No diffusion means no bubble dissolution.

Recall that if surface tension is negated, the pressure inside the bubble is equal to the ambient pressure. If the tissue pressure is equal to the ambient pressure, then there is no pressure gradient for gas diffusion.

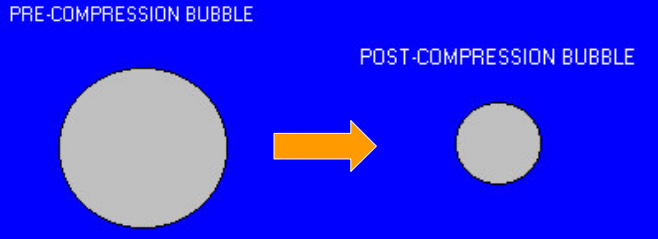
Surfactants can be thought of as tiny springs pushing against each-other at the interface.



What happens during crushing?

- When a bubble is compressed by descending, the area available for each spring lowers. Basically each spring compresses as it bumps against it's neighbors.
- But just like a real spring, eventually it can't compress any more - it runs out of travel.
- At this point springs will start popping off the bubble surface.

- More precisely, it becomes energetically favorable for a surfactant molecule to leave the surface rather than to compress further.
- The effect of surface tension is now countered and the bubble stabilizes at its new smaller radius.



Note that at first the "springs" only compact, leaving less area per spring. Once they reach their limit, then the excess springs detach.

Growing Bubbles

- Recall that bubbles grow when the dissolved gas pressure is greater than the interior bubble pressure.
- This means that small bubbles require a greater "super-saturation" in order to be stimulated into growth, because the effect of surface tension is proportionally greater for smaller bubbles.
- Therefore crushed nuclei are better for divers than uncrushed nuclei.

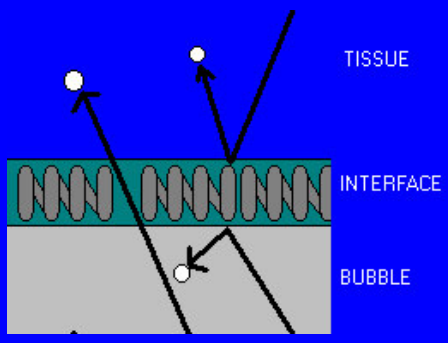
Wait a second - didn't you just say that the surface tension was negated in the crushed nuclei?

- This would mean that small bubbles should grow just as easily as large bubbles.
  - **– But this doesn't happen! –**
- At first the bubble expands, but then the springs "lose contact" with each-other, so they can't push against each-other, and the effect from the surfactant molecules is lost.
- Thus, surface tension reigns supreme.

Recall that the pressure required for inflation, the surface pressure, is 2*gamma/radius. Therefore the smaller bubbles require a greater super-saturation, even though both are initially stabilized.

Do surfactants have any other effects?

- Yes - they form a barrier to diffusion.
- The closer they are squeezed together, the stronger the barrier to diffusion.



Kunkle vs. Yount

- There are two main bubble surfactant models out there:

- One by Dr. Thomas Kunkle
- One by Dr. David Yount

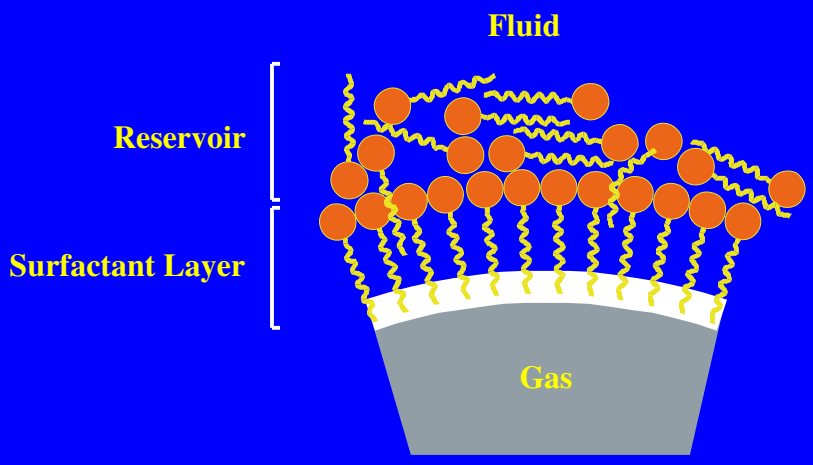
Kunkle's model

- Assumes that when surfactants leave the bubble they don't return or interact in any way.
- Fully accounts for the "springiness" of the springs.
- The diffusion barrier strength depends on the space available for each surfactant.

Yount's Model

- Assumes that there is a reservoir of surfactants "hanging around" just outside the bubble.
- Accounts for the transfer of surfactant molecules between the reservoir and the bubble surface.
- Uses "unspringy springs", the springs either don't push back or else push back at their "popping-off" threshold. They act more like billiard balls than springs.

Surfactant Reservoir

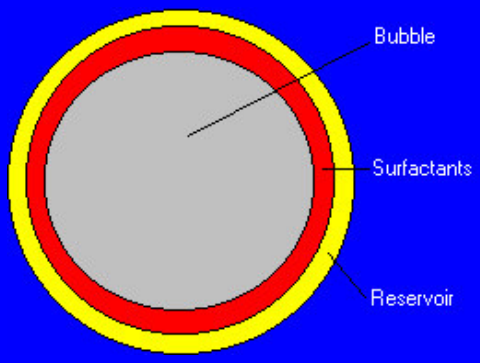


Note that only the surfactants in the surfactant layer can oppose surface tension, those in the reservoir are not aligned and can't "push back".

What's the deal with "Varying Permeability"?

- The surfactants either don't form a diffusion barrier, or completely block diffusion.
- This "impermeability" occurs after about 300 fsw of compression, so is not really a concern for most divers.
- An impermeable bubble won't be crushed as much as a permeable bubble because gas doesn't diffuse out as it shrinks.

The Reservoir



- The VPM also accounts for an electrostatic force between the reservoir and the surface.

The Electrostatic Forces

- The pressure balance equation is:
  $\mathbf{P_{bubble} + (2\ \gamma_c/radius) - B = P_{amb} + 2\ \gamma/radius}$
- **B** is the sum of various electrical and chemical attractions and repulsions.
- γ_c accounts for the springy "push back" effect of the surfactants.

Gamma-C is the maximum "anti-surface tension" that the surfactants can withstand before popping out of the reservoir. Note that this doesn't have to equal the surface tension itself, since the B term can make up the differences.

What we need to know about bubble crushing.

- We assume that the gas pressure in the bubble is equal to the outside tissue pressure - aka diffusive equilibrium.
- Ignoring oxygen effects, this means that P_{bubble} is equal to $P_{ambient}$, because $P_{ambient}$ would equal the dissolved gas pressure (P_{dis}).

Note that things are still simple if the ambient pressure doesn't equal the tissue dissolved gas pressure. It just means that different values of B (previous slide) are required.

- Using the pressure equation:

  before crushing:

  $$P_{tis} + 2\,\gamma_c/r_o - B_o = P_{surface} + 2\,\gamma/r_o$$

  after crushing:

  $$P_{tis} + 2\,\gamma_c/r_{crush} - B_{crush} = P_{depth} + 2\,\gamma/r_{crush}$$

- Where P_{tis} is the dissolved gas pressure (assumed equal to $P_{surface}$), r_o is the initial radius, and r_{crush} is the final radius.
- Setting B_o equal to B_{crush} gives us the equation for the crushed radius.

The CRUSHING formula:

$P_{crush} = P_{depth} - P_{tis}$

CF = Crush factor = $2 (\gamma_c - \gamma)$

$$r_{crush} = 1/((P_{crush}/CF) + 1/r_o)$$

The Meta-Stable state

- A different **B** value is used as the tissue saturates, to represent the nuclei forming a semi-stable state.
- The nuclei are exponentially restored to their original size as surfactants return from the reservoir to the interface.
- This process occurs over many days, but may occur faster in living organisms.

Decompression and Nuclei

- Even a bubble not stimulated to growth will expand with a drop in ambient pressure.
- The same equations are used:
  During saturation:
  $$P_{dis} + 2\,\gamma_c/r_s - B_s = P_{depth} + 2\,\gamma/r_s$$
  After decompression:
  $$P_{dis} + 2\,\gamma_c/r_d - B_d = P_{surface} + 2\,\gamma/r_d$$
- The **s** subscript refers to saturation, **d** refers to decompression.

Bubble Growth

- Bubbles grow when the super-saturation pressure is greater than **$2\,\gamma$/radius** (surface tension).
- Note that nuclei growth during decompression makes it easier for nuclei to evolve into full-fledged bubbles.
- All of the previous equations can be combined to find the smallest bubble stimulated into growth.

Bubble Numbers:

- The VPM predicts that there is an exponential distribution of nuclei - lots of small ones and a few big ones.
- The number of nuclei stimulated into growth is related to the minimum size stimulated into growth by the following equation:

$$N_{stimulated} = N_{total} \left(e^{-K * r_{stimulated}}\right)$$

Take Home Messages

- Greater super-saturation stimulates more bubbles into growth
- Greater crushing pressures help minimise the number of stimulated bubbles
- Saturation decompressions must be more conservative to allow for the loss of the crushing effects.

After a really long saturation dive, all of the crushed nuclei have been restored to their original size. This means that they're far easier to "grow" than are nuclei on regular recreational dives.

VPM and dive tables

- There is a lot of confusion about how the VPM is integrated in dive models.
- The concept is actually quite simple, but this simplicity is somewhat hidden by the elegant procedures used to generate the dive tables.

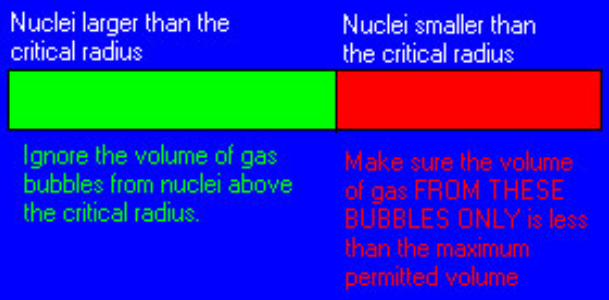
The VPM uses an iterative root finding procedure which converges on the optimal staging procedure very quickly, however this procedure can look a little “intimidating” and hides the fact that all that is happening is that the allowed tissue gradient is gradually being increased until the total permitted gas volume is reached in each compartment.

Minimum Bubble Number

- The VPM assumes that there is a minimum bubble number (regardless of bubble size) that can be tolerated without decompression sickness.
- If this is true, then keeping the super-saturation below that required to stimulate the critical number of nuclei should prevent decompression sickness.

This hypothesis was conceived because the VPM doesn’t tell us the size of bubbles, only how many are stimulated into growth. Dr. Yount however noticed that the DCS incidence was quite strongly correlated with the number of bubbles predicted to grow by the VPM. The VPM predicted a straight line relationship of super-saturation vs. crushing pressure, and this is what is observed in practice. Other models predicted this too, but what was particularly interesting was that the VPM also predicted a curvature of this line as the crushing pressure approached the impermeable regime. This was actually observed in rats subjected to extreme pressure changes, though it is unclear if the observed curvature is due to impermeability or other factors relating to the severity of the dives.

- This assumption works great for saturation exposures, but is too conservative for normal (no-deco/mild deco) dives.
- Solution - assume that there is a maximum volume of gas that is allowed, ONLY counting nuclei from below a critical radius



A constant bubble number limit would require either VERY conservative recreational diving, or VERY dangerous saturation diving. The solution was to have a mixed limit process, where the phase limit is important for short dives, but where the limit converges to the constant bubble limit predicted for saturation diving. This phase limit makes some intuitive sense, it is conceivable that the body can withstand more free bubbles for a short time than it could withstand indefinitely.

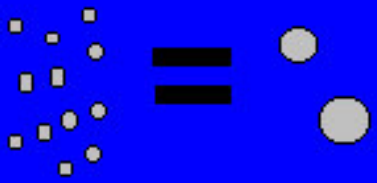
Half-times and bubble growth

- "Fast tissues" remove inert gas faster than slow tissues, meaning that bubbles don't have time to grow as big as they do in slow tissues.
- Initially the bubbles grow faster because of the typically higher pressure difference, but this is greatly outweighed by the quick removal of source gas.

There is competition between bubbles and blood for the gas in the tissues. Bubbles in fast tissues run out of gas for growth much sooner than bubbles in slow tissues. However most dive tables allow a higher gradient in the fast tissues, precisely because the bubbles can't grow as fast. However this higher gradient that normally is allowed means that bubbles in fast tissues initially grow faster than those in slow tissues (even though in the end the slow tissue bubbles usually grow bigger).

Many small or few big

- This critical volume concept means fast tissues can have lots of small bubbles, while slow tissues can have hardly any bubbles above the minimum number.
- A greater super-saturation is allowed for fast tissues.



Faster tissues have higher allowed gradients. These gradients stimulate many more bubbles into growth, but because the bubbles are small the maximum free gas limit is still maintained.

Increasing Gradients

- The VPM starts out by just stimulating the minimum safe number of bubbles.
- The maximum allowed super-saturation is then increased, and the volume of excess gas in each compartment is compared to the maximum permitted.
- If it is less than allowed, the super-saturation is increased again and again, until the compartment maximum is reached.

As an example of how this works, imagine that a gradient, Gmin, just stimulates the "safe" bubbles, leaving "Vlim" as the amount of free gas allowed. The next cycle would allow a gradient of 150% Gmin, leaving 50% of Vlim left over. The next cycle might allow 180% of Gmin, leaving 20% of Vlim left over. Eventually it converges to 212% of Gmin with no V left over. At this point the phase limit is met.

Does the VPM apply?

- It certainly has shown that it can be used to generate successful dive tables.
- It has some support from human and animal data.
- It has apparently been successful during data fitting by Dr. Wienke with the new Reduced Gradient Bubble Model.

Other candidate models

- Many of the successes of the VPM (deeper predicted decompression stops, etc) can also be explained by models of diffusive bubble growth and "phase equilibrium" models (where there is an excess of available nuclei for the gas to grow into bubbles).
- Impossible at present to tell which model is correct, so best to reserve judgement.

Other ways to stabilize nuclei

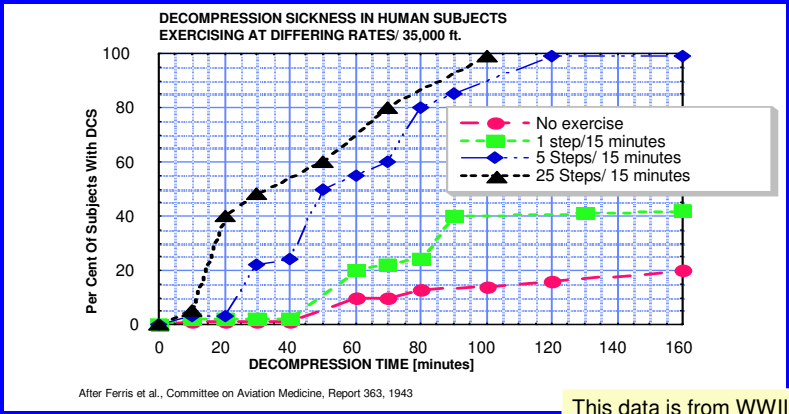
- Hydrophobic crevices can also form nuclei (you see this in your beer glass).
- It is clear that nuclei are NOT forming out of pure water, that would require super-saturation's greater than the depth of the ocean.
- Short-lived nuclei can also be continuously created by stresses in muscles and joints. These nuclei may only be partially stabilized, and have a life-span of minutes to hours

Creation of new nuclei

- Note that the VPM doesn't deal with creation of new nuclei, only with the stabilization of those created nuclei.
- These nuclei, created by stresses during movement, are likely to be the reason why decompression sickness is more likely if exercise is performed prior to or during decompression.

Dr. Powell of NASA has done a significant amount of research into this. It turns out that bend resistance can be greatly increased by complete bed rest for several hours to days prior to decompression. It is also shown that even doing a few stair steps can increase the chances of decompression sickness. He's also found that the right shoulder forms bubbles more easily than the left, since this shoulder is typically more active. However it has also been shown that MILD exercise during decompression decreases the risk of the bends by increasing the removal of gas from the tissues.

Exercise and nuclei



After Ferris et al., Committee on Aviation Medicine, Report 363, 1943

The effect of exercise is shown above, aviators who did step exercises had greater incidences of decompression sickness.

This data is from WWII, when high altitude bombing made understanding aviation decompression sickness a strategic priority. Dr. Powell has posted two papers on the decompression list's FTP site, one of which is the source of this graph.

Does that mean I should rest on the deco-line?

- Not necessarily.
- It is true that exercise creates more nuclei.
- But exercise also increases the removal of gas from tissues, and has been found to be beneficial in some studies.
- What is clear is that strenuous exercise must be avoided.
- It is not clear when and where mild exercise should or should not be performed

Model of the Future?

- Current evidence suggests that both stabilized, VPM style nuclei and short lived, movement generated nuclei are important in decompression sickness.
- These two effects operate on long term and short term time scales.
- The model of the future will likely account for both of these effects

Bottom line

- Both phase equilibrium, diffusive bubble growth and VPM models have been used to successfully generate dive tables.
- All of these models make suggestions of the same nature (deeper stops and lower super-saturations), so we don't really have a way to discriminate amongst them.
- But because they make similar suggestions, any of these bubble models is likely to be superior to standard "Haldanean" tables.

Conclusion

- VPM recommendations make sense from a variety of perspectives.
- Surfactant stabilized micronuclei may or may not prove to be a key player in human decompression sickness, but regardless the pioneering work of Kunkle and Yount has greatly broadened our understanding of how bubbles form and stabilize - their contribution should not be underestimated.