MECHANISM FOR BLOATER FORMATION IN BRINED CUCUMBERS

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───────────────ABSTRACT───────────────

The susceptibility of pickling cucumbers to bloater damage during storage in CO_2-charged brine depended upon the internal gas composition of the cucumbers before brining. Gas extracted from fresh cucumbers consisted of about 75% N_2, 20% O_2, and 6.0% CO_2. Replacement of that gas with CO_2 or O_2 reduced the susceptibility of the fruit to bloater damage upon subsequent storage in carbonated brine. Bloater damage was related directly to % N_2 and inversely to % CO_2 in the internal gas of the cucumbers when they were brined. These and other findings are the basis of the following mechanism we propose to explain bloater formation of cucumbers in brine containing CO_2. When cucumbers are brined, liquid clogs the intercellular gas spaces of the tissues that normally permit rapid diffusion of gases in fresh cucumbers. The liquid-clogged layer encloses the internal gases within the fruit and functions as a differentially permeable barrier to N_2 and CO_2. Since N_2 is the predominant gas within the fresh fruit, and since CO_2 concentration in the brine is high, a diffusion gradient for CO_2 exists toward the fruit interior. CO_2, which is much more water soluble than N_2, diffuses from the brine into the fruit faster than N_2 can diffuse from the fruit. Ultimately, the transfer of CO_2 to the fruit interior results in sufficient internal gas pressure due to CO_2 plus N_2 to rupture the flesh, causing a gas pocket (bloater formation).

INTRODUCTION

PURGING of CO_2 from the brine of fermenting cucumbers with N_2 or air has been shown to greatly reduce bloater damage in the brine-stock cucumbers (Etchells et al., 1973; Fleming et al., 1973, 1975; Costilow et al., 1977). Many pickle companies now purge their brines to reduce losses. Although N_2 has been generally recommended as the purging gas, some briners are either experimenting with or are using air because of its relatively low cost. The use of air presents possible problems with softening, off colors and flavors, and lowering of brine acidity (Fleming et al., 1975; Potts and Fleming, 1979).

Economically, it would be desirable to minimize the amount of N_2 required for purging. For this reason, Fleming et al. (1978) tested the susceptibility of cucumbers to various levels of CO_2 in the brine in order to establish a critical level of CO_2 for bloater damage. Concentration of CO_2 in the brine was controlled by bubbling various mixtures of CO_2 in N_2 through the cucumber brines. Bloater damage resulted from this artificial means of carbonation in heated and unheated cucumbers and in fermented and unfermented cucumbers. They concluded, therefore, that bloater damage can occur by a physicochemical mechanism, independent of metabolism and CO_2 production from microbial action or cucumber tissue. Etchells et al. (1968) earlier suggested a physicochemical mechanism for bloater damage, and indicated that *supersaturated* levels of CO_2 were needed for bloater formation to occur. Fleming et al. (1978) showed, however, that bloater damage can occur at *subsaturation* levels of CO_2 in the brine. The critical level

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of CO_2 for bloater damage depended on numerous variables, including brine temperature, salt concentration, and the time when CO_2 was added to the brine.

If carbonation was begun immediately after brining, the cucumbers did not bloat extensively, even after extended carbonation. Bloater damage was extensive, however, if carbonation was begun about 1 day after brining. After about a month or longer in brine storage, the cucumbers were no longer susceptible to bloater damage by artificial carbonation, even when the brine was saturated with CO_2. These cucumbers did bloat, however, if subjected to supersaturated levels of CO_2 due to yeast fermentation.

The objective of our study was to gather sufficient data on the gas composition and rates of gas exchange of fresh and brined cucumbers so that we might develop a working hypothesis for the mechanism of bloater formation due to carbonation of brined cucumbers. Specifically, we: (a) determined rates of exchange of N_2, CO_2, and O_2 in fresh and brined cucumbers, and (b) studied the relation between internal gas composition of cucumbers before brining and bloater damage of the cucumbers in artificially carbonated brine.

MATERIALS & METHODS

Cucumbers

Size no. 3 pickling cucumbers (3.8–5.1 cm diam) were obtained from nearby pickle companies. Only fruit free of obvious physical damage and disease were used. Brined cucumbers were evaluated for bloater damage according to Etchells et al. (1974), and bloater indexes were calculated according to Fleming et al. (1977).

Gas exchange of fresh cucumbers

Cucumbers (1.9 kg) were packed into 3.8-liter (1-gal) glass jars. Each jar was then sealed with a screw-on cap fitted with a 250-ml expansion reservoir calibrated to measure brine expansion volume during bloater formation (Fleming et al., 1973). The jar cap also contained portholes through which were inserted a glass gas dispersion tube and a 0.8 cm diam glass rod to support the reservoir (Fig. 1). Air, CO_2, O_2, or N_2 was introduced through a flowmeter into the jar of cucumbers.

Brining

After gas exchange treatment, brine was poured through the reservoir and into the jar. During brine addition, the gas flow was allowed to continue so that air was excluded from the jar. The brine contained 9.8% (w/v) NaCl, 0.32% (v/v) glacial acetic acid, and 0.2% sodium benzoate. When the jar was filled, the gas flow was discontinued, and brine added to the 50 ml mark in the reservoir. Brines were artifically carbonated by bubbling pure CO_2 (50 ml/min) through the brines, as described earlier (Fleming et al., 1978). Expansion volume of the brined cucumbers was determined from the rise in brine level in the reservoir (Fleming et al., 1973) and was expressed as percent of the volume of cucumbers in the jar. Expansion volume is directly related to bloater formation (Fleming et al., 1973; 1978).

Gas extraction and analysis

Fruit were immersed in a 2M $MgSO_4$ solution which had been adjusted to pH 2.5 with HCl and which was contained in an inverted bell jar. An inverted, plastic funnel was placed over the fruit within the bell jar and pushed into the solution until all gas was displaced from the funnel; then, the funnel was sealed with a rubber serum cap. A vacuum desiccator lid connected to a vacuum pump was then placed on the bell jar, and the system was subjected to a vacuum of 0.1 atmosphere for about 15 sec. Gases in the interior of the fruit
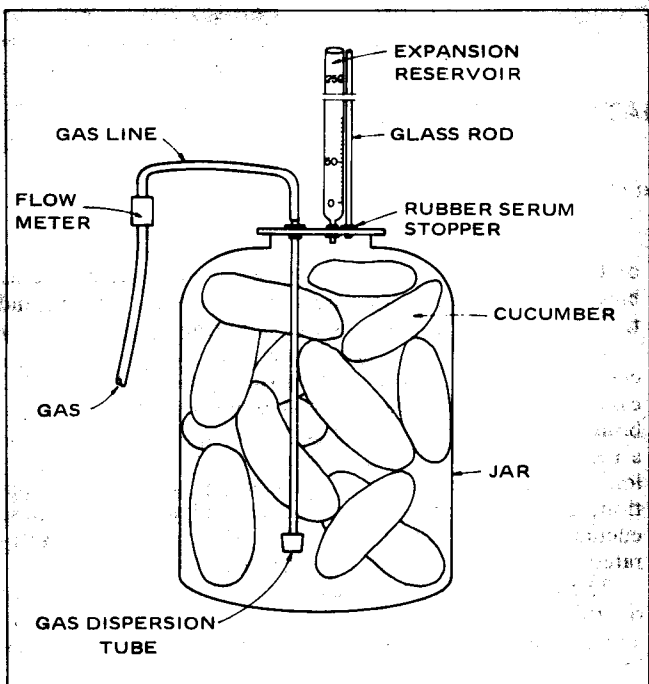
Fig. 1—Jar-reservoir assembly used to expose cucumbers to gases prior to brining and to subsequently brine the cucumbers.

Fig. 2—Internal gas composition of cucumbers exposed to CO_2.

expanded, escaped from the fruit surface as streaming bubbles, and were collected in the funnel. For fruit which had been under brine for several days, it was necessary to puncture their surface with a hypodermic needle immediately prior to gas extraction, otherwise they exploded at the low pressure. After return to atmospheric pressure, a 0.5-cc sample of the gas was removed with a syringe through the rubber serum cap and its composition analyzed with a Hamilton-Fisher Gas Partitioner, model no. 29. Gas analyses are reported as percentage composition by volume of the extracted gas sample, using pure O_2, N_2, or CO_2 as calibration standards. Failure of composition to total 100% represents analytical variations. The high aqueous solubility of CO_2 can present serious problems in such a procedure. However, we found that by using acidified $MgSO_4$ according to Jorge (1978), the composition of the headspace gas was highly stable.

Rubber balloon model

Gas-filled balloons were used to demonstrate principles involved in bloater formation. An apparatus identical to that shown in Figure 1 was used, except that the cucumbers were replaced by a submerged, deflated balloon attached through its opening to a capillary tube fitted to a rubber serum stopper in the jar lid (balloons were inflated and deflated several times to increase their elasticity prior to use in the experiments). Jars were filled with water and carbonated overnight to saturate the water with CO_2. Gas mixtures of 200 ml volume at room temperature were introduced by syringe into the balloons through the serum stoppers and capillary tube to initiate the experiment. The initial gases placed inside the balloons within three jars were 100% N_2, 100% CO_2, and a 1:1 (v/v) mixture of CO_2 and N_2. Expansion of the balloons was determined from the rise in the water in the expansion reservoir upon continued carbonation of the water within the jars at 50 ml of CO_2/min.

Exchange rates of fresh versus brined cucumbers

The rates at which N_2 and CO_2 would exchange in fresh cucumbers and in cucumbers that had been brined for 3 days were measured. Fresh cucumbers were placed in a series of jars, and the jars were then flushed with CO_2 at a flow rate of 500 ml/min for 1 hr so that their internal atmosphere was 100% CO_2. One-half of these jars were filled with CO_2-saturated brine and CO_2 was bubbled through the brine at 50 ml/min CO_2 for 3 days. The remaining jars were filled with carbonated brine to wet the surfaces of the fresh fruit and the brine was immediately removed in a manner such that CO_2 continued to flow into the jar during this surface wetting procedure.
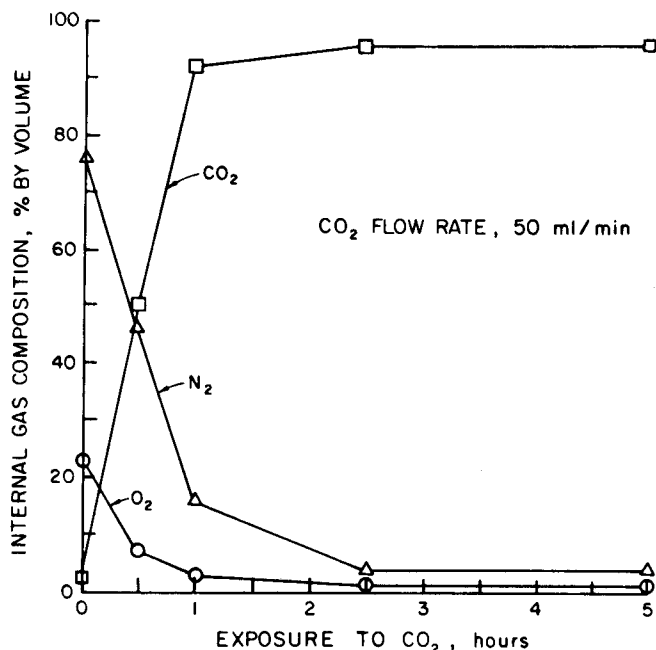
These wetted, fresh fruit were then exposed within the jars to pure N_2 at a flow rate of 50 ml/min. Immediately prior to introduction of N_2 into the jar and after 15, 30, 45, and 60 min of N_2 exposure, the internal gas of the cucumbers was extracted and analyzed as described above. The fruit brined for 3 days were drained and the procedure described above for introducing N_2 into the jars and periodically analyzing the internal atmospheres of the fruit was carried out.

RESULTS

Gas exchange in fresh cucumbers

The natural internal atmospheres of four separate harvests of pickling cucumbers averaged 5.7% CO_2 (SD 2.8%), 20.5% O_2 (SD 1.3%), and 75.2% N_2 (SD 1.5%). These values are consistent with findings of Jorge (1978).

When cucumbers were exposed to a CO_2 atmosphere, their internal gas composition changed from ca 2% CO_2 to over 90% within 1 hr, at a CO_2 flow rate of 50 ml/min (Fig. 2). Cucumbers treated in this manner are hereinafter referred to as "CO_2-exchanged." The percentages of N_2 and O_2 in the fruit interior decreased correspondingly. Changes in internal gas composition were even more rapid at a flow rate of 500 ml CO_2/min, being ca 90% complete within 0.5 hr. Thus, the internal gas of fresh pickling cucumbers apparently can exchange rapidly with the external atmosphere. When CO_2 was bubbled (50 ml/min for 5 hr) through freshly brined cucumbers, before the cucumbers became susceptible to bloater damage by brine carbonation, the internal gas composition of the fruit was 89% CO_2, 1% O_2, and 12% N_2. Thus, cucumbers also are capable of rapid gas exchange immediately after brining.

Bloating susceptibility of CO_2-exchanged cucumbers

The magnitude and rate of expansion volume changes in CO_2-exchanged cucumbers, which were subsequently brined and carbonated, varied inversely with the time the cucumbers had been exposed to a CO_2 atmosphere prior to brining (Fig. 3). The bloater index of CO_2-exchanged cucumbers was directly related to the % N_2 and inversely
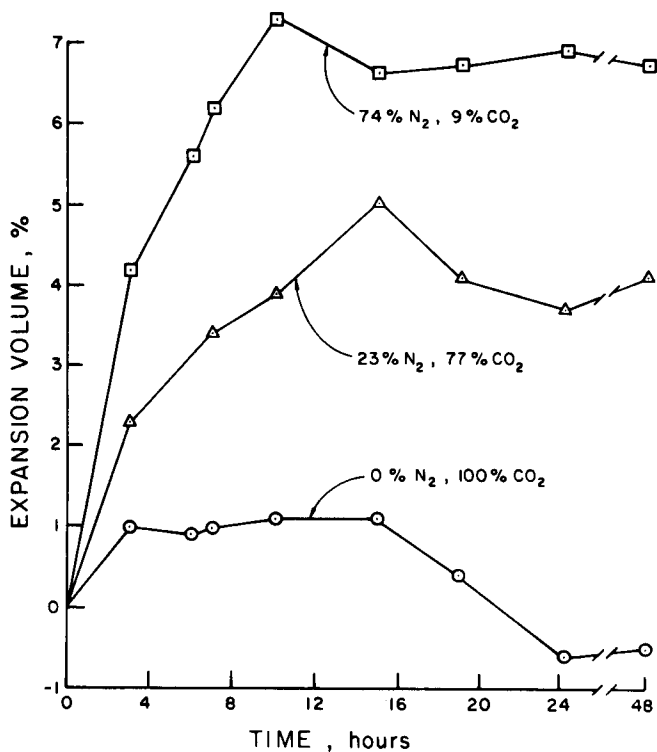
Fig. 3—Expansion volume changes in CO_2-exchanged cucumbers upon brining and carbonation. Cucumbers contained gases of the indicated compositions prior to brining. See Table 1 and Fig. 4 for related data.
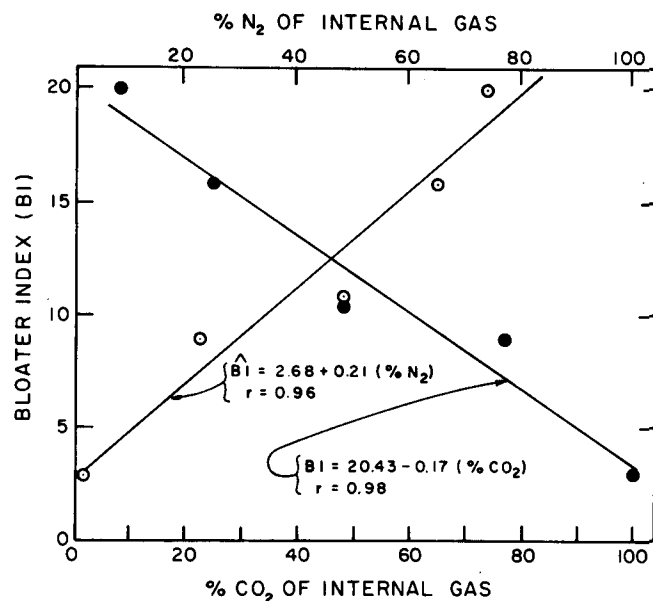

Fig. 4—Effects of % N_2 and % CO_2 in the internal gas of fresh pickling cucumbers on bloater damage upon subsequent brining and carbonation.

related to the % CO_2 composition of the internal gas of the cucumbers prior to brining (Fig. 4). Bloater damage and the maximum % expansion volume were directly related, as has been shown previously (Fleming et al., 1978). Bloater damage consisted of balloon, lens, and honeycomb types (Table 1) and was typical of damage incurred in brine-fermented cucumbers.

Immediately after cucumbers were exchanged with CO_2 or O_2, their internal gas consisted mostly of the exchange gas (Table 2). Exchange of the internal gas of cucumbers with CO_2 or O_2 reduced bloater damage upon subsequent brining and carbonation (Table 2). Cucumbers without gas exchange served as controls, showing the effects of normal internal gas composition on bloater damage.

Effects of CO_2 and O_2 exchange gases on internal gas

composition of cucumbers after a 2-day storage in brine were determined (Table 3) for comparison with internal composition immediately after gas exchange (Table 2). The internal gas of both CO_2- and O_2-exchanged cucumbers contained mostly CO_2 after the 2-day brine storage. The 5.1% O_2 in the O_2-exchanged and brined cucumbers (Table 3) contrasted greatly with the 86% O_2, which the fruit contained immediately after O_2 exchange (Table 2). Again, bloater damage was significantly lower in CO_2- or O_2-exchanged cucumbers than in cucumbers that were not exchanged with pure gases.

Particularly interesting in the O_2-exchanged cucumbers was the visual observation of complete cure (translucent as compared to white, opaque flesh in fresh cucumbers) when the fruit were cut and examined 2 days after brining (Fig.

Table 1—Bloating susceptibility of CO_2-exchanged cucumbers to carbonation when brined

CO_2-exchange treatment[a]		Bloater damage after carbonation			
(min)	(flow, ml/min)	Balloon[b] (%)	Lens (%)	Honeycomb[b] (%)	Bloater index
0	50	35 SM	5 S	60 SM	20.0
15	50	25 SA	15 SM	45 S	14.0
30	50	15 SM	10 SM	40 SM	13.5
45	50	15 SM	10 S	40 SM	11.5
60	500	10 S	0	0	2.0

[a] CO_2 was allowed to flow into 1-gal jars of cucumbers at the times and rates indicated before introducing the cover brine.
[b] Letters following numerals indicate the severity of bloater damage: S = slight; M = moderate; A = advanced. When two letters are shown, the first indicates the degree of damage in the majority of the cucumbers. See Etchells et al. (1974).

Table 2—Effects of exchange gas on internal gas composition of cucumbers prior to brining and on bloater damage upon subsequent carbonation of the brined cucumbers

	Internal gas comp.[a] (%)			Bloater damage after carbonation	
Exchange gas	CO_2	O_2	N_2	Max expansion volume (%)	Bloater index
None	8.9	21.9	74.1	9.2	20.0
CO_2	101.5	0.9	2.4	4.5	3.0
O_2	5.0	86.4	4.0	3.2	6.2
LSD 0.05				1.6	9.2

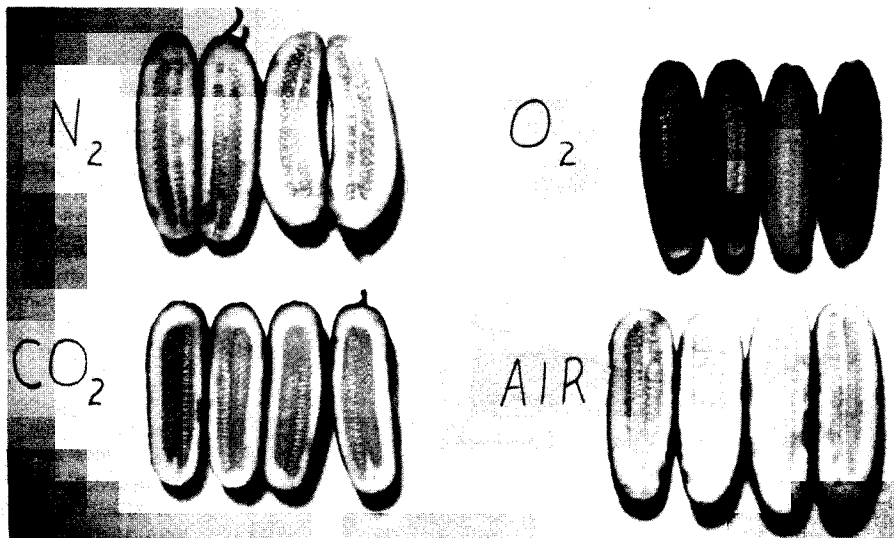[a] Cucumbers exposed to exchange gas, 500 ml/min, for 1 hr before internal gas composition was analyzed.

Fig. 5—Effect of O_2 exchange of fresh cucumbers on internal appearance of the flesh 2 days after brining. Note the fully-cured appearance of the O_2-exchanged cucumbers as compared to the raw (white, opaque) or partially cured appearance of the CO_2-exchanged, air (not exchanged) and N_2-purged cucumbers. See Table 3 and footnotes for details.

5). This rapid visual cure did not result with the other treatments detailed in Table 3. Also, we noted that O_2-exchanged cucumbers absorbed brine rapidly immediately upon immersion in brine. Apparently, the brine filled the air spaces within the tissue, and thereby, resulted in the cured appearance.

Comparison of rates at which N_2 exchanged with CO_2 in fresh and brined cucumbers

A comparison of the rates of CO_2 removal from fresh and brined cucumbers was determined by exposing CO_2-exchanged fruit to a flow of N_2. CO_2 removal was more rapid from fresh than from brined cucumbers upon exposing the surface-dried cucumbers to N_2. Also, the internal % N_2 increased more rapidly in fresh than brined fruit (Fig. 6).

Rubber balloon model for bloater formation

Upon exposure of gas-filled balloons to carbonated water, the water steadily rose in the expansion reservoirs a net total of 265 ml after 2 hr when the balloon initially contained 100% N_2, a net total of 128 ml when the balloon initially contained 1:1 (v/v) CO_2 and N_2, and 0 ml when the balloon initially contained only CO_2 (Fig. 7). We subsequently demonstrated that water displaced into the expan-

sion reservoir was almost quantitatively related to measured volumes of air added to the balloons by a syringe through the rubber serum stoppers. Thus, hydrostatic pressure effects and physical resistance of the balloon to expansion were negligible in the apparatus.

Periodic analyses of the composition of gas contained within the balloons during the course of volume changes revealed a constantly increasing % CO_2 and decreasing % N_2 in both balloons which contained N_2 gas (data not shown). However, within the limits of experimental error, no appreciable net loss in N_2 from the balloons occurred during the 2-hr experiment, when volume changes were

Table 3—Effects of exchange gas on internal gas composition of cucumbers after 2-day brine storage and on bloater damage upon subsequent carbonation of the brined cucumbers

Exchange gas	N_2 purged after brining and before carbonation	Internal gas comp. (%)[c]			Visual cure[c] (%)	Bloater index[d]
		CO_2	O_2	N_2		
None	Yes[b]	2.1	3.7	93.3	20	13.9
None	No	49.7	4.8	47.5	20	17.8
CO_2[a]	No	97.7	1.3	5.9	45	3.0
O_2[a]	No	83.3	5.1	17.3	100	0.0
LSD 0.05		12.0	5.2	12.4	–	12.4

[a] Fresh cucumbers were exposed to a gas flow of 500 ml/min for 1 hr prior to addition of brine.
[b] Purged continuously with nitrogen at 50 ml/min after addition of brine.
[c] Determined 2 days after brining. See Figure 5 for visual appearance of the cut cucumbers.
[d] A duplicate lot of cucumbers was carbonated at 50 ml CO_2/min, starting 3 days after brining and continuing for 2 days for the purpose of determining bloating susceptibility of the variously treated cucumbers.
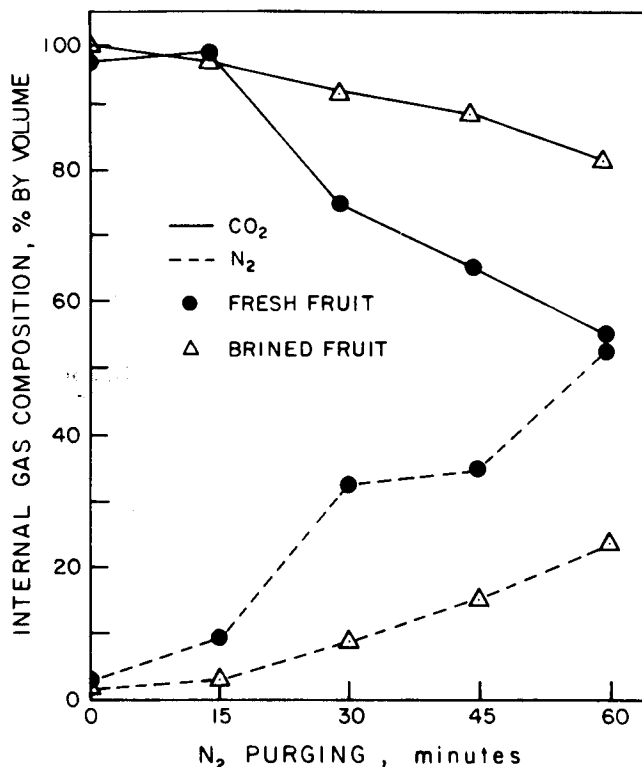

Fig. 6—Changes in the internal gas composition of fresh and brined cucumbers during N_2 purging.
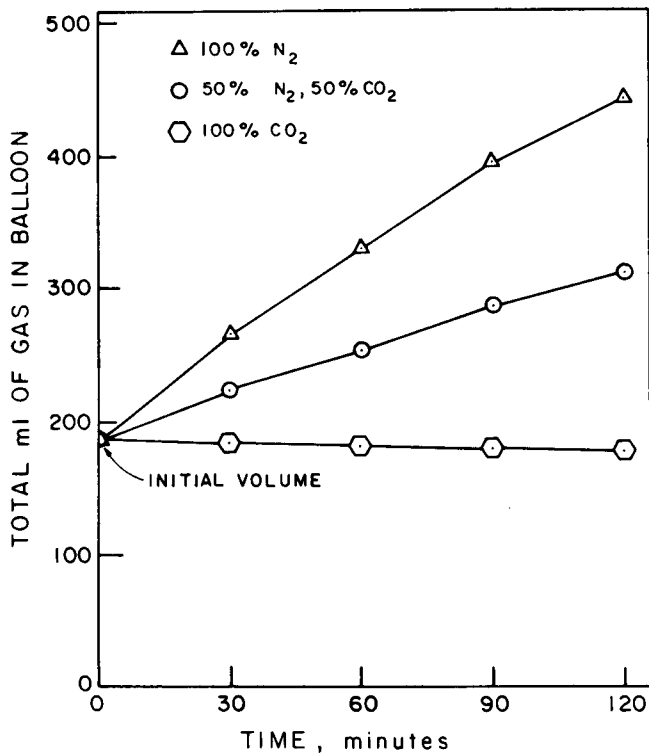
Fig. 7—Increase in volumes of gas-filled rubber balloons placed in CO_2-saturated water. The initial composition of gases in the balloons is given.

Table 4—Properties of gases in water and in air

Variable	Gas[c]		
	CO_2	O_2	N_2
Diffusion coefficient			
In air (cm²·S⁻¹)[a]	0.139	0.178	—[d]
In water (cm²·S⁻¹ X 10⁵)[b]	1.71[18]	1.98[18]	2.02[22]
Solubility in water[a]			
g/100g water, 27° C	0.1366	0.0038	0.0017

[a] From Hodgman et al. (1955).
[b] From International Critical Tables (1929).
[c] Superscript numbers indicate temperature (°C).
[d] Data not given.

taken into account. Thus, volume changes were caused primarily by movement of CO_2 from the brine into the balloons.

DISCUSSION

ETCHELLS et al. (1968) studied the gaseous fermentations of brined cucumbers produced by pure cultures of lactic acid bacteria and proposed the following mechanism for bloater formation: "The fermentation gas, which is produced solely in the cover brine, diffuses into the cucumber via the brine in a supersaturated state, and is released and accumulates at a location of structural weakness inside the cucumber fruit,..." They confirmed their hypothesis by showing that brine supersaturated with CO_2 from sodium carbonate caused bloater formation typical of that caused by microbially-produced CO_2.

Their hypothesis fails to explain, however, how bloater damage can occur at subsaturation levels of CO_2. Serious bloater damage occurred in artificially carbonated, brined cucumbers at 52 and 66% CO_2 saturation, e.g., depending on brine temperature (Fleming et al., 1978). The results of our study show that the internal gas composition of cucumbers at the time of brining can greatly influence their susceptibility to bloater damage upon brining.

Mechanism of bloater formation at subsaturation levels of CO_2

The following hypothesis may explain how bloater formation occurs when brined cucumbers are exposed to subsaturation levels of CO_2 in the surrounding brine. We propose that CO_2 diffuses into the brined fruit more rapidly than N_2 diffuses out, such that, eventually, gas pressure within the fruit exceeds the external pressure. Tissues then rupture, and pockets of gas accumulate (bloater formation) inside the fruit. Differential rates of gas diffusion in brined cucumbers are due to the formation of a continuous, liquid-clogged outer layer of tissue which is not present in fresh fruit, and the lower water solubility of N_2 than CO_2. Physical constants for gas diffusion and solubility (Table 4), and the following further evidence support this hypothesis.

The fleshy mesocarp of plant tissue contains intercellular air spaces (Esau, 1976). Fresh pickling cucumbers contain about 5–9%, by volume, of gases (Veldhuis et al., 1939; Jorge, 1978). These gases can rapidly exchange with the ambient gas atmosphere, as shown by our study and as illustrated in Figure 8A. The internal gas composition in Figure 8A is typical of that in fresh cucumbers, although we found the composition to vary. Air composition is that reported by Weast (1973).

Stomata are present in the cucumber epidermis (Smith et al., 1979) and may be an avenue through which gases pass. The rate of exchange between internal and external gases was much slower for brined than for fresh cucumbers (Fig. 6). We think that the intrusion of liquid into the skin and air spaces of the outer mesocarp tissue of brined cucumbers clogs the normal avenues for diffusion (Fig. 8B).
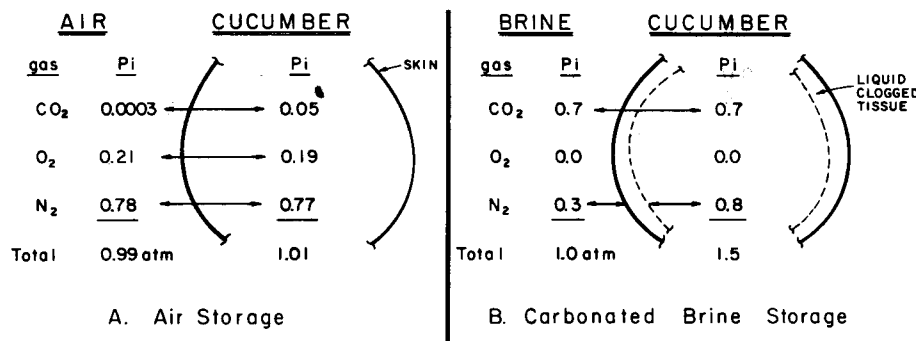
Fig. 8—Hypothetical exchange of gases of cucumbers held in air and in carbonated brine. Pi is the partial pressure, in atmospheres. See text for discussion.

Liquid intrusion into the tissue could occur soon after brining as a consequence of O_2 from the internal atmosphere of the cucumber being converted to CO_2 with a resultant drop in internal gas pressure due to dissolution of CO_2 in the tissue fluids as proposed by Fleming et al. (1980). Additional support for the formation of a liquid-clogged layer is the fact that brined fruit, but not fresh fruit, exploded when exposed to 0.1 atmosphere in the gas extraction apparatus, unless the fruit surface was intentionally punctured prior to gas extraction. Increased resistance to gas diffusion in avocado fruit, as a consequence of fruit softening, has been attributed to liquid clogging of the air spaces by cell exudates (Ben-Yehoshue et al., 1963).

Liquid clogging of air spaces in outer mesocarp and skin tissue (Fig. 8B) would cause the enclosure of internal gases, which consist primarily of N_2 in nonexchanged cucumbers. We propose that in the brined cucumbers, the liquid layer functions as a differentially permeable barrier to CO_2 and N_2. The much greater water solubility of CO_2 than N_2 (Table 4) would allow a greater diffusion rate of CO_2 than N_2 through this aqueous barrier. Diffusion coefficients of these gases in water are not greatly different (Table 4). It is the difference in solubility of gases, therefore, that largely accounts for differences in relative diffusion rates in water for O_2, CO_2, and N_2 (1.0, 23.1, and 0.53, respectively; Krogh, 1919) and in body fluids (1.0, 20.3, and 0.53, respectively; Guyton, 1971).

Bloater damage results, therefore, from the entrapment of N_2 inside of brined cucumbers by outer, liquid-clogged tissue and a subsequent increase in the internal, partial pressure of CO_2 (Fig. 8B). The CO_2 may originate within the tissue, or from carbonation of the brine surrounding the cucumbers. Ultimately, when the internal total gas pressure exceeds one atmosphere, the tissues give way, and gas pockets form (bloated areas). The onset of bloater formation occurs when the internal pressure, due to CO_2 plus N_2, exceeds resistance by the tissue. The brine may contain a subsaturation level of CO_2, therefore, for bloater formation. Oxygen-exchanged cucumbers did not bloat appreciably, apparently because O_2 was converted to CO_2 by tissue respiration as suggested by Fleming et al. (1980).

If cucumbers are carbonated immediately upon brining, bloater damage is minimal, even with extended brine carbonation (Fleming et al., 1978). Apparently in this case, N_2 is displaced from the cucumbers by CO_2 before intercellular gas spaces become clogged and restrict the rate of N_2 removal from the tissue.

Bloating of brined cucumbers is analogous to the expansion of the rubber balloons, as shown in Figure 7. Rubber is over 10 times more permeable to CO_2 than the N_2 (International Critical Tables, 1929). CO_2 diffused from the surrounding carbonated liquid into the balloon in proportion to the CO_2 diffusion gradient. The rubber, therefore, acted like a differentially permeable membrane, as did the hydrated layer which forms in brined cucumbers.

Although microbial fermentation was excluded in all cucumber brining experiments reported herein, we believe that the above hypothesis for bloater formation also applies when the source of CO_2 is from microbial growth.

Implications

The internal gas composition of pickling cucumbers before brining influences their bloating susceptibility during brine storage. Thus, factors which influence the gas composition of cucumbers prior to or during brining should be considered in relation to brining properties, especially in relation to bloater damage. We and others have observed unexplained variations in bloater damage of pickling cu-

cumbers. Physiological state of the fruit, as it influences gas composition, would be a prime factor for further study.

The possibility of intentionally altering the gas composition of fresh cucumbers prior to brining, in order to reduce susceptibility to bloater damage of the fruit during subsequent brining, has been explored (Fleming et al., 1980). That study showed that exchange of the internal gas with CO_2 or O_2 will greatly reduce susceptibility of the cucumbers to bloater damage by carbonation. The study also showed that the use of O_2 as the exchange gas offers unique possibilities because O_2-exchanged cucumbers took up brine much more rapidly, and thus, acquired a more rapid appearance of cure than cucumbers with a normal internal atmosphere.

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