The pH of beverages in the United States

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Sweetened and flavored beverage consumption has increased dramatically over the past 35 years in the United States with carbonated soft drinks being consumed the most frequently, and most often by children, teens, and young adults.[1-3] In 1942, the annual production of soft drinks was approximately 60 12-ounce servings per person; that number has increased almost 10-fold since 2005.[4] Between 1999 and 2002, daily carbonated soft drink and fruit drink consumption by 13- to 18-year-olds was 26 ounces, and the Center for Science in the Public Interest has reported that in 2004, total consumption of these drinks for every man, woman, and child was approximately 68 gallons per year.[4] The prevalence of dental erosion in the 21st century has also increased due to our enhanced preference for sweet and sour.[5] The consumption of acidic beverages contributes to an erosive oral milieu and should be of concern to the dental practitioner.[6-9]

Supplemental material is available online.

The pH of commercial nonalcoholic, nondairy beverages ranges from 2.1 (lime juice concentrate) to 7.4 (spring water).[10] Commercially available beverages with a pH of less than 4.0 are potentially damaging to the dentition.[11] Acids are added to beverages and compose a flavor profile giving the beverage a distinctive taste. Acids provide a tartness and tangy taste that helps to balance the sweetness of sugar present in the beverage; they are key factors in the taste of the beverage. Phosphoric acid is added to cola drinks to impart tartness, reduce growth of bacteria and fungi, and improve shelf-life. Citric acid, a

ABSTRACT

Background. Dental erosion is the chemical dissolution of tooth structure in the absence of bacteria when the environment is acidic (pH < 4.0). Research indicates that low pH is the primary determinant of a beverage's erosive potential. In addition, citrate chelation of calcium ions may contribute to erosion at higher pH. The authors of this study determined the erosive potential measured by the pH of commercially available beverages in the United States.

Methods. The authors purchased 379 beverages from stores in Birmingham, Alabama, and categorized them (for example, juices, sodas, flavored waters, teas, and energy drinks) and assessed their pH. They used a pH meter to measure the pH of each beverage in triplicate immediately after it was opened at a temperature of 25°C. The authors recorded the pH data as mean (standard deviation).

Results. Most (93%, 354 of 379) beverages had a pH of less than 4.0, and 7% (25 of 379) had a pH of 4.0 or more. Relative beverage erosivity zones based on studies of apatite solubility in acid indicated that 39% (149 of 379) of the beverages tested in this study were considered extremely erosive (pH < 3.0), 54% (205 of 379) were considered erosive (pH 3.0 to 3.99), and 7% (25 of 379) were considered minimally erosive (pH ≥ 4.0).

Conclusions. This comprehensive pH assessment of commercially available beverages in the United States found that most are potentially erosive to the dentition.

Practical Implications. This study's findings provide dental clinicians and auxiliaries with information regarding the erosive potential of commercially available beverages. Specific dietary recommendations for the prevention of dental erosion may now be developed based on the patient's history of beverage consumption.

Key Words. Erosive potential; commercial beverages; pH; dental erosion.

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substance naturally occurring in citrus drinks and added to many others, imparts a tangy flavor and functions as a preservative. Malic acid occurs naturally in apples, pears, and cherries, and is added to many noncarbonated beverages such as fruit drinks, fortified juices, sports drinks, and iced teas because it enhances the intrinsic flavor. Malic acid also is added to artificially sweeten carbonated beverages to intensify taste and reduce the amount of other added flavorings. These additives give the beverage its distinctive sugar and acid signature taste.

Dental erosion is the irreversible acidic dissolution of surface tooth structure by chemical means in the absence of microorganisms. It primarily occurs when hydrogen ions interact with the surface fluorapatite and hydroxyapatite crystals after diffusion through plaque-pellicle biofilm—a process termed proton-promoted dissolution.[12] Erosion may initially progress through the enamel lamellae, exposing dentinal tubules leading to dentinal sensitivity; however, with continuous erosive insult to the surface enamel, larger areas of the dentoenamel junction will eventually become exposed, leading to enhanced sensitivity.[7,13,14] As the oral cavity pH drops to less than 4.0, the tooth surface erodes, and with each unit of decrease in pH there is a 10-fold increase in enamel solubility resulting in a 100-fold increase in enamel demineralization as the pH approaches 2.0 from 4.0.[11] Importantly, the consumption of beverages with higher concentrations of available hydrogen ions (pH $<$ 4.0) results in the immediate softening of the tooth surface that becomes quite susceptible to removal by abrasion and attrition.[15]

The frequent consumption of acidic beverages is a developing problem for children, teenagers, and adults. The dramatic increase in consumption of acidic soft drinks, fruit juices, fruit drinks, sports drinks, and carbonated beverages is now thought to be the leading cause of dental erosion observed among children and adolescents.[16-18] A literature review of dental erosion in children indicates its prevalence may range from 10% to 80%.[19] Primary teeth, having a thinner enamel layer, are more susceptible to rapid erosion into dentin, leading to exposure of the dental pulp.[19] It is evident that erosion causes many clinical problems, with restorative treatment becoming necessary to replace lost tooth structure, eliminate dental pain, and restore function and esthetics.

Research has indicated pH, not titratable acidity, is the critical determinant of a beverage's erosive potential.[10,19-24] Citrate may also contribute to dental erosion by removing calcium ions through ligand-promoted dissolution (chelation) at a higher pH approaching 6.[12]

The purpose of this study is to determine the hydrogen ion concentration (pH) of beverages including new products that are commercially available in US stores, gas stations, and vending machines. Information obtained from this study will enable dental care practitioners to make appropriate dietary beverage suggestions when counseling patients on the damaging effects of acid in drinks.

METHODS

We purchased nonalcoholic, nondairy beverages from convenience stores, grocery stores, gas stations, and vending machines in the Birmingham, Alabama, area. We studied and categorized a total of 379 beverages. Groups included waters and sport drinks (Table 1); juices and fruit drinks (Table 2); sodas (Table 3); and energy drinks, teas, and coffee (Table 4). We used an Accumet AR15 pH meter (Fisher Scientific) to measure the pH of each beverage in triplicate immediately after opening at a temperature of 25°C. We recorded the pH data as range and mean (standard deviation [SD]). Nutritional information labels on the containers were used to determine the type of acids added to the beverages.

RESULTS

All pH data were expressed as range and mean (SD). Seventy waters and sports drinks had a pH range of 2.67 to 7.20 and a mean (SD) value of 3.31 (0.77) (Table 1). Fifty-one juices had a pH range of 2.25 to 4.69 and a mean (SD) value of 3.48 (0.47) (Table 2). Seventy-eight fruit drinks had a pH range of 2.43 to 3.87 and a mean (SD) value of 2.99 (0.31) (Table 2). Ninety-four sodas had a pH range of 2.32 to 5.24 and a mean (SD) value of 3.12 (0.52) (Table 3). Sixty-eight energy drinks had a pH range of 2.47 to 3.97 and a mean (SD) value of 3.13 (0.29) (Table 4). Seventeen teas had a pH range of 2.85 to 5.18 and a mean (SD) value of 3.48 (0.77); coffee had a pH of 5.11 (Table 4). Most beverages tested had a pH lower than 4.0 (354 of 379; 93%) (Tables 1-4). Relative beverage erosivity zones based on data from studies of apatite solubility in acid indicated 39% (149 of 379) of the beverages tested were considered extremely erosive (pH $<$ 3.0), 54% (205 of 379) were considered erosive (pH = 3.0-3.99), and 7% (25 of 379) were considered minimally erosive (pH $\geq$ 4.0) (Figure[25]). The most acidic beverages tested with a pH lower than 2.4 were lemon juice (pH = 2.25), RC Cola (pH = 2.32), Coca-Cola Classic (pH = 2.37), Coca-Cola Cherry (pH = 2.38), and Pepsi (pH = 2.39). Citric acid, followed by phosphoric acid, and then malic acid were the most frequently added acids to the drinks tested.

DISCUSSION

Laboratory studies have determined the pH of beverages for human consumption.[6,10,22,24,26-29] Our study determined the pH of 379 beverages available to the US consumer and is the most comprehensive in terms of

ABBREVIATION KEY. **NIDCR:** National Institute of Dental and Craniofacial Research.

TABLE 1

pH of waters and sports drinks.*

WATERS AND SPORTS DRINKS	pH (STANDARD DEVIATION)
Extremely Erosive	
Activ Water Focus Dragonfruit	2.82 (0.04)
Activ Water Vigor Triple Berry	2.67 (0.01)
Gatorade Frost Riptide Rush	2.99 (0.01)
Gatorade Lemon-Lime	2.97 (0.01)
Gatorade Orange	2.99 (0.00)
Powerade Fruit Punch	2.77 (0.01)
Powerade Grape	2.77 (0.01)
Powerade Lemon Lime	2.75 (0.01)
Powerade Mountain Berry Blast	2.82 (0.01)
Powerade Orange	2.75 (0.02)
Powerade Sour Melon	2.73 (0.00)
Powerade Strawberry Lemonade	2.78 (0.01)
Powerade White Cherry	2.81 (0.01)
Powerade Zero Grape	2.97 (0.01)
Powerade Zero Lemon Lime	2.92 (0.00)
Powerade Zero Mixed Berry	2.93 (0.01)
Powerade Zero Orange	2.93 (0.01)
Erosive	
Activ Water Power Strawberry Kiwi	3.38 (0.03)
Clear American (flavored water) Kiwi Strawberry	3.70 (0.01)
Clear American (flavored water) Pomegranate Blueberry Acai	3.24 (0.01)
Clear American (flavored water) Tropical Fruit	3.07 (0.01)
Clear American (flavored water) White Grape	3.43 (0.01)
Dasani Grape	3.05 (0.01)
Dasani Lemon	3.03 (0.01)
Dasani Strawberry	3.03 (0.01)
Gatorade Blueberry Pomegranate Low Calorie	3.21 (0.01)
Gatorade Fierce Grape	3.05 (0.00)
Gatorade Fierce Melon	3.05 (0.00)
Gatorade Fruit Punch	3.01 (0.01)
Gatorade Rain Berry	3.17 (0.01)
Gatorade Rain Lime	3.19 (0.01)
Gatorade Rain Strawberry Kiwi	3.17 (0.01)
Propel Berry	3.01 (0.00)
Propel Grape	3.10 (0.01)
Propel Kiwi Strawberry	3.17 (0.00)
Propel Lemon	3.03 (0.00)
S. Pellegrino Sparkling Natural Mineral Water	4.96 (0.09)
Skinny Water Acai Grape Blueberry	3.81 (0.02)
Skinny Water Goji Fruit Punch	3.67 (0.01)
Skinny Water Raspberry Pomegranate	3.68 (0.01)
Sobe Life Water Acai Fruit Punch	3.22 (0.01)
Sobe Life Water Blackberry Grape	3.15 (0.01)
Sobe Life Water Cherimoya Punch	3.28 (0.00)
Sobe Life Water Fuji Apple Pear	3.53 (0.01)
Sobe Life Water Mango Melon	3.29 (0.01)
Sobe Life Water Strawberry Dragonfruit	3.32 (0.01)
Vidration Vitamin Enhanced Water Defense Pomegranate-Acai-Blueberry	2.92 (0.01)
Vidration Vitamin Enhanced Water Energy Tropical Citrus	2.91 (0.01)
Vidration Vitamin Enhanced Water Multi-V Lemon Lime	3.59 (0.01)
Vidration Vitamin Enhanced Water Recover Fruit Punch	3.61 (0.01)
Vitamin Water Connect Black Cherry-Lime	2.96 (0.01)
Vitamin Water Dwnld Berry-Cherry	3.04 (0.01)
Vitamin Water Energy Tropical Citrus	3.15 (0.01)
Vitamin Water Essential Orange-Orange	3.23 (0.00)
Vitamin Water Focus Kiwi-Strawberry	3.04 (0.01)
Vitamin Water Multi-V Lemonade	3.19 (0.01)
Vitamin Water Power C Dragonfruit	3.05 (0.00)
Vitamin Water Revive Fruit Punch	3.65 (0.01)
Vitamin Water Spark Grape-Blueberry	3.19 (0.01)
Vitamin Water XXX Acai-Blueberry-Pomegranate	2.98 (0.01)
Vitamin Water Zero Go-Go Mixed Berry	3.08 (0.01)
Vitamin Water Zero Mega C Grape-Raspberry	3.05 (0.00)
Vitamin Water Zero Recoup Peach-Mandarin	3.01 (0.01)
Vitamin Water Zero Rise Orange	3.46 (0.00)
Vitamin Water Zero Squeezed Lemonade	3.19 (0.00)
Vitamin Water Zero XXX Acai-Blueberry-Pomegranate	3.05 (0.01)
Minimally Erosive	
Aquafina regular	6.11 (0.23)
Birmingham, Alabama, municipal water	7.20 (0.05)
Dasani regular	5.03 (0.04)
Perrier carbonated mineral water	5.25 (0.10)

* For manufacturer information, please see the Appendix (available online at the end of this article).

beverage numbers and diversity. An increase in beverage diversity in the marketplace probably accounts for the large number of beverages procured.

Our results are consistent with reported beverage pH values by other investigators. For example, we determined the pH of Coca-Cola was 2.37 (Table 3) as compared with 2.46,[21] 2.45,[24] 2.48,[26] 2.53,[30] 2.39,[22] 2.40,[25] 2.49,[31] and 2.53[28]; the pH of Schweppes Tonic Water was 2.54 (Table 3) as compared with 2.50[6] and 2.48[25]; the pH of Gatorade Lemon-Lime was 2.97 (Table 1) as compared with 2.93,[31] 2.95,[27] 3.01,[21] 2.90,[10] 3.08,[29] 3.17,[24] and 3.29[22]; the pH of Pepsi was 2.39 (Table 3) as compared with 2.53,[25] 2.36,[22] 2.39,[24] 2.30,[10] 2.46,[26] and 2.53[28]; and the pH of apple juice was 3.57 and 3.66 (Table 2) as compared with 3.60,[10] 3.41,[24] and 3.60.[32]

The pH of extrinsic solutions (dietary beverages) coming into contact with the dentition appears to be the main determinant of dental erosion; the hydrogen ion concentration or acidity, as measured in pH, is primarily responsible for the immediate dissolution and softening of surface tooth structure (erosive

TABLE 2

pH of fruit juices and fruit drinks.*

FRUIT JUICES	pH (STANDARD DEVIATION)
Extremely Erosive	
Lemon juice	2.25 (0.01)
Minute Maid Cranberry Apple Raspberry	2.79 (0.01)
Minute Maid Cranberry Grape	2.71 (0.01)
Ocean Spray Cranberry	2.56 (0.00)
Ocean Spray Cran-Grape	2.79 (0.01)
Ocean Spray Cran-Pomegranate	2.72 (0.01)
Ocean Spray Strawberry Kiwi Juice Cocktail	2.90 (0.01)
V8 Splash Berry Blend	2.94 (0.01)
V8 Splash Strawberry Kiwi	2.99 (0.01)
V8 Splash Tropical Blend	2.93 (0.00)
Erosive	
Amp Energy Juice Mixed Berry	3.62 (0.01)
Amp Energy Juice Orange	3.60 (0.01)
Barber's Orange Juice	3.81 (0.01)
Dole Pineapple Juice	3.40 (0.01)
Juicy Juice Apple	3.64 (0.01)
Juicy Juice Berry	3.78 (0.01)
Juicy Juice Sparkling Apple	3.47 (0.01)
Juicy Juice Sparkling Berry	3.50 (0.01)
Juicy Juice Sparkling Orange	3.49 (0.01)
Minute Maid Apple Juice	3.66 (0.01)
Minute Maid Natural Energy Mango Tropical	3.34 (0.02)
Minute Maid Natural Energy Pomegranate Berry	3.33 (0.01)
Minute Maid Natural Energy Strawberry Kiwi	3.40 (0.01)
Minute Maid Orange Juice	3.82 (0.01)
Minute Maid Pineapple Orange	3.71 (0.01)
Minute Maid Ruby Red Grapefruit Juice	3.07 (0.03)
Naked Blue Machine	3.81 (0.01)
Naked Orange Mango	3.75 (0.01)
Ocean Spray Orange Juice	3.83 (0.01)
Ocean Spray Pineapple Peach Mango Juice Blend	3.64 (0.01)
Ocean Spray Ruby Red	3.07 (0.01)
Simply Apple	3.67 (0.01)
Simply Orange Orange Juice	3.78 (0.00)
Tango Energy Juice	3.47 (0.00)
Tropicana 100% Juice Apple Juice	3.50 (0.02)
Tropicana 100% Juice Orange Juice	3.80 (0.01)
Tropicana Apple Orchard Style Juice	3.57 (0.00)
Tropicana Grape Juice	3.29 (0.01)
V8 Fusion Cranberry Blackberry	3.56 (0.01)
V8 Fusion Pomegranate Blueberry	3.66 (0.00)
V8 Fusion Strawberry Banana	3.66 (0.00)
Very Fine Grapefruit Juice	3.22 (0.03)
Welch's 100% Grape Juice	3.38 (0.00)
Welch's Apple Juice	3.57 (0.01)
Welch's Orange Juice	3.73 (0.00)

* For manufacturer information, please see the Appendix (available online at the end of this article).

TABLE 2 (CONTINUED)

FRUIT JUICES	pH (STANDARD DEVIATION)
Minimally Erosive	
Campbell's Tomato Juice	4.01 (0.01)
Naked Protein Zone	4.69 (0.01)
Tropicana Orange Juice (With Calcium)	4.09 (0.01)
V8 Vegetable Juice	4.23 (0.01)
V8 Vegetable Juice Low Sodium	4.17 (0.01)
V8 Vegetable Juice Spicy Hot	4.19 (0.00)
FRUIT DRINKS	**pH (STANDARD DEVIATION)**
Extremely Erosive	
Barber's Lemonade	2.69 (0.00)
Barber's Orange Drink	2.96 (0.00)
Bug Juice Berry Raspberry	2.99 (0.01)
Bug Juice Grapey Grape	2.83 (0.00)
Country Time Lemonade	2.72 (0.01)
Crystal Light Fruit Punch	2.96 (0.02)
Crystal Light Raspberry Ice	2.77 (0.01)
Hi-C Tropical	2.81 (0.03)
Kool-Aid Mix Cherry	2.71 (0.00)
Kool-Aid Mix Grape	2.83 (0.01)
Kool-Aid Mix Lemon-Lime	2.73 (0.01)
Kool-Aid Mix Orange	2.77 (0.01)
Kool-Aid Mix Pink Lemonade	2.66 (0.01)
Kool-Aid Mix Tropical Punch	2.69 (0.00)
Minute Maid Fruit Punch	2.86 (0.00)
Minute Maid Lemonade	2.57 (0.01)
Minute Maid Orangeade	2.85 (0.00)
Minute Maid Pink Lemonade	2.59 (0.00)
Simply Lemonade	2.61 (0.01)
Snapple Kiwi Strawberry	2.77 (0.01)
Snapple Mango Madness	2.89 (0.01)
Sobe Black and Blueberry Brew	2.69 (0.00)
Sobe Citrus Energy	2.63 (0.00)
Sobe Power Fruit Punch	2.43 (0.02)
Sobe Strawberry Banana	2.62 (0.01)
Sun Fresh Lemonade	2.68 (0.01)
Sunny D Smooth	2.92 (0.01)
Sunny D Tangy Original	2.86 (0.01)
Tropicana Cranberry Cocktail	2.70 (0.01)
Tropicana Juice Beverage Cranberry	2.59 (0.00)
Tropicana Juice Beverage Grape	2.58 (0.00)
Tropicana Lemonade	2.70 (0.01)
Tropicana Twister Blue Raspberry Rush	2.62 (0.00)
Tropicana Twister Cherry Berry Blast	2.63 (0.00)
Tropicana Twister Orange Strawberry Banana Burst	2.89 (0.01)
Tropicana Twister Strawberry Kiwi Cyclone	2.59 (0.01)
Welch's Blueberry Kiwi Blast	2.57 (0.01)
Welch's Cranberry	2.59 (0.02)
Welch's Grape Juice Cocktail	2.92 (0.01)

* For manufacturer information, please see the Appendix (available online at the end of this article).

TABLE 2 (CONTINUED)

FRUIT DRINKS	pH (STANDARD DEVIATION)
Welch's Ruby Red Grapefruit Juice	2.97 (0.01)
Erosive	
Barber's Fruit Punch	2.96 (0.00)
Bug Juice Fruity Punch	3.09 (0.00)
Bug Juice Leapin Lemonade	3.06 (0.00)
Bug Juice Whistlin Watermelon	3.40 (0.01)
CapriSun Surfer Cooler	3.08 (0.00)
Crystal Light Green Tea Raspberry Mix	3.11 (0.02)
Fuze Banana Colada	3.45 (0.03)
Fuze Blueberry Raspberry	3.20 (0.01)
Fuze Green Tea Honey and Ginseng	3.28 (0.02)
Fuze Orange Mango	3.34 (0.02)
Fuze Peach Mango	3.53 (0.01)
Fuze Strawberry Banana	3.54 (0.01)
Fuze Strawberry Guava	3.55 (0.02)
Fuze Strawberry Melon	3.18 (0.01)
Fuze Tropical Punch	3.17 (0.01)
Jumex Guava	3.38 (0.02)
Jumex Mango	3.41 (0.01)
Jumex Peach	3.33 (0.02)
Jumex Strawberry Banana	3.68 (0.01)
Kool-Aid Burst (Tropical)	3.07 (0.01)
Little Hug Grape	3.09 (0.01)
Little Hug Orange	3.00 (0.01)
Mondo (Legendary Berry)	3.07 (0.01)
Mondo (Primo Punch)	3.10 (0.01)
Sesame Street Elmo's Punch	3.87 (0.01)
Sobe Fuji Apple Cranberry (low calorie)	3.16 (0.01)
Sobe Orange Carrot	3.34 (0.00)
Sobe Pina Colada	3.25 (0.01)
TumE Yummies Fruitabulous Punch	3.35 (0.00)
TumE Yummies Orangearific	3.34 (0.01)
TumE Yummies Soursational Raspberry	3.18 (0.00)
TumE Yummies Very Berry Blue	3.33 (0.00)
Vitamin Stix Dragonfruit Acai	3.11 (0.01)
Vitamin Stix Passionfruit Citrus	3.19 (0.01)
Vitamin Stix Strawberry Kiwi	3.06 (0.01)
Welch's Orange Pineapple	3.20 (0.01)
Welch's Strawberry Kiwi	3.03 (0.01)

potential) by acidic beverages composed of weak acids, for example, citric and phosphoric acid.[10,12,19-24] The titratable acidity or buffer capacity—intrinsic to these acids—does not play as critical a role in dental erosion as pH because of the limited time exposure the dentition has with ingested liquids during each drinking and swallowing episode.[19,20,22,33,34] Therefore, pH or hydrogen ion concentration (acidity) at the time of dental exposure is the important chemical parameter to assess when determining the erosive potential of beverages.

Teeth erode in the pH range of 2.0 to 4.0, although surface enamel starts to demineralize as the pH drops to less than 5.5 when the external milieu of the oral cavity becomes undersaturated for hydroxyapatite.[35] Apatite solubility studies indicate a logarithmic increase in apatite solubility as pH drops under laboratory equilibrium conditions as can be seen in the solubility curve (Figure).[25,36] Apatite solubility above pH 4.0 is minimal; a drop of 1 unit to 3.0 results in a 10-fold increase in apatite solubility. Moreover, as pH drops from 3.0 to 2.0 there is an increase in apatite solubility that approaches 1,000 grams per liter (Figure). Based on the apatite solubility curve in the figure, we propose that the chemical erosive potential of beverages be segregated into 3 zones:

- extremely erosive: pH lower than 3.0;
- erosive: pH 3.0 to 3.99;
- minimally erosive: pH more than or equal to 4.0.

Furthermore, the relative erosivity zones (extremely erosive, erosive, minimally erosive) of 379 beverages as determined by pH testing indicated 39% (149 of 379) were extremely erosive ($pH < 3.0$), 54% (205 of 379) were erosive ($pH = 3.0\text{-}3.99$), and 7% (25 of 379) were minimally erosive ($pH \geq 4.0$). Although apatite solubility as a function of pH is on a continuum, the segregation of erosive potential into 3 discrete zones would be helpful to the dental clinician when providing a dietary guide of relative beverage erosivity to the patient. The prevailing paradigm for dental erosion remains: as the pH of the oral milieu decreases, the solubility of apatite on the tooth surface increases logarithmically.[11]

Dental erosion from beverages is primarily caused by phosphoric acid and citric acid; both are triprotic acids with 3 available hydrogen ions, enabling proton-promoted dissolution.[12,37] Chelation or ligand-promoted dissolution by anionic citrate contributes to enamel demineralization by the removal of calcium ions at a higher pH range approaching 6.[12] At the erosive pH of 3, only 3% of citrate ions are appropriately ionized to chelate calcium ions, indicating their contribution to the erosive process at this pH is minimal.[38] However, if anionic citrate were to remain within the oral cavity for extended time intervals, allowing the pH to rise to 6, chelation could play a contributing role in the erosive process. For example, the eating of citrus fruits more than twice a day has been associated with dental erosion.[39] Nevertheless, high concentrations of hydrogen ions reflected by low pH from citric or phosphoric acid results in undersaturation for both fluor- and hydroxyapatite, leading to dental erosion. Hence, pH is the controlling parameter in determining the erosive potential of beverages.[11,19-24]

Knowledge of beverage pH is essential for the development of preventive strategies for patients with clinical erosion.[7,40,41] The elimination of extremely erosive drinks ($pH < 3.0$), minimizing erosive drinks ($pH = 3.0\text{-}3.99$), and substituting drinks with a ($pH \geq 4.0$) would be

TABLE 3

pH of sodas.*

SODA	pH (STANDARD DEVIATION)
Extremely Erosive	
7UP Cherry	2.98 (0.01)
Boylan's Black Cherry	2.76 (0.02)
Boylan's Grape	2.91 (0.01)
Boylan's Sugar Cane Cola	2.54 (0.01)
Canada Dry Ginger Ale	2.82 (0.01)
Coca-Cola Caffeine Free	2.34 (0.03)
Coca-Cola Cherry	2.38 (0.03)
Coca-Cola Cherry Zero	2.93 (0.01)
Coca-Cola Classic	2.37 (0.03)
Coca-Cola Lime Diet	2.96 (0.03)
Coca-Cola Zero	2.96 (0.03)
Crush Grape	2.76 (0.01)
Crush Orange	2.87 (0.01)
Dr. Pepper	2.88 (0.04)
Fanta Grape (2 liter)	2.67 (0.02)
Fanta Orange	2.82 (0.02)
Fanta Pineapple (2 liter)	2.79 (0.02)
Fanta Strawberry	2.84 (0.01)
Grapico	2.77 (0.03)
Hansen's Cane Soda Cherry Vanilla Crème	2.91 (0.01)
Hansen's Cane Soda Kiwi Strawberry	2.59 (0.01)
Hansen's Cane Soda Mandarin Lime	2.57 (0.01)
Hansen's Cane Soda Pomegranate	2.55 (0.00)
Hawaiian Punch (Fruit Juicy Red)	2.87 (0.01)
Jolly Rancher Grape	2.60 (0.01)
Jolly Rancher Orange	2.88 (0.01)
Jones Blue Bubblegum	2.99 (0.01)
Jones Green Apple Soda	2.65 (0.01)
Jones Mandarin Orange	2.93 (0.00)
Jones M.F. Grape	2.89 (0.02)
Jones Orange & Cream Soda	2.79 (0.01)
Jones Strawberry Lime	2.81 (0.02)
Mr. Pibb Xtra	2.80 (0.01)
Natural Brew Draft Root Beer	2.90 (0.00)
Pepsi	2.39 (0.03)
Pepsi Max	2.74 (0.01)
Pepsi Max Ceasefire	2.70 (0.01)
Pepsi Wild Cherry	2.41 (0.03)
RC Cola	2.32 (0.02)
Schweppes Tonic Water	2.54 (0.03)
Sunkist Orange	2.98 (0.01)
Sunkist Peach	2.89 (0.01)
Sunkist Strawberry	2.99 (0.01)
Tab	2.72 (0.01)
Vault	2.77 (0.02)
Vault Red Blitz	2.80 (0.01)
Vault x	2.89 (0.03)
Erosive	
7UP	3.24 (0.02)
7UP Diet	3.48 (0.00)
A&W Cream Soda	3.86 (0.01)
Ale 8-One	3.13 (0.01)
Boylan's Orange Cream	3.59 (0.01)
Boylan's Orange Soda	3.22 (0.00)
Boylan's Original Birch Beer	3.80 (0.00)
Buffalo Rock Ginger Ale	3.23 (0.01)
Coca-Cola Caffeine Free Diet	3.04 (0.01)
Coca-Cola Diet	3.10 (0.05)
Dr Pepper Cherry	3.06 (0.02)
Dr Pepper Diet	3.20 (0.00)
Dr Pepper Diet Cherry	3.32 (0.01)
Fresca (1 liter)	3.08 (0.01)
Grapico Diet	3.04 (0.01)
Hansen's Cane Soda Black Cherry Diet	3.47 (0.02)
Hansen's Cane Soda Creamy Root Beer Diet	3.73 (0.01)
Izze Sparkling Blackberry	3.28 (0.01)
Izze Sparkling Clementine	3.27 (0.01)
Izze Sparkling Pomegranate	3.01 (0.01)
Jones Cream Soda	3.04 (0.01)
Jones Red Apple	3.40 (0.02)
Jones Root Beer	3.42 (0.02)
Mellow Yellow	3.03 (0.00)
Mountain Dew (regular)	3.22 (0.07)
Mountain Dew Code Red	3.27 (0.01)
Mountain Dew Diet	3.18 (0.01)
Mountain Dew Voltage	3.05 (0.01)
Mug Root Beer	3.88 (0.02)
Pepsi Diet	3.02 (0.01)
Sierra Mist	3.09 (0.02)
Sierra Mist Diet	3.31 (0.01)
Sprite	3.24 (0.05)
Sprite Zero	3.14 (0.01)
Sunkist Diet	3.49 (0.01)
Sunkist Solar Fusion Tropical Mandarin	3.02 (0.01)
Welch's Grape Soda	3.11 (0.02)
Minimally Erosive	
A&W Root Beer	4.27 (0.02)
A&W Root Beer Diet	4.57 (0.00)
Barq's Root Beer	4.11 (0.02)
Boylan's Creme Soda	4.17 (0.02)
Boylan's Diet Black Cherry	4.00 (0.01)
Boylan's Diet Root Beer	4.05 (0.02)
Boylan's Root Beer	4.01 (0.01)
Canada Dry Club Soda	5.24 (0.03)
IBC Root Beer	4.10 (0.02)
Maine Root Root Beer	4.36 (0.02)

* For manufacturer information, please see the Appendix (available online at the end of this article).

TABLE 4

pH of energy drinks and teas and coffee.*

ENERGY DRINKS	pH (STANDARD DEVIATION)
Extremely Erosive	
24:7 Energy Cherry Berry	2.61 (0.01)
180 Blue Orange Citrus Blast	2.82 (0.00)
180 Blue With Acai	2.82 (0.01)
5-Hour Energy Berry	2.81 (0.03)
5-Hour Energy Extra Strength	2.82 (0.00)
5-Hour Energy Lemon-Lime	2.81 (0.00)
Amp Energy Elevate	2.79 (0.01)
Amp Energy Overdrive	2.78 (0.01)
Amp Energy regular	2.81 (0.01)
Amp Energy Sugar Free	2.86 (0.01)
Jolt Blue Bolt	2.96 (0.00)
Jolt Passion Fruit	2.82 (0.01)
Jolt Power Cola	2.47 (0.01)
Meltdown Energy Peach Mango	2.77 (0.00)
No Fear regular	2.97 (0.02)
Orange County Choppers	2.78 (0.02)
Purple Stuff Lean	2.87 (0.01)
Redline Peach Mango	2.74 (0.02)
Redline Princess Exotic Fruit	2.85 (0.01)
Redline Triple Berry	2.77 (0.01)
Rockstar Energy Drink	2.74 (0.01)
Rockstar Punched (Energy + Punch)	2.83 (0.01)
Rockstar Recovery	2.84 (0.01)
Erosive	
Crunk Citrus	3.20 (0.01)
Crunk Energy Drink	3.31 (0.01)
Crunk Grape Acai Energy Drink	3.30 (0.01)
Crunk Low Carb Sugar Free	3.34 (0.00)
Drank	3.09 (0.01)
Fuel Energy Shots Lemon Lime	3.97 (0.01)
Fuel Energy Shots Orange	3.44 (0.01)
Full Throttle Blue Agave	3.10 (0.01)
Full Throttle Citrus	3.09 (0.01)
Full Throttle Red Berry	3.08 (0.01)
Hydrive Blue Raspberry	3.45 (0.01)
Hydrive Citrus Burst	3.03 (0.01)
Hydrive Lemon Lime	3.42 (0.01)
Hydrive Triple Berry	3.15 (0.01)
Jolt Ultra Sugar Free	3.14 (0.00)
Killer Buzz	3.23 (0.01)
Killer Buzz Sugar Free	3.36 (0.00)
Monster Assault	3.58 (0.01)
Monster Energy	3.48 (0.01)
Monster Hitman Energy Shot	3.44 (0.01)
Monster Khaos	3.47 (0.01)
Monster Low Carb	3.60 (0.01)
Monster M-80	3.29 (0.00)
Monster MIXXD	3.35 (0.00)
Nitrous Monster Anti-Gravity	3.64 (0.01)
Nitrous Monster Killer B	3.31 (0.00)
Nitrous Monster Super Dry	3.46 (0.00)
No Fear Sugar Free	3.06 (0.01)
NOS Fruit Punch	3.32 (0.00)
NOS Grape	3.27 (0.01)
NOS High Performance Energy Drink	3.31 (0.01)
NOS Power Shot	3.03 (0.02)
Redbull regular	3.43 (0.01)
Redbull Shot	3.25 (0.03)
Redbull Sugar Free	3.39 (0.00)
Redbull Sugar Free Shot	3.28 (0.02)
Redline Xtreme Grape	3.23 (0.01)
Redline Xtreme Triple Berry	3.24 (0.01)
Redline Xtreme Watermelon	3.41 (0.00)
Rhinos Energy Drink	3.51 (0.01)
Rhinos Sugar Free Energy Drink	3.32 (0.01)
Rockstar Energy Cola	3.14 (0.01)
Rockstar Juiced Energy + Guava	3.16 (0.01)
Rockstar Juiced Energy + Juice Mango Orange Passion	3.05 (0.01)
Rockstar Sugar Free	3.15 (0.03)
TEAS AND COFFEE	**pH (STANDARD DEVIATION)**
Extremely Erosive	
Admiral Iced Tea Raspberry	2.94 (0.00)
Arizona Iced Tea	2.85 (0.03)
Lipton Green Tea With Citrus	2.93 (0.00)
Lipton Green Tea With Citrus Diet	2.92 (0.00)
Nestea Iced Tea With Natural Lemon Flavor	2.94 (0.01)
Nestea Red Tea Pomegranate and Passion Fruit	2.87 (0.01)
Snapple Peach Tea	2.94 (0.01)
Snapple Raspberry Tea	2.92 (0.00)
Erosive	
Admiral Iced Tea Green Tea	3.72 (0.01)
Admiral Iced Tea Mango	3.41 (0.00)
Admiral Iced Tea Sweet Tea	3.76 (0.01)
Arizona Diet Green Tea + Ginseng	3.29 (0.01)
Snapple Diet Raspberry Tea	3.39 (0.02)
Snapple Diet Peach Tea	3.32 (0.01)
Minimally Erosive	
Milo's Famous Sweet Tea	4.66 (0.02)
Milo's No Calorie Famous Sweet Tea	5.18 (0.03)
Red Diamond Tea Fresh Brewed Sweet Tea	5.04 (0.02)
Starbucks Medium Roast	5.11 (0.05)

* For manufacturer information, please see the Appendix (available online at the end of this article).

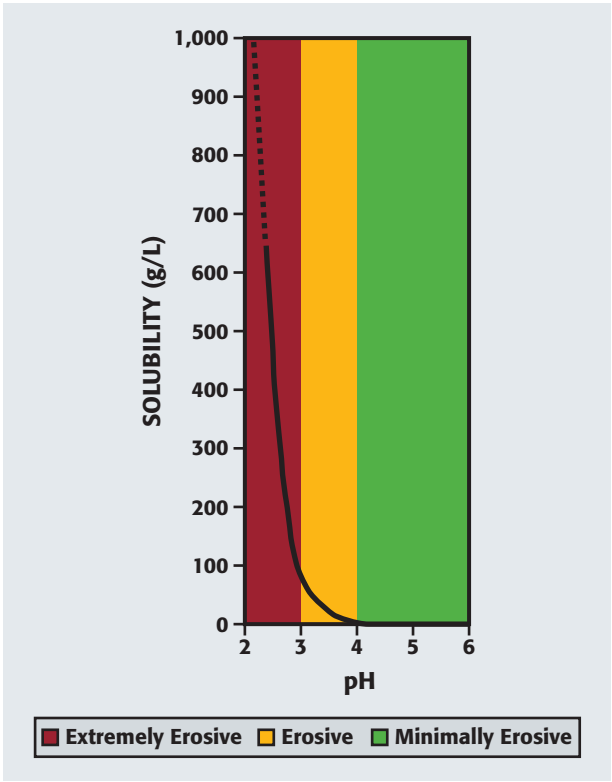

Figure. Erosion zones based on theoretical solubility of apatite as a function of pH. g: Grams. L: Liters. *Adapted with permission of S. Karger AG from Larsen and Nyvad.*[25]

prudent advice for the prevention of erosion. Fluoride does not prevent erosion because highly acidic environments solubilize fluorapatite and calcium fluoride.[35,42,43] Xerostomic conditions exacerbate the erosive process from lack of saliva essential for the dilution and buffering of hydrogen ions in the oral cavity.[39,44] The primary dentition of children is highly susceptible to the erosive process and low pH beverages should not be placed in a baby bottle, especially at sleep time when the mouth is xerostomic. Athletes may have decreased salivary flow rates due to dehydration from profuse sweating after prolonged, intense physical activity and should rehydrate with water.[45] Geriatric patients taking medications with xerostomic side effects are vulnerable to erosion, and the exposure of cementum and dentin due to gingival recession allow for root demineralization and hypersensitivity from contact with erosive drinks.[7,14,46] Obviously, saliva is an important ameliorating milieu for the abrogation of dental erosion by not only diluting and buffering extrinsic acids, but also providing the source of glycoproteins that coat the tooth surface as the protective acquired pellicle.[20,43,44] However, when acidic beverage consumption is excessive, saliva provides the dentition limited protection from erosion.[47]

CONCLUSIONS

Studies suggest that pH is the primary determinant of beverage erosive potential. We determined the pH of 379 nonalcoholic, nondairy beverages and assessed them for relative erosivity. Relative beverage erosivity zones based on previous studies of apatite solubility in acid indicated 39% (149 of 379) of the beverages tested were considered extremely erosive (pH $<$ 3.0), 54% (205 of 379) were considered erosive (pH $=$ 3.0-3.99), and 7% (25 of 379) were considered minimally erosive (pH $\geq$ 4.0). The most acidic beverages tested with a pH of less than 2.4 were lemon juice (pH $=$ 2.25), RC Cola (pH $=$ 2.32), Coca-Cola Classic (pH $=$ 2.37), Coca-Cola Cherry (pH $=$ 2.38), and Pepsi (pH $=$ 2.39). Information obtained from this study will enable dental care practitioners to make appropriate dietary suggestions when counseling patients about the damaging dental effects of acids in the beverages they drink. ■

SUPPLEMENTAL DATA

Supplemental data related to this article can be found at: http://dx.doi.org/10.1016/j.adaj.2015.10.019.

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