A method and apparatus for fractionating liquid jets into a plurality of unitary, discrete liquid droplets for successively impacting a selected area, for example in the oral cavity, for stimulating the gum tissues and for cleaning the teeth and interdental spaces. Such a system for the practice of body care, for example, oral hygiene, generally comprises a reservoir for the liquid to be fractionated, a nozzle member for directing the fractionated jet against the area to be stimulated and cleaned, a pump for supplying the liquid under pressure from the reservoir to the nozzle member, and a suitable conduit for transferring the liquid from the reservoir to the pump and from the pump to the nozzle member. In a first embodiment, means are provided for producing vibrations and transferring the vibrations to the nozzle member to cause the liquid jet to divide into a plurality of unitary, discrete liquid droplets after exiting from the nozzle member. The parameters for the production of such liquid droplets are disclosed and include the ejection velocity of the jet, the fluid flow velocity through the nozzle, the nozzle opening diameter, the frequency of pulsation, the diameter of the formed droplets, and the distance from the tip at which the liquid droplets are completely formed and separated. The effect of the rugosity of the nozzle, the surface tension of the fluid, and the efficiency of the system are also disclosed. In a second embodiment, the physical construction of the nozzle effectively fractionates the jet and comprises an obturating member disposed in the free end of the nozzle member which includes a plurality of passages located therethrough. The cross-sectional area of each of the passages is much smaller than the adjacent liquid conduit of the nozzle member.

25 Claims, 11 Drawing Figures
FIG. 1.

FIG. 2.

FIG. 4.

<table>
<thead>
<tr>
<th>DROPLET PARAMETER</th>
<th>NOZZLE OPENING DIAMETER AT 500 cps, 5 M/SEC. EJECTION VELOCITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOZZLE SIZE</td>
<td>0.2 M M</td>
</tr>
<tr>
<td>DIAMETER OF DROPLET</td>
<td>0.77 M M</td>
</tr>
<tr>
<td>SURFACE PRESSURE</td>
<td>3.82 g/cm²</td>
</tr>
<tr>
<td>WEIGHT</td>
<td>0.239 mg</td>
</tr>
<tr>
<td>RELATIVE HARDNESS OF DROPLET</td>
<td>1</td>
</tr>
<tr>
<td>RATIO OF CROSS SECTIONAL AREAS OF NOZZLE</td>
<td>1</td>
</tr>
<tr>
<td>RATIO OF CORRESPONDING AREA OF DROPLET</td>
<td>1</td>
</tr>
<tr>
<td>FLOW RATES</td>
<td>1</td>
</tr>
</tbody>
</table>

TYPICAL CHARACTERISTICS OF DROPLETS PRODUCED AT A FREQUENCY OF 500 cps AND AN EJECTION VELOCITY OF 5M/SEC. FOR THE EXTREME NOZZLE OPENING DIAMETERS
FIG. 3.

TABLE OF MAJOR CHARACTERISTICS OF THE METHOD AND APPARATUS FOR PRODUCING DISCRETE LIQUID DROPLETS

<table>
<thead>
<tr>
<th>DIAMETER OF OPENING (MM)</th>
<th>MINIMUM</th>
<th>≤ 0.15 TO 0.2 MM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAXIMUM</td>
<td>≤ 1.1 MM</td>
</tr>
<tr>
<td>FREQUENCY OF VIBRATION (cps)</td>
<td>MINIMUM</td>
<td>200 cps</td>
</tr>
<tr>
<td></td>
<td>MAXIMUM</td>
<td>5000 cps</td>
</tr>
<tr>
<td>EJECTION VELOCITY</td>
<td>MINIMUM</td>
<td>THEORETICAL: 1.221f; WHERE V = VELOCITY (CM/SEC; f = VIBRATION FREQUENCY (cps); AND f = DIAMETER OF LIQUID JET (CM))</td>
</tr>
<tr>
<td></td>
<td>MAXIMUM</td>
<td>PRACTICAL: 2.51f</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 ≤ V ≤ 7 m/sec.</td>
</tr>
</tbody>
</table>

CHARACTERISTICS OF DROPLETS PRODUCED THERBY

<table>
<thead>
<tr>
<th>DIAMETER OF DROplet</th>
<th>f = 2 \left[ \frac{3/4 \pi \alpha^2 S \mu^2}{f} \right]^{1/3} WHERE f = VIBRATION FREQUENCY (cps); S = CROSS SECTION OF NOZZLE OPENING; \alpha = CONTRACTION COEFFICIENT; AND \mu = JET VELOCITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>DISTANCE OF FORMATION</td>
<td>MINIMUM</td>
</tr>
<tr>
<td></td>
<td>MAXIMUM</td>
</tr>
<tr>
<td>SURFACE PRESSURE OF DROPLET</td>
<td>T = SURFACE TENSION</td>
</tr>
<tr>
<td></td>
<td>p = \frac{4T}{d} (72 DYNEs/CM FOR WATER IN AIR); AND D = DIAMETER OF DROPLET (CM)</td>
</tr>
<tr>
<td>WEIGHT OF DROPLET</td>
<td>p = \frac{4}{3} \pi r^3 \gamma; \gamma = 1 g/CM^2 FOR WATER</td>
</tr>
</tbody>
</table>
FRACTIONATED LIQUID JET

CROSS-REFERENCE TO A RELATED APPLICATION

The subject matter of this application is related to the subject matter disclosed and claimed in United States patent application Ser. No. 227,640, filed Feb. 17, 1972, which is a continuation of Ser. No. 887,586, filed Dec. 23, 1969, both now abandoned, both assigned to the assignee of this application.

BACKGROUND OF THE INVENTION

This invention relates to a method and apparatus adapted to provide body care and especially suited for oral hygiene. More particularly, this invention relates to a method and apparatus for fractionating liquid jets into a plurality of unitary, discrete, liquid droplets for successively impacting a selected area, for example, the oral cavity, to stimulate the gum tissues and to clean the teeth and interdental spaces. Still more particularly, this invention relates to the characteristics of such a method and apparatus in terms of the theoretical and practical limits of the precise parameters involved for the production of such liquid droplets.

In the prior art, a number of methods and apparatuses for caring for the body with a flow of fluid have been developed. Devices are known for cleansing and massaging the external bodily surfaces of both animals and humans, ranging from such simple fluid lavage devices as the well-known showerhead and whirlpool baths to more specialized fluid massage techniques and devices. For particularized body care, specialized methods and devices have been developed including, by way of example, vaginal and anal douching apparatuses, and wound lavage devices. It is thus a broad aim of this invention to provide a method and apparatus broadly directed to body care by the use of a liquid jet which has been fractionated into a plurality of unitary, discrete liquid droplets.

In the art of oral hygiene, it has long been a problem to find an effective and sufficient solution to the problem of cleaning the teeth and massaging the gum tissues while also cleaning interdental spaces. Perhaps the best known solution rests in the conventional manually operated toothbrush, a device which has proved highly ineffective in cleaning the interdental spaces and massaging the gums for a number of reasons, including the lack of vigor of the user and the time involved to achieve even a partially effective gum massage and interdental cleaning. Where additional apparatus has been used for interdental cleaning and gum massaging, such as a protrusion on the handle of the toothbrush, or toothpick-like devices, the result has been similarly ineffective for the reasons stated above, as well as because of the requirement that the interdental cleaning and gum massage takes on the character of a separate and distinct operation beyond that of merely brushing the teeth. Accordingly, the prior art has proposed a number of appliances for dental care which are intended for cleaning the interdental spaces as well as massaging the gums of the users, but also achieving an effective cleaning of the teeth. For example, the British Pat. No. 382,430 and the corresponding U.S. Pat. No. 1,995,424 to K. E. L. Guinness, in particular, describe an appliance especially aimed for use by dentists which comprises the combination of a nozzle projecting a liquid onto the teeth and/or gums of the patients, a reservoir for the liquid to be projected, and a device for pumping the liquid intermittently from the reservoir to the nozzle to form a jet of liquid which is pulsed at a frequency of about 3,300 or 3,600 pulsations per minute.

An apparent improvement of this device has also been described in U.S. Pat. No. 3,227,158 to J. W. Mattingly. This improvement consists substantially of the limitation of the jet pulsation frequency to values on the order of 1,200 to 1,600 pulsations per minute to accommodate the relaxation time of the mucous membranes of the gums which are subjected to the impact of the pulsating, but continuous jet. The relaxation time is that time which is necessary for the gum tissues to recover to their normal state after having been locally compressed by the jet and was there considered to be determined with a view toward optimizing the massaging effect on the gum tissues.

Whereas these appliances have apparently effectively allowed massaging the gums at a more or less efficacious manner, none of them has, however, provided a radical solution of the problem, faced by humans at least daily, of cleaning the teeth and the interdental spaces of the mouth.

Thus, whereas a jet of liquid delivered by one or the other of the above described appliances is of a pulsed nature and consequently produces on the teeth surfaces to be cleaned a continuous jet of liquid pulsed at a frequency corresponding to that of the pulsations with which the jet is actuated, the disaggregation by the jet of the deposits which may cover the surfaces occurs only very slowly and in a generally unsatisfactory manner even when a very large amount of liquid is projected onto those surfaces.

It has also been noted in this connection that when a liquid thread segment, having a mass corresponding to that emitted by a nozzle during the period of one pulsation of the jet, is projected onto a surface covered with a deposit, the disaggregation of that deposit does not practically occur except in the impact zone of the liquid thread segment and then only at the instant when the impact occurs since the mass of liquid which arises thereafter on the deposit simply flows over the deposit to erode only the peripheral parts of the deposit. Thus, the phenomenon of the buffer zone largely defeats the disaggregating impact of the later-arriving fluid. For these purposes, the buffer zone can be defined as the damping phenomenon on the impact surface caused by an incident liquid jet as the result of the residual fluid film which remains present on the impact surface.

Since the issuance of the patents previously mentioned, appliances for effecting only a mechanical or pneumatic massage of the gums, and toothbrushes with increasingly perfected action, have also been proposed. For example, an electric toothbrush identified by the trademark Broxodent includes an oscillatory motor which confers a particular effectiveness to the brush, especially with regard to cleaning the teeth, and to a lesser extent, the interdental spaces, while somewhat massaging the gums.

Moreover, certain other devices have been proposed which represent a compromise between the pulsed jet appliances previously described and the toothbrushes having mechanically driven brushes. These devices comprise a reservoir for liquid, a pump feeding a flexible conduit from this reservoir, and a handle arranged
at the free end of the conduit for removably supporting either a nozzle or a small vibrating brush, the latter being intended to palliate the problems mentioned above. For example, the use of this device generally requires a long and fastidious operation, especially if the device in question is used in turn by various members of a family each having his own nozzle and small brush. The user thus must remove the brush or nozzle of another family member from the apparatus, fit his nozzle thereon, clean his teeth by jet projection, remove the nozzle, and replace it by his own brush to conclude the cleaning, then rinse the brush and perhaps rinse the nozzle. In addition to these practical drawbacks, this device has another undesirable feature which is primarily economic, namely the wear of the small brushes which have to be periodically replaced.

Accordingly, it is an object of this invention to provide a method and apparatus for body care and especially for oral hygiene, which obviates the problems of the prior art.

It is another object of this invention to provide a method and apparatus for fractionating liquid jets into a plurality of unitary, discrete liquid droplets for use in body care, and especially for use in oral hygiene for stimulating the gum tissues and for cleaning the teeth and interdental spaces.

It is a more specific object of this invention to provide, in one embodiment thereof, means for imparting vibrations to a nozzle for transmitting liquid from a reservoir under pressure thus to fractionate the jet into a plurality of liquid masses.

It is an additional object of this invention, and another embodiment thereof, to provide a nozzle structure which is capable of producing a plurality of unitary, discrete liquid droplets without requiring means for imparting a vibration to the nozzle.

It is still another object of this invention to consider the effect of various parameters such as the ejection velocity of the jet, the velocity of fluid flow through the nozzle, the nozzle diameter, the frequency of vibration, and the like, on the production of a plurality of such droplets for successively impacting a selected area to be massaged and/or cleaned.

It is an additional object of this invention to consider, in addition to the parameters mentioned above, the effect of nozzle rugosity, the effect of buffer zone damping, and the relative efficiency of certain body care devices.

These and other objects of this invention will become apparent from the written description of the invention which follows, taken in conjunction with the accompanying drawings.

### BRIEF DESCRIPTION OF THE INVENTION

This invention, directed to overcoming the problems of the prior art and to achieving the aforementioned objectives, comprises a method and apparatus for fractionating liquid jets into a plurality of discrete, unitary liquid droplets which, when projected onto an area of the body stimulate and clean that area. In particular, such liquid droplets, when projected on the teeth and/or gums of the user, stimulate the gum tissues and clean the teeth and interdental spaces. Such a system for the practice of oral hygiene generally comprises a reservoir for the liquid, such as water or water and a suitable mouthwash, nozzle means for projecting a liquid to a desired location in the mouth of the user, and means for supplying the liquid under pressure from the reservoir to the nozzle member. According to the invention, means are provided for fractionating the liquid into a plurality of discrete unitary liquid droplets which are substantially free from voids within each of the droplets for successively impacting the area to be cleaned and/or stimulated. In a first embodiment, means are provided for generating a vibration and for transmitting the vibrations to a nozzle means where the vibrations are imparted to the liquid passing therethrough to cause the liquid to divide into a plurality of discrete, unitary liquid droplets after exiting from the nozzle means. The useful diameters of nozzle to produce such droplets are included in a range between about 0.2 and about 1.1 mm, and preferably between about 0.4 and 0.6 mm. The frequency of vibration is generally greater than about 200 cps to assure a minimum efficacy and less than about 5,000 cps to avoid cavitation in the fluid so that the droplets are substantially free from voids within each of the droplets. The diameter of the formed droplets is larger than the diameter of the nozzle opening from which they are issued, a factor which is opposite to that possessed by liquid droplets from jets produced by ultrasonic vibrations in which the diameter of the jet is smaller than the diameter of the opening. The ejection velocity of the jet is at least about 2 m/s which provides a certain efficacy and, at maximum, is about 7 m/s in the best cases. The ejection velocity is generally limited by the turbulence of the jet so that the ejection velocity is preferably in the range between about 2 and about 5 m/s. The liquid droplets thus formed according to the invention are entirely formed and separated when they are at a distance from the tip of the opening of the nozzle ranging from about 3 times to about 90 times the diameter of the nozzle, and this distance appears to be proportional to the ejection speed of the liquid. The droplets produced according to the invention from a nozzle having a diameter of 0.2 mm for a preferred frequency of 500 cps and an ejection velocity of 5 m/sec have a surface pressure of 3.82 g/cm² and a weight of 0.239 mg (for water) for droplets having a diameter of 0.77 mm. Under the same conditions of frequency and ejection velocity, droplets from a nozzle having a diameter of 1.1 mm have a diameter of 2.6 mm, a surface pressure of 1.13 g/cm² and a weight of 9.2 mg. The development of these parameters, both calculated and observed, is discussed in greater detail hereinafter in this description of the invention.

In a second embodiment, the construction of the nozzle member and the nozzle means causes the jet to be fractionated. An obturating member is disposed in the free end of the nozzle member and includes a plurality of passages therethrough. Since the cross-sectional area of each of the passages in the obturating member is much smaller than the adjacent liquid conduit in the nozzle member, an aberration of the streamline of the liquid is established which causes the liquid to fractionate into unitary, discrete liquid droplets after the liquid exits from the free end of the nozzle member.

The effect of the damping on the later-arriving liquid by liquid resting on the surface of impact is largely overcome by the successive impacting of the fractionated liquid jet according to the invention. The impact rate is substantially equal to the number of droplets produced by the fractionating means per unit of time.
BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings:
Fig. 1 illustrates a first embodiment of a body care device suitable for use for oral hygiene according to the present invention;
Fig. 2 is a partial view of the nozzle tip which illustrates at a highly magnified scale the manner by which the liquid jet is fractionated into a plurality of unitary, discrete liquid droplets at the outlet of the nozzle of the device;
Fig. 3 is a summary of the characteristics of the droplets and parameters of the device for producing such droplets according to the invention;
Fig. 4 is a table comparing a number of characteristics of the droplets produced from 0.2 and 1.1 mm nozzle diameters, under specific conditions of frequency and ejection velocity;
Fig. 5 shows a second embodiment of an appliance for body care according to the invention;
Fig. 6 is a partial longitudinal sectional view, not in scale, taken along line 6-6 of Fig. 5;
Fig. 7 is a sectional view taken along line 7-7 of Fig. 6;
Fig. 8 shows a detailed sectional view of the nozzle shown in Fig. 6 which illustrates the manner by which the liquid jet is fractionated at the outlet of the nozzle or according to the second embodiment;
Fig. 9 illustratively shows the application of a pulsed, continuous liquid jet to dental residues;
Fig. 10 illustratively depicts the application of a fractionated liquid jet produced according to the invention to dental residues and illustrates the manner in which the buffer zone effect has been overcome; and
Fig. 11 is a photographic illustration of the buffer zone for the case of a single jet of pulsed fluid compared to the plurality of jets providing a plurality of unitary, discrete liquid droplets according to the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In Fig. 1, the apparatus of the first embodiment of the invention comprises a reservoir 10 which contains a mass of liquid 11 which may be water, a solution of analgesic, mouthwash, toothpaste or the like in water, or another suitable fluid. A conduit 12 is connected to an opening in the wall of the reservoir 10 to conduct the liquid 11 to a pump 13. Pressurized liquid is provided from the outlet of the pump 13 to the inlet 14 of a nozzle 15 through the conduit 16. Preferably, the conduit is flexible to permit the user to manipulate the nozzle 15.

The nozzle 15 may be produced in a number of shapes and sizes depending on the ultimate end use. The nozzle 15 is connected to a source 17 of vibrations and both are contained in a suitable casing 18, designated illustratively in phantom outline in Fig. 1, designed to permit the user to guide the flow of liquid 20 which exudes from the tip 21 of the nozzle 15 to the desired location on the body, for example, to a selected area in the mouth.

The vibrator 17 is energized by periodic electrical signals produced by an electronic vibration generator 22 which is amplified by an amplifier 23. The preferred frequency range for the signal frequency is on the order of about 200 to about 5,000 cps. One specific example of the type of generator contemplated for use in this invention is electro-magnetic vibrators.

When the generator 22 is off, and if the tip of a nozzle 15 has an opening having a circular cross section, the flow through this nozzle is cylindrical and equilibrated for its generally effective length under the action of its internal cohesion strength. This equilibrium is, however, relatively precarious and can be broken as soon as the jet 20 is subject to any perturbation produced at its origin, e.g., at the outlet of the nozzle 15. Particularly, it has been known that when a jet is submitted near its origin to relatively high frequency vibration, the form of the jet is altered. The alteration in jet form is exponentially increasing from the outlet of a nozzle 15.

If the frequency of vibration applied to the liquid 20 is constant, the flow of liquid from the outlet of the nozzle 15 is altered in such a manner that the flow profile of the liquid 20 exhibits a plurality of spaced contractions which increase in magnitude with an increase in distance from the tip 21 of the nozzle 15. Thus, as can best be seen in Fig. 2, the streamline of liquid 20 from the tip 21 is characterized by a plurality of contractions 25 which increase in magnitude until the jet of liquid breaks into a plurality of unitary, discrete liquid droplets 26. Primarily because of the surface tension of a liquid, the masses 26 ultimately assume the shape of a generally spherical liquid droplet 27. As will be discussed, the plurality of liquid droplets 27 are effectively used for cleansing the selected area on the body, for example, the dental surfaces to be cleaned.

A number of parameters relating to the physical characteristics of the nozzle, the frequency of vibration, the fluid flow characteristics, and the like, are of interest in producing the liquid droplets contemplated by this invention by means of electro-magnetic vibrators. These parameters are herein set forth based upon the empirical studies of the applicants with reference to their theoretical basis.

Ejection Velocity

While there is theoretically no limit in a vacuum with a perfect nozzle opening, i.e., one without rugosity, and a laminar flow of liquid therethrough, for a maximum ejection velocity, the minimum ejection velocity of the liquid jet for a given nozzle diameter and a predetermined vibrator frequency can be calculated in order to produce a maximum number of liquid droplets (which are adjacent to one another and do not touch). A jet of fluid having an ejection velocity of less than that indicated herein will not produce discrete liquid droplets, and the liquid will no longer be fractionated.

The theoretical minimum ejection velocity for the jet 20 is given by the following formula which expresses the geometric transformation of a cylinder to a sphere:

\[ v_{\text{min}} = 1.22 \phi_j \]

where \( v \) is the velocity of the jet in cm/s, \( f \) is the frequency of the vibrator in Hz or cps, and \( \phi_j \) is the diameter of the liquid jet in cm.

However, practical trials have shown that the actual minimum velocity for a jet to produce a maximum number of liquid droplets which are adjacent to one another but not touching is about twice as high as the theoretical minimum ejection velocity for a number of reasons. When formed, the liquid droplets are generally
3,870,039

oval along the longitudinal axis, as shown by the drop-lets 26 in FIG. 2. This factor mitigates against the theoreti-cally perfect production of adjacent spherical droplets 27. Moreover, because of the superficial or surface tension of the fluid, the liquid droplets in formation and still joined (as shown between the contractions 25) must separate from each other by a certain distance so that the cylinder of water joining them has a stric-tion sufficient enough to provoke their rupture and separa-tion. This factor indicates that a greater distance be-tween droplets is necessary than that indicated by the theoretical value. Moreover, the rugosity of the nozzle produces at the surface of the liquid droplets in forma-tion a certain heterogeneity which artificially in-creases their diameter thus making it easier for the droplets to join together again if they are not suffi-ciently far from one another.

Thus, the practical formula for the minimum ejection velocity is given by:

$$v_{\text{min}} = 2.5f \phi$$

**Fluid Flow Velocity**

In addition to the ejection velocity which is the same as the fluid flow velocity at the point of exit from the nozzle 21, the fluid flow velocity must be such that a laminar, rather than a turbulent flow is produced. Since it is known that a fluid flow becomes turbulent when the Reynolds number is greater than 2.500 for a tube with a polished inner surface, it has been determined that the limit of liquid velocity possessing laminar flow has a maximum value of about 4 m/s for a nozzle opening of 0.2 mm diameter and a maximum value of about 7 m/s for a nozzle opening of 1.1 mm diameter. It has been observed practically that the jet can only be dis-equilibrated by the vibrations of the nozzle to form liq-uid droplets in the case when the flow is laminar.

Those limits can be verified by the use of the Rey-nolds formula. The Reynolds formula is:

$$\pi \sigma = (v \phi / \nu)$$

where $\nu$ is the flow velocity in c/s, $\phi$ is the diameter of the fluid cross section in cm, and $\nu$ is the kinematic viscosity coefficient which, for water at 20°C is 0.01 cm²/s.

Since fluid flow becomes turbulent when the Rey-nolds number is greater than 2.500 for a tube with pol-ished inner surfaces, calculation with the above for-mula shows that with a mean diameter of 0.6 mm, the flow becomes turbulent with a velocity of about 4 m/s. Thus, since the jet can only be dis-equilibrated by vibra-tions to form discrete liquid droplets when the flow is laminar, and the nozzle diameters may range from 0.2 to about 1.1 mm, as will be discussed hereafter, the practical limits for liquid velocity are in the range of about 4 to about 7 m/s.

**Diameter of Nozzle Opening**

It has been found that if the diameter of the nozzle opening is greater than about 1.1 mm, it is no longer possible to form stable liquid droplets because the droplets become "too soft" due to their mass which is too heavy relative to the surface tension on one hand, and due to the ease with which the fluid droplets are deformed when they come in contact with the air.

Thus, it has been found that the minimum nozzle opening diameter to produce discrete liquid droplets is between about 0.15 and about 0.20 mm because in this area the relative rugosity of the nozzle opening be-comes important. The relative rugosity of the nozzle opening is defined by the ratio of the opening rugosity, in micro-inches or micro-meters, to the diameter of the opening. At such diameters, the roughness of the inner part of the diameter, measured by the rugosity, be-comes preponderant and the jet tends to break down into a mist rather than produce the liquid droplets.

In order to better define the difference between the relative hardness of a liquid droplet which is formed from the nozzle opening having a diameter of 1.1 mm and a droplet from a nozzle opening having a diameter of 0.2 mm, the ratio of the relative hardness of the droplets can be calculated. The diameter of the liquid droplets formed after exit from the outlet of a nozzle is given by the relation:

$$\phi = \frac{3}{4\pi} \left( \frac{3}{5} \alpha / S \cdot \nu / f \right)^{1/3}$$

where $f$ is the vibration frequency of the nozzle, $S$ is the cross-sectional area of the nozzle opening, $\alpha$ is the con-traction coefficient of the opening, and $\nu$ is the velocity of the jet.

Practical trials and calculations have determined that the contraction coefficient of the opening is about 0.97 for a nozzle opening having a diameter of about 1.1 and about 0.92 mm for a nozzle opening of about 0.2 mm. Thus, for the particular case of a jet having an ejection velocity of 5 m/s, and a vibration frequency of 500 cps, liquid droplets each having a diameter of 2.6 mm are produced from a nozzle opening having a diameter of 1.1 mm while liquid droplets each having a diameter of 0.77 mm are produced from a nozzle opening of 0.2 mm.

The surface pressure $p$ acting on a droplet of liquid due to the surface tension of the liquid can be calcu-lated by the formula:

$$p = \frac{(4T/\phi)}{\pi}$$

where $T$ is the surface tension equal to 72 dynes/cm for water in contact with air, and $\phi$ is the diameter of the droplets in cm.

Thus, for a nozzle opening having a diameter of 1.1 mm and producing liquid droplets each having a diam-eter of 2.6 mm as indicated above, the surface pressure is 1.13 g/cm², whereas for a nozzle opening having a di-ameter of 0.20 mm and producing liquid droplets each having a diameter of 0.77 mm as shown above, the sur-face tension is 3.82 g/cm².

From the foregoing, it is apparent that by diminishing the section of the nozzle opening by more than 30 times (from a nozzle with a diameter of 1.1 mm to a nozzle with a diameter of 0.2 mm), and keeping the other pa-rameters exactly the same for both nozzles, i.e., the ejection velocity and fractionating frequency are the same, the cross-sectional area of the liquid droplets is reduced by 10.4 times. Furthermore, the flow rate of the small opening is about 40 times smaller than that of the large opening which thus illustrates the superiority of a jet having a small diameter, particularly in those instances where the jet is used for oral lavage where it is desired to minimize fluid flow in the mouth of the user. This feature is a significant advantage of the in-vention when used for oral hygiene.

In order to take into consideration all parameters re-lating to the difference of the relative hardness between the two droplets considered in the above examples, the respective weights of the droplets must be introduced.
The weight of a spherical droplet is defined by the equation:

\[ W = \frac{4}{3} \pi r^3 \rho \]

where \( \rho \) is 1 g/cm\(^3\) for water.

Calculation with this formula shows that each of the droplets having a diameter of 2.6 mm produced from a nozzle opening having a diameter of 1.1 mm has a weight of 9.2 mg, while each of the droplets having a diameter of 0.77 mm produced from a nozzle opening having a diameter of 0.20 mm has a weight of only 0.239 mg. If the ratio between the weights of these two droplets is calculated, it is found that each of the droplets produced from the nozzle opening having a diameter of 1.1 mm is 38.5 times heavier than each of the droplets produced by the nozzle opening having a diameter of 0.2 mm.

Furthermore, the surface tension, which tends to maintain each of the droplets in its spherical form, is 3.4 times smaller in the case of a droplet produced by the nozzle opening having a 1.1 mm diameter than in the case of a droplet produced by a nozzle opening having a 0.2 mm diameter. Thus, each of the droplets having a diameter of 2.6 mm is 130 times softer and more vulnerable than each of the droplets having a diameter of 0.77 mm, with the same ejection velocity and fractionating frequency.

Vibration Frequency

The frequency of vibration to produce the subject liquid droplets is within the range of about 200 cycles per second to about 500 cycles per second. Practical trials have shown that for a water jet produced from a nozzle having a diameter of 1.1 mm, it was not possible to exceed a vibration frequency of about 500 cycles per second to obtain a fractionation of the jet because the damping of the vibration transmission through the water is proportional to the vibration frequency and to the water mass, and thus, to the nozzle diameter.

It has also been found that the droplets which were more easily formed in the higher range of frequencies and velocities were produced when the diameter of the nozzle opening was in the range between 0.4 and 0.6 mm. This occurred because with such diameters, the droplets were on one hand not "too soft" and, on the other hand, not preponderantly influenced by the nozzle opening rugosity.

Formation Distance

The distance measured from the tip of the nozzle where the droplets are entirely formed and separated from each other were found in practical tests to be extremely variable and to depend on many factors. However, this distance seemed to increase proportionally with the ejection velocity of the liquid. This distance was measured between less than 3 times the diameter of the nozzle opening and up to 90 times this diameter in extreme cases.

The droplets may also be produced from a jet subjected to acoustical vibrations or to hydraulic pressure vibrations in the frequency range disclosed.

The parameters discussed above are tabulated in FIGS. 3 and 4.

FIGS. 5–8 illustrate a second embodiment of the invention. In FIG. 5, as in FIG. 1, the overall system for the practice of dental hygiene comprises a reservoir containing a liquid, a pump and suitable conduits for conducting the liquid from the reservoir to the pump and from the pump to the nozzle member. As will be seen, the construction of the nozzle member causes the fractionation of the liquid jet into a plurality of unitary, discrete liquid droplets according to the invention.

An obtrating member is disposed in the opening defined by the tip of the nozzle member, which surrounds the free end of the passage. The member consists, for example, of a small cylindrical block of synthetic material having in the central portion thereof a plurality of longitudinal micropassages which are arranged equidistantly in a circular locus about the center of the member.

These micropassages preferably have a diameter which is much less than that of the adjacent passage, for example, on the order of 0.2 to 0.5 mm, while the adjacent passage has a diameter on the order of 1.5 to 2.0 mm.

As in the case of nozzle member 15 in FIG. 1, if the nozzle member does not include member 55, the jet produced by the nozzle is generally cylindrical, in equilibrium along its entire effective length under the action of its internal cohesive forces.

If the liquid jet is subjected to a perturbation, as discussed in connection with FIG. 1, the equilibrium of the jet may be destroyed. This occurs in the apparatus shown in FIGS. 5–8 due to the presence of the obtrating member. At the outlet of the micropassages, the various produced jets are divided gradually into a plurality of discrete, unitary liquid droplets.

The slight liquid take-off which occurs at the inlet of each micropassage gives rise to an instability in the remainder of the micropassage, which is of sufficient magnitude to create this fractionation. Moreover, the sudden change of cross-section which the liquid coming from the pump encounters at the level of the upstream face of the obtrating member is the source of reflections and refractions of pressure waves within the liquid in the passage, as well as within the liquid in each micropassage. Thus, this structure causes an oscillatory pressure phenomenon, the frequency of which corresponds to that of the production of droplets and which seems to be inversely proportional to the length of the micropassages.

It is to be noted, in particular, that when the micropassages have a diameter of 0.2 mm and a length of 8 mm, for example, divided jets of 20,000 droplets per minute have been obtained, while with micropassages of the same cross section, but having twice the length, i.e., 16 mm the number of droplets becomes essentially equal to 10,000 per minute.

Each of the jets produced by the appliance is thus divided into a series of liquid "projectiles" having a somewhat spherical shape, the effect of which has turned out to be particularly important with regard to cleaning the teeth and the interdental spaces, as was discussed in connection with FIGS. 3 and 4.

The parameters discussed in connection with FIGS. 1 and 2 have been confirmed by a laboratory experiment apparatus comprising a nozzle from which a pressurized water jet with a continuous flow was produced. The jet was fractionated into discrete liquid droplets by means of a thin rotating disc provided with equally spaced indentations along the periphery of the disc and driven by an electric motor. By this apparatus, the jet having an adjustable ejection velocity was frac-
tionated by an adjustable fractionating frequency. The desired fractionating frequency was obtained by the modification of the rpm of the motor and, if necessary, changing the number of indentations on the disc.

Cleaning trials have shown that the greater a jet is fractionated the better its cleaning action, all other conditions being similar. In this respect, it was noted that a fractionated jet was even more effective than a continuous jet using twice as much water.

In FIG. 9, the food residue 31 is shown as being con-
tacted by the continuous portion of a pulsed jet 32 of liquid such as one which would be produced by devices described earlier in this specification. FIG. 10, on the other hand, shows the food residue 31 being successively impacted by a plurality of discrete, unitary liquid droplets which are produced according to the inven-
tion.

In the case of FIG. 9, the solid jet 32 partially disaggregates the central part of the food residue 31 only during its initial impact, while the water flow which arrives later and strikes the food residue 31 is considerably slowed because the water which arrived earlier and has formed a water film 33, acts as a buffer between the residue 31 to be disaggregated and the jet 32. Thus, the water flows across the surface of the food residue 31 in a superficial manner and its disaggregating action is re-
stricted primarily to an erosion of the peripheral areas of the residue.

As shown in FIG. 10, the disaggregating process is improved because each liquid mass successively per-
cusses the food residue 31 without formation of a buff-
ering water film. Thus, there are as many impacts per time unit as there are produced drops. Accordingly, a high efficiency of disaggregation of food residues is achieved. Moreover, the explosion effect at each im-
 pact, of each droplet is added to that of crushing the droplet on the deposit, thus contributing to further im-
provement of the efficiency with which the jet disaggre-
gates the deposit.

Thus, the cleaning effected in the case of the projection of a plurality of liquid droplets is far better than the cleaning obtained by a pulsed jet projection, even at a rate of 3,000 pulsations per minute for the same rate of liquid discharge from a single nozzle. Similarly, for the same washing quality, the quantity of liquid em-
ployed in using a device according to the invention, is far less than that necessary by the presently marketed devices. It is also clear that the washing time will also be reduced accordingly.

The efficiency of the above described device is such that it is possible not only to remove the small residues from the teeth but also the large deposits covering the entire surface of each tooth. In particular, the food particles wedged in the interdental spaces which are very difficult to reach even with the more efficient electric toothbrush are effectively removed with the method and apparatus of the invention.

It is also apparent that the devices according to the invention can also be used to provide an efficient mas-
saging of the gums in addition to their described clean-
ing functions. This is accomplished by adding a pulsa-
tion at an appropriate frequency to the liquid column supplying the nozzle 15. Thus, it is possible, for ex-
ample to equip such a device with a pump 13 having a dis-
continuous operation, for example a piston pump, able to supply the nozzle 15, and which is pulsed at a suit-
able frequency, partially determined by the relaxation time of the gum mucous tissue. When a pulsation is added to the liquid, the vibrator 17 produces a fractionated jet as previously described.

By way of further explanation, the buffer zone can be defined as the damping phenomenon on the incident liquid jet by the residual film still present on the impact surface. To show its effect, spraying trials have been made against a transparent pane of glass which permitted examination of the buffer zone through the glass. By means of a stroboscopic light, the phenomenon was clearly visualized as shown in FIG. 11.

In FIG. 11, the buffer zone is shown on the left hand side thereof for the case of a single pulsed jet of liquid compared with a 6 micro-jet nozzle according to the invention pulsed at the same frequency for visualization, as shown on the right hand side of the photograph of FIG. 11.

From FIG. 11, it is clearly shown that the jet on the left has a buffer zone much thicker than the jet on the right because the whiter the aspect of the water on the photograph, the thicker the film of water. At the level of the impact of the jet, shown by the whiter dot in the center of the left hand portion of the photograph, it appears that this dot which should be absolutely white in the case of direct contact of the fluid with the glass sur-
face is blurred, which proves that the jet is strongly damped or buffered. On the contrary, in the case of the nozzle with 6 jets according to the invention, as shown on the right hand portion of the photograph, it can be observed that outside the jets, within the zone which resembles the orange-like sections, there is practically no buffer zone since those portions are black.

Furthermore, at the impact point of the six jets, six very white dots are visible, which proves that each of the six reaches the glass surface with full energy and without interference by a buffering water film. This photographic illustration confirms FIGS. 9 and 10.

The invention may be embodied in other specific forms without departing from its spirit or essential characteristics. The present embodiments are, therefore, to be considered in all respects as illustrative and not restrictive, the scope of the invention being indi-
cated by the claims rather than by the foregoing de-
scription, and all changes which come within the mean-
ing and range of the equivalents of the claims are there-
fore intended to be embraced therein.

What is claimed is:

1. An apparatus for body care comprising means for storing a liquid, nozzle means for projecting the liquid at an ejection velocity within a predetermined range to a selected area, said nozzle means including a nozzle having an opening having a diameter in the range of about 0.2 to about 1.1 mm, means for supplying the li-
quid under pressure from said storing means to said noz-
kle means, and means for fractionating the liquid at a frequency in the range of about 200 to about 5,000 cps into a plurality of unitary, discrete liquid droplets for successively impacting said selected area with said plu-
rality of unitary, discrete liquid droplets, wherein said droplets are further characterized in that each of said droplets successively percusses said selected area at an impact rate substantially equal to the number of dro-
plets produced by said fractionating means per unit of time, said droplets having a diameter when formed which is larger than the diameter of the opening in the nozzle.
2. The apparatus as set forth in claim 1 wherein said nozzle means projects said liquid at an ejection velocity in the range of about 2 to about 7 m/sec.

3. The apparatus as set forth in claim 1 wherein the number of droplets produced by said nozzle means is equal to the fractionating frequency.

4. The apparatus as set forth in claim 1 wherein said fractionating means comprises means for transmitting said vibrations to said liquid within said nozzle means whereby the liquid divides into said plurality of unitary, discrete liquid droplets after exit from said nozzle means.

5. The apparatus as defined in claim 1 wherein said fractionating means for producing said unitary, discrete liquid droplets is included in a portion of said nozzle means.

6. The apparatus as defined in claim 1 wherein said nozzle defines a passage for the conduction of said liquid therethrough, one end of said passage being connected to said supplying means for receiving said liquid under pressure and further including means disposed in said other end of said passage for fractionating said liquid into a plurality of unitary, discrete liquid droplets.

7. The apparatus as defined in claim 6 wherein said fractionating means includes an obstructing orifice for fractionating said liquid into said plurality of unitary, discrete liquid droplets, said obstructing member defining at least one passage therethrough, the cross-sectional area of said passage in said obstructing member being small as compared to the cross-sectional area of said passage in said nozzle member.

8. The apparatus as set forth in claim 7 wherein the diameter of said passage in said obstructing member is on the order of about 0.2 to about 0.5 mm and the diameter of said passage in said nozzle member is on the order of about 1.5 to about 2.0 mm.

9. The apparatus as defined in claim 8 wherein said obstructing member defines a plurality of passages therethrough, the cross-sectional area of each of said passages being small as compared to the cross-sectional area of said passage in said nozzle member.

10. The apparatus as set forth in claim 9 wherein the diameter of each of said passages in said obstructing member is on the order of about 0.2 to about 0.5 mm and the diameter of said passage in said nozzle member is on the order of about 1.5 to about 2.0 mm.

11. The apparatus as set forth in claim 1 wherein said droplets ultimately assume an approximately spherical shape after exit from said nozzle within a distance of about 3 to about 90 times the nozzle opening diameter.

12. The apparatus as set forth in claim 11 wherein each of the spherical droplets has substantially the same diameter.

13. The apparatus as set forth in claim 1 wherein said nozzle means projects said liquid at an ejection velocity in the range of about 2 to about 7 m/s and having a practical minimum governed by the formula:

\[ v = 2.5f \phi \]

where

- \( v \) = velocity
- \( f \) = frequency of vibration
- \( \phi \) = diameter of liquid jet

14. The apparatus as set forth in claim 1 wherein the velocity of said liquid through said nozzle has a Reynolds number less than about 500.

15. In a system for the practice of oral hygiene which is capable of cleaning the teeth and interdental spaces and stimulating the gum tissues of the type which comprises means for storing a liquid to be projected into the oral cavity of the user, nozzle means, including a nozzle having an opening having a diameter in the range of about 0.2 to about 1.1 mm, for projecting said liquid at an ejection velocity within a predetermined range into said oral cavity; and means for providing said liquid under pressure from said storing means to said nozzle means, the improvement comprising:

- means for fractionating the projected liquid at a frequency in the range of about 200 to about 5,000 cps into a plurality of unitary, discrete liquid droplets for successively impacting a selected area within said oral cavity with said plurality of unitary, discrete liquid droplets, wherein said droplets are characterized as substantially entirely composed of said fluid and substantially free from voids within each of said droplets, and wherein said droplets in said plurality of said droplets are further characterized in that each of said droplets successively percsuses said selected area at an impact rate substantially equal to the number of droplets produced by said fractionating means per unit of time, said droplets having a diameter when formed which is larger than the diameter of the opening in the nozzle.

16. The apparatus as set forth in claim 15 wherein said nozzle means projects said liquid at an ejection velocity in the range of about 2 to about 7 m/sec.

17. The apparatus as set forth in claim 15 wherein the number of droplets produced by said nozzle means is equal to the fractionating frequency.

18. A method for the practice of body hygiene comprising the steps of:

- providing a source of liquid under pressure to be projected at an ejection velocity within a predetermined range from an opening in a nozzle having a diameter in the range of about 0.2 to about 1.1 mm against a selected area of the body of the user,
- fractionating said liquid at a frequency in the range of about 200 to about 5,000 cps into a plurality of unitary, discrete liquid droplets having a diameter when formed, which is larger than the diameter of the opening in the nozzle, for successively impacting said selected area with said plurality of unitary, discrete liquid droplets, wherein said droplets are characterized as substantially entirely composed of said fluid and substantially free from voids within each of said droplets, and wherein said droplets in said plurality of droplets are further characterized in that each of said droplets successively percsuses said selected area at an impact rate substantially equal to the number of droplets produced by the step of fractionating per unit of time, and
- projecting the fractionated liquid against said selected area.

19. The method as defined in claim 18 wherein said body hygiene is oral hygiene and said selected area is an area within the oral cavity of the user.

20. The method as set forth in claim 18 wherein the step of projecting is further defined as projecting the fractionated liquid at an ejection velocity in the range of about 2 to about 7 m/sec.

21. The method as set forth in claim 18 wherein the step of fractionating is further characterized in that the number of droplets produced by said nozzle is equal to the fractionating frequency.
22. The method as set forth in claim 18 wherein the step of fractionating includes the steps of generating vibrations in said frequency range and transmitting said vibrations to said liquid within said nozzle means whereby the liquid divides into a plurality of unitary, discrete liquid droplets after exit from said nozzle.

23. The method as defined in claim 18 wherein the step of fractionating is further defined by the step of causing said liquid to flow from a passage having a first cross-section to a passage having a second cross-section which is small compared to said first cross-section.

24. The method as set forth in claim 18 wherein the step of projecting includes the step of projecting said liquid by an ejection velocity in the range of about 2 to about 7 m/s and having a practical minimum governed by the formula:

\[ v = 2.5f \phi \]

where

- \( v \) = velocity
- \( f \) = frequency
- \( \phi \) = diameter of liquid jet

25. The method as set forth in claim 18 wherein the step of fractionating includes the step of passing the liquid through an opening having a Reynolds number less than about 2,500.

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