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METHODS AND DEVICES FOR HANDLING A FLUID AND DELIVERING THE FLUID TO THE EYE

Abstract

Methods and devices for handling a fluid and delivering the fluid to the eye. The device has a vibrating element with a plurality of openings through which a fluid is ejected when the vibrated. An enclosure defines a chamber which holds a single application of the fluid. The enclosure may be biased against the vibrating element with a spring load developed in whole or part by the resilient structure of the enclosure. The chamber may be substantially empty after the single application.

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Background/Summary

FIELD OF THE INVENTION

[0001] The invention is directed to methods and devices for handling a fluid and for delivering the fluid to the eye.

BACKGROUND OF THE INVENTION

[0002] Fluid delivery to the eye presents a number of challenges. The fluid should be provided with a controlled droplet size and delivered at a controlled velocity for comfort while delivered at high enough velocity to deliver the entire dose. Another challenge with fluid delivery to the eye is the need for rapid delivery so that an eye blink does not interfere with delivery.

[0003] Fluid delivery devices for the eye have used a piezoelectric element to vibrate an element, such as a plate, with holes through which the fluid is ejected. A problem with many of these devices is that they are typically “wet” systems in which the fluid is exposed through the holes in the plate when stored which may lead to undesirable evaporation and contamination between uses.

SUMMARY OF THE INVENTION

[0004] The present invention is directed to methods and devices for handling a fluid and delivering the fluid to the eye. In one aspect, the fluid to be delivered to the eye is contained in an enclosure which holds the fluid to be dispensed in a chamber defined by the enclosure. The enclosure holds the dose of fluid in proximity to the openings so that the fluid may be ejected in a short amount of time and with little residual volume left.

[0005] The enclosure has a lip positioned adjacent a vibrating element having openings through which the fluid is ejected. The lip may be unattached to the vibrating element but still in contact with the vibrating element or may be spaced apart a short distance so that surface tension holds the fluid in the chamber. The vibrating element may have a relatively small maximum amplitude when vibrated which is less than an average separation distance between the lip and the vibrating element or less than a minimum separation distance between the lip and the vibrating element.

[0006] The enclosure may also be shaped to cooperate with the vibrating element to avoid capillary feed near the openings in the vibrating element. To this end, the enclosure may be spaced apart from the vibrating element so that at least 75%, at least 95%, or all of the openings are spaced at least 0.014 from the nearest part of the enclosure. Capillary feed may be incorporated in other aspects of the invention without departing from those aspects of the invention. The enclosure is also shaped so that all of the fluid can reach the openings in a short period of time. The enclosure has an internal surface in contact with the fluid shaped so that at least 75%, at least 95%, or even all, of the internal surface is no more than 0.060 inch, or no more than 0.040 inch, from a nearest of the plurality of openings. Stated another way, the enclosure has an internal surface shaped so that the chamber is formed with at least 75%, at least 95%, or all, of the internal surface has direct line of sight to at least one of the openings. The inner surface of the enclosure may be hydrophobic over at least 70% of the inner surface in contact with fluid.

[0007] The lip may be biased against the vibrating element with a modest force to prevent the fluid from escaping while not overly dampening vibrations. The lip may exert a force of no more than 3 gram-f on the vibrating element measured in the direction of a central axis of the vibrating element. The lip may also apply a spring load to the vibrating element so that minor displacements due to

temperature, pressure or shock from an impact (dropped) can be accommodated. The spring load may also help to address manufacturing tolerances which affect the load applied by the lip to the vibrating element. The lip may exert a spring load on the vibrating element with an average spring constant of no more than 60 gram-f/mm for displacements up to 0.050 mm. The enclosure itself may be resilient with a wall of the enclosure having a tapered portion with a relatively thin wall to provide flexibility. The tapered portion of the wall and has a ratio of radial displacement to longitudinal displacement of at least 1 to 3, at least 1 to 2 and may be at least 1 to 1. Stated another way, the tapered portion also extends radially with respect to the open end of the enclosure for at least half of an effective radius of the open end of the enclosure. The lip and/or the vibrating element may have a PTFE coating adjacent to the other to reduce friction therebetween. The coating(s) may extending around at least 270 degrees when viewed along the central axis.

[0008] The enclosure may allow air into to replace ejected fluid through the openings and/or between the lip and the vibrating element and may include no dedicated vent opening. The maximum amplitude may be somewhat small which permits air to enter the chamber while still preventing fluid from escaping from the chamber. The enclosure to vibrating element interface defines an enclosed border (which may be defined by either the vibrating element or the enclosure) which is somewhat larger than the extent of the openings with an excess area which extends radially outwardly at least 0.3 times the effective radius of the enclosed feed area.

[0009] The enclosure may include a wall opening through the wall which exposes the chamber through the wall. The wall opening. The wall opening extends through the wall to expose the chamber through the wall without permitting fluid to escape while permitting air to enter when fluid is ejected. The wall opening has a longitudinal dimension measured from the lip in the direction of the central axis and a radial dimension measured in a radial direction relative to the central axis. The enclosure also has an internal wall with a side facing the openings in the vibrating element. The longitudinal dimension of the wall opening is at least 80% of a separation distance between the vibrating element and the side of the enclosure facing the openings. The radial dimension of the wall opening may be no more than 10%, or no more than 5%, of an equivalent circumference of the lip.

[0010] The wall opening tapers as it extends proximally away from the lip. The wall opening extends from the lip proximally and a circumferential dimension of the wall opening tapers down as the wall opening extends proximally from the lip. The wall opening tapers so that a tapered shape is oriented in the direction of the fluid inlet to the chamber when viewed along the central axis. The wall opening may also extend through the frustoconical portion of the wall and may extend proximally from the lip for at least 80% of the length of the frustoconical portion.

[0011] The fluid may be delivered rapidly and at relatively high velocity and pressure to encourage all of the fluid to gather in the chamber. The total downstream volume of the fluid path from a pump or valve which isolates the chamber may be sized somewhat larger than the volume to permit the fluid to move within the enclosure somewhat and coalesce into a single droplet due to surface tension. The volume of the fluid may be 40%-70% of the total downstream volume.

[0012] The enclosure may also split the fluid flow into at least two (and may be three, four or more) inlets to the chamber. Each of the inlets directs the fluid at a sidewall before being directed at the plurality of openings. The enclosure has a main inlet which directs the flow in a direction within 30 degrees of the central axis while the inlets to the chamber are oriented 60-90 degrees from the central axis and directed at the sidewall. The enclosure may be an integrally formed structure which defines the chamber.

[0013] The pump may have a first part and a second part which reciprocate between a stored position, to a forward stroke position and back to the stored position in a single cycle. A cavity is formed between the two parts in which the fluid is drawn and subsequently expelled into the chamber. An air make-up chamber may also be coupled to the pump to force air into a fluid container during each cycle to actively vent the fluid container.

[0014] The present invention may be practiced as a device or method. As to the device it is understood that a therapeutic delivery device may be separated into reusable and disposable portions in innumerable different combinations. As such, the present invention provides inventive concepts that may be logically grouped together in various ways which define a subset of the device which may be a disposable or reusable portion. For example, the fluid container may be replaced with the enclosure or may be independent and, therefore, may be claimed in either manner. The enclosure may form part of a reusable device together with the vibrating element or may be part of a disposable (with or without the fluid container) without departing from the scope of the invention. The claimed invention lies in the methodology and structure rather than in specific delineation of the disposable and reusable parts. Thus, it is understood that the disposable parts may be defined in virtually any suitable manner and the claims may define any such limited aspect or combination. As further examples, the claims may define the pump and the fluid container, the enclosure and the vibrating element, or even a single structure such as the enclosure by itself. Each of these could be part of reusable device, a single-use device, or as a disposable and may be claimed as such.
[0015] These and other features will become apparent from the following description of the preferred embodiments, claims and drawings.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
[0016] FIG. **1** shows a device for handling a fluid and delivering the fluid to the eye with a cap removed for introducing a fluid container.
[0017] FIG. **2** shows a vibrating element with openings through which the fluid is ejected.
[0018] FIG. **3** shows the locking mechanism for the fluid container.
[0019] FIG. **4** shows a first housing part with an outer cover removed to show a shutter with an aperture through which the fluid is dispensed.
[0020] FIG. **5** shows a cross-section of a second housing part which houses the control system and battery.
[0021] FIG. **6** shows a front view of the device with the outer cover removed.
[0022] FIG. **7** shows the fluid delivery path from the fluid container to an enclosure.
[0023] FIG. **8** shows a cross-section of the enclosure.
[0024] FIG. **9** shows another cross-section of the enclosure.
[0025] FIG. **10** shows a perspective view of the enclosure.
[0026] FIG. **11** shows a bottom view of the enclosure including the flow splitting chamber.
[0027] FIG. **12** shows an enlarged cross-sectional view of the enclosure.
[0028] FIG. **13** shows a cross-sectional view with the device in a stored position.
[0029] FIG. **14** shows the pump advanced during the forward stroke with fluid contained in pump.
[0030] FIG. **15** shows the pump at full forward stroke.
[0031] FIG. **16** shows the pump at the end of fluid delivery through the tube and into the enclosure.
[0032] FIG. **17** shows the pump during the return stroke.
[0033] FIG. **18** shows a front view with the shutter in a stored position.
[0034] FIG. **19** shows a front view with the shutter in a ready position.
[0035] FIG. **20** shows a rear view of the device with the pump in a stored position.
[0036] FIG. **21** shows a rear view of the device with the pump in the full forward stroke position.
[0037] FIG. **22** shows a perspective view of the device with the pump return springs removed.
[0038] FIG. **23** shows a perspective view with the cap and outer cover removed.
[0039] FIG. **24** shows a perspective cross-sectional view of the fluid delivery path and shutter.
[0040] FIG. **25** shows the shutter mechanism and a firing button in a stored position.

[0041] FIG. **26** shows the shutter in a ready state with the shutter spring loaded.
[0042] FIG. **27** shows actuation of the firing button which releases the shutter.
[0043] FIG. **28** shows the shutter displaced upwardly by the pump spring at the end of the fluid delivery.
[0044] FIG. **29** shows a partial cross-section of the device showing the shutter mechanism.
[0045] FIG. **30** shows a perspective view of FIG. **29**.
[0046] FIG. **31** shows the shutter in the ready state and a sensor which prevents delivery of fluid when the shutter is blocking fluid delivery.
[0047] FIG. **32** shows a plan view of another enclosure having a wedge-shaped wall opening.
[0048] FIG. **33** is a perspective view of the enclosure of FIG. **32**.
[0049] FIG. **34** is a side view of the enclosure of FIGS. **32-33**.
[0050] FIG. **35** is a cross-sectional view of the enclosure of FIG. **34**.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0051] The present invention is directed to methods and devices for handling a fluid and delivering the fluid to the eye. Referring to FIGS. **1**, **2** and **7**, a device **1** is shown which includes a fluid ejector **2** (FIG. **2**) and a fluid handler **14** (FIG. **7**). The fluid ejector **2** includes a vibrating element **4** having a plurality of openings **6** which is vibrated with a piezoelectric element **15** coupled to the vibrating element **4**. The term fluid as used herein refers to any flowable substance and does not refer only to the liquid state of a material.
[0052] The device **1** has a housing **5** which may include a first housing part **7** and a second housing part **9** which lock together with any suitable engagement such as a twist or snap-fit. Referring to FIG. **5**, a control system **11** which includes a printed circuit board **13** is mounted to the first housing part **7**. The control system **11** is coupled to and controls the piezoelectric element **15** as is known in the art. A battery **19** powers the control system **13** and the driving electronics for the piezoelectric element **15** as is known in the art. The fluid handling system **14** is coupled to the second housing part **9**. The control system **11** may be reusable while the fluid handler **14** may be disposable. Furthermore, the fluid may be held in a fluid container **17** which may be locked to the first housing **7** to prevent removal so that the fluid handler **14** is disposable after (with) the first fluid container **17**. Of course, the fluid handling system **14** may also be used with more than one container **17** or the container **17** may have a reservoir that is filled without departing from numerous aspects of the invention. Furthermore, the entire system **1** may be disposable or reusable or separated into disposable and reusable portions in any manner without departing from most aspects of the present invention.
[0053] The piezoelectric element **15** may be an annular disc **23** coupled to either a delivery side **8** or a fluid side **10** of the vibrating element **4** with the openings **6** positioned in an open central region **26** of the annular disc **23**. The piezoelectric element **15** may be made of any suitable material (such as Lead zirconate titanate; an intermetallic inorganic compound with the chemical formula Pb[Zr.sub.xTi.sub.1-x]O.sub.3). The piezoelectric element **15** may be bonded, adhered, molded or otherwise coupled to the vibrating element in any suitable manner as is known in the art. A flexible circuit **21** is in electrical communication with the piezoelectric element **15** to control the piezoelectric element **15**. The flexible circuit **21** is coupled to the control system **1** (see FIG. **5**) which controls the piezoelectric element **15** to induce vibrations in the piezoelectric element to vibrate the element **4** and eject fluid from the openings **6**. The vibrating element **4** is vibrated at a frequency of 100 to 160 khz which may be a resonant frequency. The resonant frequency may be predetermined, measured, determined or tuned as is known in the art. The driving frequency of the piezoelectric element **15** is described further below. Of course, the frequency of operation may be at a frequency other than a resonant frequency.
[0054] The fluid side **10** of the vibrating element **4** at the openings **6** is in contact with the fluid to be delivered and ejects the fluid to the delivery side **8**. Fluid is ejected through the openings **6** toward the eye when the vibrating element **4** is vibrated. The openings **6** may taper from the fluid

side **10** to the delivery side **8**. For example, the opening **6** at the fluid side may have a diameter of 160-240 microns (and may be 200 microns) while the diameter at the delivery side may be 20-60 microns (and may be 40 microns). A column of consistent diameter (20-60 microns) extends to the delivery side **8** and has a length of 10-40 microns and may be about 25 microns in length. The openings **6** may have a curved wall between the fluid and delivery sides with a radius of curvature of 100 microns. The openings **6** at the fluid side **10** and the delivery side **8** may have a circular cross-sectional shape. As used herein, the cross-sectional area (or other dimension) may be defined by an effective diameter (or effective radius) for a circle having the same area.

[0055] The vibrating element **4** may have a thickness of 100 to 180 microns, or 120-160 microns, and may be about 140 microns, and may be made of any suitable material such as PEEK or Polyimide, with additional layers consisting of copper, polyimide, nickel, and/or gold. The vibrating element **4** may have a thickness of 125 microns and the coating/plating having a total thickness of about 15 microns so that the vibrating element **4** has thickness of about 140 microns. Of course, numerous other configurations may be practiced within the scope of the invention with respect to the materials and manufacture of the vibrating element **4** and piezoelectric element **15** and dimensions of the openings **6**.

[0056] Fluid may be ejected so that an average ejection velocity is 2.5 m/s to 15 m/s, as it leaves the opening **6** at the delivery side **8** and may be about 5-6 m/s. The vibrating element **4** defines a central axis CA which is a central orientation of the plurality of openings **6** defined by a geometric center of the ejection orientation of the plurality of openings **6**. For a circular pattern of openings **6** of even density distribution with a flat vibrating element **4** the central axis CA extends perpendicular to plane of vibrating element **4** at the center of the circular pattern of openings **6**. Stated another way, the central axis CA is perpendicular to a plane defined by the vibrating element **4** and is aligned with the geometric center of the ejection direction that the openings **6** are aligned or with a geometric center of a spray pattern created by the plurality of openings **6**. The central axis CA may be defined by an average or geometric center without departing from scope of the invention when, for example, the openings **6** are clustered or an irregular or asymmetrical shape or varying density of openings **6** (number of openings)/mm2 as used herein.

[0057] Referring to FIGS. **1**, **3** and **7**, multiple doses of the fluid are stored in the fluid container **17** which is locked to the housing **5** (specifically the second part **9**) when a recess **22** engages locking tabs **24** on a container lock **26**. A snap-fit connector **28** (FIG. **3**) locks to a manifold **30** (FIG. **7**) of a pump **32** described below. When the container **17** is pushed downward and locked to the housing **5**, a fluid delivery needle **34** passes through a pierceable element **36** such as a septum **38** in the container **17**. A vent needle **40**, which may be independent or concentrically arranged with the fluid delivery needle **34**, also passes through the pierceable element **36**. Fluid is drawn from the container **17** through a fluid conduit **42** with the pump **32** as explained further below. Air is drawn into an air intake lumen **27** (covered by a filter **29**) which is used to vent the container **17** as explained below.

[0058] Referring to FIGS. **7-12**, individual doses of the fluid are delivered to a chamber **16** formed by an enclosure **18** and the vibrating element **4**. The chamber **16** may be substantially dry after delivery of the fluid and dry when stored which may provide advantages over “wet” systems which may suffer from undesirable contamination or evaporation. The enclosure **18** has a wall **44** with a lip **46** positioned adjacent the fluid side of the vibrating element **4**. The lip **46** extends around the plurality of openings **6**. The enclosure **18** and the vibrating element **4** together define the chamber **16** or the chamber **16** may be defined by the enclosure **18** bounded by an open end **33** of the enclosure **18** while the. open end **33** is bounded and defined by the lip **46**. The wall **44** extends from the open end **33** to a hub **35** which has a main inlet **52**. The main inlet **52** is coupled to a lumen **54** formed in a tube **56** through which fluid is delivered by the pump **32**. The enclosure **18** may be formed together with the tube **56** or as separate parts as shown. The tube **56** may be formed with the manifold **30** which may be defined as part of the pump **32** so that the pump **32** delivers the

fluid directly to the enclosure **18**. The manifold **30** has a mounting rib **31** (FIG. **22**) which engages the housing. The tube **56** may also be defined separate from the pump **32** as used herein, for example, the tube **56** may be part of the enclosure **18** (either as a disposable or a reusable part).

[0059] The lip **46** of the enclosure **18** is positioned adjacent to the fluid side **10** of the vibrating element **4** to prevent the fluid from escaping or leaking between the lip **46** and the vibrating element **4**. The lip **46** and the vibrating element **4** are adjacent one another along a closed loop which encircles the openings **6** and has a diameter of 0.190-0.240 inch and may be 0.210 inch. The enclosure **18** also defines a central axis CA which is a geometric center of an area bounded by the lip **46** at the open end of the enclosure **18** and oriented perpendicular to the area bounded by the lip **46**. As used herein, the term central axis CA may mean any one of the definitions herein applicable and may be interchanged when applicable and such substitutions are expressly incorporated wherever the term central axis CA is used such as when the two are co-linear. Of course, the central axis CA of the enclosure **18** and the central axis CA of the vibrating element **4** may be offset and/or skewed without departing from the scope of the invention as described below and the independent definitions are specifically applied.

[0060] The lip **46** of the enclosure **18** may be spaced apart from the vibrating element **4** so that the lip **46** does not impede vibrations of the vibrating element **4**. Of course, the lip **46** must be close to the vibrating element **4** so that surface tension prevents escape of the liquid. For example, the lip **46** may be spaced apart from the vibrating element **4** by less than 250 microns or less than 125 microns. The vibrating element **4** may not touch the enclosure **18** during vibration when the maximum amplitude is small enough to prevent contact. Stated another way, the lip **46** has a surface spaced apart from the vibrating element **4** less than 250 microns average, or less than 125 microns average, and is spaced apart from the vibrating element **4** for at least 270 degrees of total angular extent which does not contact the vibrating element **4**. Stated yet another way, the surface is spaced apart by a separation distance of at least 125 microns around at least 270 degrees of the plurality of openings **6** when viewed along the central axis CA. The lip **46** may extend completely around the openings **6** without contacting the vibrating element **4** even during vibration for fluid delivery. The interface on either side may be interrupted rather than continuous without departing from the scope of the invention. For example, the surface of the lip **46** may contact the vibrating element **4** along four small sections which span 20 degrees each so that the lip **46** does not contact the vibrating element **4** along at least 270 degrees even though not continuous. As used herein, the chamber **16** is defined by the enclosure **18** and the vibrating element **4** so long as the fluid is prevented from escaping between the enclosure **18** and the vibrating element **4** and the chamber **16** shall be defined as the fluid retaining space even though the chamber **16** is not entirely enclosed. The term “lip” as used herein simply refers to the surface adjacent the vibrating element **4** and does not require any particular structure or shape and may simply be an end of the wall **44** or coating at the end of the wall **44**. For example, the lip **46** may be wider like a flange, a rim of a rigid cup, or a rippled surface, undulating or sawtooth shaped surface without departing from the meaning of “lip” as used herein. Although the fluid may be held in the chamber **16** by surface tension along the lip **46** when the lip **46** is spaced from the vibrating element **4**, the majority of the fluid may be free of capillary feed features as is sometimes used in the prior art. Such prior art systems that incorporate capillary feed typically do so along the fluid feed area immediately adjacent to the openings **6** in the vibrating element **4**. As described below, the present invention may provide sufficient space adjacent to the openings **6** so that capillary action is not required or incorporated to deliver fluid to the openings **6**.

[0061] The lip **46** may also be in contact with the vibrating element **4**, rather than spaced apart, while not overly restraining the vibrating element **4** and still retaining the fluid. To this end, the lip **46** may be biased against the vibrating element **4** with a relatively low force. For example, the force exerted on the vibrating element **4** by the lip **46** may be less than 3 gram-force, and may be less than 2 gram-force, measured in a direction of the central axis CA of the enclosure **18** (and the

vibrating element **4** as well). The lip **46** may also exert a controlled spring load on the vibrating element **4** with an average spring constant of no more than 60 gram-f/mm or even no more than 40 gram-f/mm for displacements up to 0.050 mm in the direction of the central axis CA. The controlled spring constant may aid in operation in extreme conditions which may affect interaction of the lip **46** and vibrating element **4** for extreme temperatures, pressures, and impact loads (dropped). The controlled spring constant may also aid in manufacturability in that manufacturing tolerances can affect the load ultimately exerted by the lip **46** on the vibrating element **4**.

[0062] The lip **46** and/or the wall **44** may also be made of a resilient material for compliant contact between the lip **46** and the vibrating element **4** and the resilient material and geometry of the enclosure **18** may contribute to develop the spring force response. For example, the lip **46** may be made of a material having a durometer of less than 60 A. The wall **44** may have a thickness of 0.003 to 0.007 inch surrounding the chamber **16**. The resilient nature of the enclosure **18** may be provided by the material of the lip **46** itself and/or mechanically with a tab, leaf spring, coil spring, cantilever, a resilient mounting for the container **17**, or any other suitable mechanism or combination. For example, the enclosure **18** may be a rigid cup with an elastomer coating along the rim with an appropriate spring exerting a force on the cup in accordance with this aspect of the invention.

[0063] The wall **44** of the enclosure **18** includes a sidewall **56** which may also contribute, and in some cases the largest amount, to the resilient nature of the engagement with the vibrating element **4**. The sidewall **56** extends from the lip **46** to the hub **35** and extends completely and around the central axis CA. The resilient nature of the enclosure **18** may be provided for in whole or part by the shape of the sidewall **56**. The sidewall **56** may have a tapered portion **60** extending from a large end (diameter of 0,210 to 0.220 inch) to a small end (diameter of 0.180 to 0.190 inch) with the large end positioned nearer to the vibrating element **4** (and may be adjacent the lip **46** at the distal end) and surrounds and encompasses a larger area than the small end. The tapered portion **60** of the sidewall **56** may also include a first frustoconical portion **62** extending from the lip **46** and a radial extension **64** extending primarily radially inward from the small end of the first frustoconical portion **62** to the hub **35**. The radial extension **64** extends radially inward with respect to a central axis CA of the enclosure **18**. The orientation and relative dimensions of the parts of the wall **44** and sidewall **56** are described herein with reference to a cross-sectional shape at a plane on which the central axis CA (of the vibrating element **4** and/or the enclosure **18**) lies for a total angular extent of at least 270 degrees when viewed along the central axis CA (or completely around the central axis CA as shown). The radial extension **64** extends radially inward at least 20% of an equivalent radius of the open end. The radial extension **64** may have a ratio of radial to longitudinal displacement of at least 3 to 1 relative to the central axis CA with the central axis CA representing the longitudinal direction and may be positioned 0.014 to 0.030 inch or 0.014 to 0.040 inch from the vibrating element **4** measured along a central axis CA. As used herein, “equivalent radius” or “equivalent diameter” refers to the radius or diameter of a circle having the same area. The tapered portion **60** of the sidewall **56** has a second frustoconical portion **63** extending from the radial extension **64** to the hub **35**.

[0064] The tapered portion **60** of the sidewall **56** extends from the lip **46** to the hub **35**. In total, the tapered portion **60** may have a radial to longitudinal displacement ratio of at least 1 to 3, at least 2 to 3 or at least 1 to 1 relative to the central axis CA. As used herein, “tapered” does not require a gradual or continuous change and only refers to a reduction in size perpendicular to the central axis CA which represents a feed area. The reduction may be stepped or may extend substantially only radially inward like the radial extension **64** without departing from the definition of “tapered” as used herein. The tapered portion **60** of the sidewall **56** may extend radially (relative to the central axis CA of the enclosure **18**) at least 20% of an effective radius of the enclosed boundary of the lip **46** around at least 270 degrees (and may extending completely and fully around the central axis CA) of the enclosure **18** when viewed along the central axis CA. The tapered portion **60** of the

sidewall **56** may have a thickness of 0.003 to 0.007 inch and may be about 0.005 inch to enhance the flexibility of the sidewall **56**. The sidewall **56** extends to the hub **35** and a connector **66** is formed which engages an end of the tube **56** (FIG. **7**) having a mating connector (not shown). The main inlet **52** is formed by the hub **35** which receives the fluid from the lumen **54** in the tube **56**. The other end of the lumen **54** in the tube **56** receives fluid from the pump **32**.

[0065] The lip **46** may be unattached to the vibrating element **4** while still being in contact with the vibrating element **4**. The terms “no attachments”, “not attached” or “unattached” as used herein means no connection other than frictional contact. Stated another way, the lip **46** may be free to move away from the vibrating element **4** along the central axis CA. Stated still another way, the enclosure **18** (specifically the lip **46**) is unattached to have a degree of freedom in the direction of the central axis CA relative to the vibrating element **4**. Thus, the lip **46** and the vibrating element **4** may have channels and/or raised baffles or walls which may restrain lateral movement do not constitute an “attachment” as defined herein. The lip **46** may have a curved surface with a radius of curvature of about 0.005 inch to provide a rounded edge to the lip **46**.

[0066] The vibrating element **4** and lip **46** define an enclosed border **41** at the interface of the two (while each one may define the enclosed border **41** by itself in that they define the same boundary with one another). The enclosed border **41** defines an enclosed feed area **51** (FIG. **11**) at the fluid side of the vibrating element **4** which may be 5.3-5.7 mm or about 5.5 mm in diameter. The openings **6** in the vibrating element **4** encompass and define a delivery area **39** of the vibrating element **4** which is circular and has a diameter of 2.6 to 3.0 mm or stated another way of less than 3.0 mm or about 2.8 mm. Of course, other patterns and shapes other than circular may be used with the effective diameter or radius for comparison. The enclosed border **41** may be appreciably larger than the delivery area **39** in that the delivery area **39** may be no more than 75%, or no more than 50%, of the enclosed feed area **51**. Stated another way, the enclosed feed area **51** may be at least 30% larger, and may be at least 100% larger, than the delivery area **39**. Stated yet another way, the enclosed feed area **51** may be larger than the delivery area **39** so that an excess feed area **58** (defined by the enclosed feed area **51** not coextensive with the delivery area **39** when viewed along the central axis CA) is at least 30% of the delivery area **39** and may even be larger than the delivery area **39** or even up to 50% larger. The excess feed area **58** may be an annular ring for a concentric arrangement or crescent shaped for offset circular areas (which may be non-circular but represented and compared as circles when using equivalent radius or diameter). The delivery area **39** of the vibrating element **4** defines a geometric center and an effective radius for a circle of equivalent area. The enclosed feed area **51** also defines a geometric center and an effective radius for a circle of equivalent area. The geometric center of the enclosed feed area **51** may be above the geometric center of the delivery area **39** and offset by at least 0.3 times the effective radius of the delivery area **39**. The fluid held in the chamber **16** also defines a geometric center positioned less than 0.015 inch from the vibrating element **4** when measured in the direction of the central axis CA. The geometric center of the fluid may similarly be positioned at least 0.3 times the effective radius of the delivery area **39** above the geometric center of the delivery area **39** for an offset design. For a concentric embodiment, the geometric center of the fluid (or the volume of the chamber **16**) is less than 0.1 times the effective radius of the delivery area **39** from the central axis CA of the vibrating element **4**.

[0067] Although the enclosure **18** provides a relatively small chamber **16** with a small volume, the chamber **16** may provide fluid to the openings **6** without requiring capillary feed as some prior art teaches. The enclosure **18** has an internal surface **49** which defines the boundary of the chamber **16** as defined by the enclosure **18**. The fluid is held in the chamber **16** in contact with the internal surface **49**. An internal wall **45** of the enclosure **18** has a side **47** facing the openings **6** which is spaced apart from the openings **6** by a separation which may be about 0.017 inch. The spacing between the internal surface **49** of the enclosure **18** and the vibrating element **4** may be larger than a capillary spacing so that capillary action is not present. Capillary feed may impede fluid flow

when it is desired to deliver the fluid quickly and also makes it difficult to completely deliver from the feed system which presents residual fluid problems. To avoid possible capillary action and/or minimize obstruction to flow it may be desirable to have a minimum spacing between the openings **6** and the nearest part of the enclosure **18** so that at least 75%, or at least 95%, or even all, of the openings **6** have a minimum spacing of at least 0.010 inch, or at least 0.014 inch to the nearest part of the internal surface **49** of the enclosure **18**.

[0068] While it may be desirable at times to avoid capillary action, it is still desirable to provide for quick delivery of substantially all of the fluid and, thus, the enclosure **18** may still be shaped so that the fluid in the chamber **16** doesn't need to travel far to reach the openings **6** for ejection. To this end, the internal surface **49** of the enclosure **18** may be shaped so that at least 75%, or at least 95% or even all, of the fluid in direct fluid communication with the fluid in the chamber **16** is no more than 0.060 inch, or no more than 0.040 inch, from the nearest opening **6** in the vibrating element **4**. Stated another way, the chamber **16** may be shaped and formed by the internal surface **49** of the enclosure **18** so that at least 75%, 95% or even all of the fluid in the chamber **16**, and optionally all fluid in fluid communication with the fluid in the chamber **16**, has direct line of sight to the nearest opening **6**. Many prior art systems have wet feed tubes or conduits which are filled with liquid and are spaced much further than 0.060 inch from the openings **6** and must overcome surface tension and other forces which may tend to hold the fluid in the conduits which may contribute to residual volume. Thus, in some instances it may be desirable to have most, if not all, of the openings **6** separated a minimum distance from the enclosure **18** to avoid capillary action while at the same time still having all of the fluid relatively close to the openings **6** and without impediment for rapid, substantially complete delivery in a short period of time and with low residual volume. When addressing both concerns, the enclosure **18** forming the chamber **16** may be spaced apart by 0.014-0.040 inch from all of the openings **6** when viewed and measured in the direction of the central axis CA of the vibrating element **4**. “Fluid in communication” with another fluid refers to fluid that is continuous which includes feed tubes, pipes, wicks and channels which feed fluid to the openings.

[0069] The enclosure **18** may be an integrally formed structure which defines the chamber **16**. The integrally formed structure may be made of a thermoplastic elastomer and formed by a suitable method such as injection molding. One example is sold under the name Thermolast® supplied by Kraiburg as TF5CGN which is a thermoplastic elastomer.

[0070] The volume of fluid delivered may fill the chamber **16** only 75-90% full which may provide room during delivery to encourage all of the fluid to gather in the chamber **16** due to surface tension forces. Delivering the fluid at a velocity of at least 0.5 m/s (or at least 1.0 m/s) to the enclosure **18** may also encourage substantially all of the fluid ejected from the tube **56** to collect in the chamber **16** rather than being left behind as residual. Stated another way, the pump delivers the fluid at a pressure of at least 200 psi (and may be about 300 psi) which may be sufficient to achieve the velocities desired for many fluids delivered to the eye. In this manner, the small fluid amount remains a single fluid “droplet” which is fired into the enclosure **18**.

[0071] The enclosure **18** may split the flow from the main inlet **52** into a first inlet **55** and a second inlet **57** each leading to the chamber **16**. The enclosure **18** may also have a third inlet **59** and a fourth inlet **61** and all aspects of the first and/or second inlets **55**, **57** are expressly incorporated for the third and/or fourth inlets **59**, **61** and the other of the first and second inlets **55**, **57** when discussed independently and all such features and limitations are expressly incorporated for all of the other inlets. The first inlet **55** directs the fluid at the internal surface **49** of the enclosure **18**, such as the tapered portion **60** of the sidewall **56**, before being directed at the openings **6** in the vibrating element **4**. The first inlet **55** and the second inlet **57** may lead directly to the chamber **16** with the inlets both being oriented to direct all of the fluid entering the chamber **16** (or at least 90% of the fluid) at the internal surface **49** of the enclosure **18** (such as the internal surface **49** along the sidewall **56**) before being directed to the openings **6** in the vibrating element **4**. In this manner, the possibility that the fluid is forced through the openings **6** during filling of the chamber **16** may be

reduced. In particular, when the fluid is forced into the chamber **16** at a velocity or pressure as suggested herein it may be advantageous to direct the fluid into the enclosure **18** in this manner.
[0072] The main inlet **52** initially directs the fluid at the internal wall **45** opposing the openings **6** which forms part of a flow splitting chamber **66**. The internal wall **45** extends from one side of the sidewall **56** to the other relative to the central axis CA to form the inlets. The flow splitting chamber **66** splits the flow into four streams that pass through the four inlets each spaced apart from and directed at the tapered portion **60** of the sidewall **56**. The flow splitting chamber **66** may lead directly to the chamber **16** as shown or may have additional baffles or flow altering features. The main inlet **52** directs the flow in a direction within 30 degrees of the central axis CA of the enclosure **18** and may be along and aligned with the central axis CA as shown. The first inlet **55** and the second inlet **57** may be oriented to direct the fluid within 30 degrees of perpendicular to the central axis CA to avoid fluid being directed at the openings **6**. The enclosure **18** may have a third inlet and a fourth inlet which are also oriented at the sidewall **56** of the enclosure **18**. When viewed along the central axis CA of the enclosure **18**, the adjacent inlets are oriented 60-120 degrees from one another and may be about 90 degrees from the adjacent inlets **55**. **57**, **59**, **61** as shown.
[0073] The flow splitting chamber **66** has a cup-shaped wall **68** (which includes the internal wall **45**) with a concave side **70** facing toward from the vibrating element **4**. The cup-shaped wall **68** has all four inlets formed therein. The cup-shaped wall **68** extends radially outward from a central axis CA of the enclosure **18** for at least 25% of an effective radius defined by the lip **46** for an angular extent of at least 240 degrees relative to the central axis CA of the lip **46**. The first inlet **55** has a radial dimension and a longitudinal dimension relative to the central axis CA with a ratio of the radial dimension to the longitudinal dimension being 0.5 to 1.5. The first inlet **55** and the second inlet **57** extend radially inward toward the central axis to expose some of the main inlet **52** when viewed in the direction of the central axis CA, however, direct longitudinal flow from the main inlet **52** to the vibrating element **4** is prevented by the radial component to the flow which is created by the bulk of the fluid directed radially outward by the internal wall forming the bottom of the cup **68**.
[0074] The chamber **16** is also formed so that at least two, three or four inlets **55**, **57**, **59**, **61** are provided which, together with the dimensions of the chamber **16**, provide a lower energy state to encourage the fluid to collect in the chamber **16** rather than any residual part of the fluid remaining in the splitting chamber **66** or extending between the chamber **16** and the flow splitting chamber **66**. Although many aspects of the present invention are directed to minimizing residual fluid, the present invention may be practiced with some residual volume left and, in fact, some aspects the invention may be used with a wet system without departing from those aspects of the invention.
[0075] As fluid is evacuated (ejected through the openings **6**) from the chamber **16** make-up air must be introduced to vent the chamber **16** during operation. The enclosure **18** may vent air into the enclosure **18** between the lip **46** and the vibrating element **4** with the lip **46** separating sufficiently from the vibrating element **4** during vibration to vent air into the enclosure **18** without releasing fluid. Air vented between the lip **46** and the vibrating element may aid in fluid delivery by moving or displacing fluid at radially outer regions radially inward toward the openings **6** and by simply occupying these radially outer spaces (excess feed space) rather than residual fluid which might occupy this space.
[0076] Air may also be drawn into some openings **6** of the vibrating element **4** to vent the enclosure **18** as fluid is ejected through the openings **6**. The air is introduced as small bubbles in the chamber **16** which may distribute the fluid among in some sense to find “active” ejection openings **6**. The enclosure **18** may include no other vent openings, or no dedicated vent, which simplifies the system and eliminates one possible contamination path or source. Of course, a dedicated vent may be provided for the chamber **16** without departing from the invention as now described.
[0077] Referring to FIGS. **32**-**35**, another chamber **16**A and enclosure **18**A are shown which are substantially the same as the chamber **16** and the enclosure **18** and all uses and combinations and

all other disclosure related to the chamber **16** and the enclosure **18** (and all other enclosures and chambers described herein) are incorporated here. Likewise, all discussion for chamber **16**A and enclosure **18**A are also incorporated for the chamber **16** and the enclosure **18** (and all others). The enclosure **18**A has a wall **44**A with a lip **46**A adjacent the vibrating element **4** (see FIG. **2**). A wall opening **124** is formed in the wall **44**A to vent the chamber **16**A during operation. The wall opening **124** may also have dimensions which enhance the flexibility of the enclosure **18** as described below. The lip **46**A may have a PTFE coating **120** adjacent to the vibrating element **4** to reduce friction therebetween. The vibrating element **4** may similarly have a PTFE coating **122** adjacent to the lip **46** to reduce friction therebetween. The coatings **120**, **122** may extend around at least 270 degrees when viewed along the central axis CA. Of course, the coating **122** may extend entirely around the central axis CA. An inner surface **123** of the enclosure **16**, **16**A may be hydrophobic (coated or by virtue of the material property) over at least 70% of the inner surface **123** of the enclosure **18**A in contact with the fluid loaded prior to delivery.

[0078] The wall opening **124** may take any suitable shape such as a wedge-shaped opening. The wall opening **124** extends through the wall **44**A, specifically a sidewall **56**A portion of the wall **44**A, to expose the chamber **16**A. The wall opening **124** may also form a small gap **131** in the lip **46**A, which together with the geometry of the opening **124**, is small enough to prevent fluid leakage but may still be large enough to vent the enclosure **18**A by permitting air to enter when fluid is ejected. All discussion and applications concerning venting of the enclosure **18** are incorporated here such as discussion of venting between the lip **14** and the vibrating element **4**, spacing between the lip and vibrating element and the force-displacement characteristics. Thus, the lip **14**A may be in contact with the vibrating element **4** or spaced apart in any manner described herein.

[0079] The wall opening **124** has a longitudinal dimension **126** measured from the lip **46** in the direction of the central axis CA and a radial dimension **128** measured in a radial direction relative to the central axis CA. The longitudinal dimension **126** of the wall opening **124** is at least 80% of a separation **125** between the vibrating element **4** and a side **47**A of the enclosure **18**A facing the openings **6** and may extend substantially the entire length as shown. The radial dimension **128** of the wall opening **124** is not more than 10%, or no more than 5%, of an equivalent circumference of the lip **46**A. The radial dimension **128** may be about 0.025 inch while the longitudinal dimension **126** may be about 0.022 inch. The dimensions of the enclosure **18**A, the wall **124**A and the chamber **16**A may be any suitable dimensions including those associated with the enclosure **18** and all geometric relationships all of which are incorporated here.

[0080] The wall opening **124** extends from the lip **46**A proximally and may increase the flexibility of the enclosure **18**A due to its position and shape. The wall opening **124** has a circumferential dimension **130** measured in a circumferential manner relative to the central axis CA. The circumferential dimension **130** may be about 0.012 inch at the lip **46**A (same as the gap **131**) and tapers so that the two sides converge at a proximal end **132** of the wall opening **124**. The circumferential dimension **130** is defined herein as a measurement for a line segment that is perpendicular to a radial orientation of the central axis CA. The wall opening **124** tapers down as the wall opening **124** extends proximally from the lip **46**A. The wall opening **124** tapers so that a tapered shape **132** of the wall opening **124** is oriented in the direction of (“points at”) at least one of the inlets **55**, **57**, **59**, **61** to the chamber and may be oriented to align with two inlets when viewed along the central axis CA. Orienting the tapered shape **132** of the wall opening **124** with the inlet(s) **55**, **57** in this manner increases flexibility since the inlet(s) and wall opening **124** cooperate to increase flexibility given their geometric alignment. The “orientation” of the tapered opening shall be defined as the bisection of the tapered angle extending away from the wall opening **124**. The tapered shape **132** is also within 10 degrees of a radial orientation relative to the central axis CA and may be substantially radially oriented as shown. The wall opening **124** is also positioned along a frustoconical portion **62**A with the wall opening extending proximally from the lip for at least

80% of the length of the frustoconical portion **62**A.
[0081] The pump **32** is now described in more detail. The pump **32** draws discrete volumes from the fluid container **17** and delivers these volumes to the chamber **16**. The fluid container **17** may be any other suitable mechanism such as a piston/plunger associated with the fluid container **17** in some applications. The fluid container **17** may have a fluid carrying capacity which is at least 150 times the volume of the chamber **16** (or the volume of the fluid delivered) for a multi-dose device. The pump **32** may be configured to deliver the same (and optionally the only) volume each time. Of course, a variable volume pump **32** may also be used without departing from virtually all aspects of the invention.
[0082] The present invention may be used to provide single dose delivery with substantially the whole dose delivered thereby leaving little residual fluid in the chamber **16**. The vibrating element **4** may deliver the fluid from the enclosure **18** so that no more than 5%, or no more than 2%, of a total volume of the chamber **16** is occupied by residual fluid (from a previous fluid delivery) or less than 1 microliter remains. Stated another way, the vibrating element is operated to dispense substantially the entire volume of fluid in communication with the openings **6** so that no more than 5%, or no more than 2%, of the fluid volume (or less than 1 microliter) remains in the chamber **16** after the fluid is ejected and a single actuation for fluid ejection. In this manner, the chamber **16** is substantially empty after a single application of the fluid (a single firing actuation). An advantage of some aspects of the present invention over other fluid delivery systems is that the chamber **16** receives a single dose that is nearly completely delivered to leave the chamber **16** substantially dry and free of residual fluid between activations. Contamination and degradation of the fluid may be reduced compared to “wet” systems that maintain the fluid in contact with the vibrating element **4** between uses or which have incomplete delivery.
[0083] The enclosure **18** may be sized so that the enclosure **18** may be at least 70-95% full with the fluid volume as mentioned above which may help the fluid to gather in the chamber **16** as a single droplet. The chamber **16** may define a relatively small volume such as less than 14 microliters or 10-14 microliters. The fluid volume may be 7-12 microliters or 10-12 microliters. The lumen **54** in the tube **56** delivers the fluid through the main inlet **52** to the enclosure **18** with the main inlet **52** having a diameter of 0.040 to 0.060 inch and may be about 0.054 inch, The flow splitting chamber **66** may have a diameter which essentially matches the main inlet **52** of about 0.054 inch. The tube **56** extends from the main inlet **52** and may have a volume of less than 2 microliters to further minimize residual fluid. The tube **56** may be part of the enclosure **18** and may be formed with the enclosure **18** rather than as separate parts.
[0084] In use, fluid delivery to the eye may also be relatively rapid to reduce the likelihood of interference from a blink during delivery. The fluid delivery may take less than 200 ms and may even be less than 150 ms or even 100 ms. The vibrating element **4** may also be operated with a pause between periods of vibration during a single actuation. For example, the vibrating element may be driven by the piezoelectric element **15** for a first period of operation of about 26 ms with a pause of about 3.65 ms followed by a second period of operation of about 26 ms. The vibrating element **4** may be driven by the piezoelectric element **15** with two pauses with the piezoelectric element **15** being energized or activated for a first period of time, a second period of time and a third period of time with the first and second periods separated by the first pause and the second and third separated by a second pause in driving vibration of the vibrating element **4**. The first and second pauses in driving vibration may be 0.5 ms to 4.0 ms. Each of the first, second and third time periods may be 20-40 ms and the overall time of delivery may be less than 150 and even less than 100 ms and may be about 85.3 ms. Each of the first, second and third periods of vibration may be further subdivided into periods of activation for about 816 us and deactivated for about 586 us for the piezoelectric element **15**. During the deactivated time, the vibrating element **4** may continue to vibrate and eject fluid although not being actively driven by the piezoelectric element **15**. Similarly, during each pause in activation of the piezoelectric element **15** the vibrating element **4** may

continue to eject the fluid. The “pause” may be defined as a continuous deactivation of at least 2% of the total time and the total pause time for a plurality of pauses being at least 6% and may be about 8.5% of the total delivery time. The deactivated times are defined distinct from the pause in that the pause is at least 2% of the time continuous while the deactivated time is shorter and may be defined as a continuous time of 0.5-1.0% of the total delivery time and a total of the deactivated times being at least 30% of the total delivery time. Stated another way, the deactivated time is a continuous time of 2.0 to 2.5% of the first period of time (and second and third as well) and a total deactivated time of at least 30% of the first period of time. Of course, the delivery times are defined to illustrate the invention and the activation times and patterns may change depending on the surface tension of the ejected fluids.

[0085] As mentioned above, the frequency of the alternating signal used to activate the piezoelectric element **15** and subsequently activate and vibrate the vibrating element **4** is induced at a drive frequency of 100 kHz to 160 KHz. Furthermore, the frequency is selected by the control system **11** as a randomized frequency centered about the drive frequency (ranging from 100 kHz to 160 kHz) for each of the plurality of activations during a single delivery and may be randomized at least 20 and may be at least 40 times. Stated another way, the vibration frequency is changed (randomly in a manner centered on the drive frequency) on average at least 33 times for a single firing actuation so that the piezoelectric element **15** is driven at a frequency for no more than 3% of the delivery time (average) before being changed. It is believed that the chaotic nature of the randomization of the drive signal may aid in ejecting fluid. The randomized nature may be provided by a predetermined randomized set of values which are applied to the centered operating frequency or the randomized values uniquely generated by the control system **11**.

[0086] The vibrating element **4** may also be designed to vibrate with a relatively low maximum amplitude. For example, the vibrating element **4** may vibrate with a maximum amplitude of less than 2 microns, less than 1.5 microns or within a range of 0.5-1.5 microns, 0.8-1.2 microns or may be about 0.8 microns. The maximum amplitude of the vibrating element **4** may also be relatively small compared to the size of the openings **6** in the vibrating element **4**. For example, the maximum amplitude may be no more than 5%, or no more than 3%, of an effective diameter of the cross-sectional shape of the openings **6** at the delivery side. For example, when the maximum amplitude is 1.0 microns and the average diameter of the openings **6** at the delivery side is 40 microns the maximum amplitude is only 2.5% of the average diameter or about 2.5% of the average diameter of the fluid droplets ejected. The maximum amplitude also represents a relatively small amount compared to the thickness such as no more than 5.0% or even no more than 3.0% of the thickness of the vibrating element **4** (measured from the fluid side to the delivery side). As used herein, the thickness may be an average thickness for the area bounded by the openings **6**. Operation at low amplitude may also contribute to venting through the openings **6** in that air may be admitted through some of the openings **6** having even low displacements. Operation at low amplitude may also help maintain fluid containment between the lip **46** and the vibrating element **4**. When the lip **46** is spaced apart from the vibrating element **4**, the lip **46** may be spaced apart an average distance greater than the maximum amplitude of the vibrating element **4** during vibration. Stated another way, the maximum amplitude is less than an average separation distance between the surface of the lip **46** and the vibrating element **4**.

[0087] Referring to FIGS. **13-17**, the housing is partially removed to expose the pump **32**. The pump **32** delivers fluid from the fluid container **17** to the chamber **16** through the lumen **54** in the tube **56** and through the main inlet **52** (see FIG. **12**). The fluid container **17** may be any suitable container such as a vial, ampoule, bag, bladder or a fixed container that is filled without departing from the scope of the present invention. Similarly, the pump **32** may be any suitable mechanism for delivering the fluid to the enclosure **18** without departing from various aspects of the invention. The fluid container **17** has a pierceable cap **70** which is pierced by a delivery needle **34** and the vent needle **40**. The delivery needle **34** defines part of a delivery flow path and the vent needle **40**

defines part of a vent path. The delivery flow path extends to the pump **32** and from the pump **32** through the tube **56** and the main inlet **52** into the chamber **16**. Referring to FIGS. **3** and **13**, the delivery needle **34** and the vent needle **40** are mounted to a container support **70** on which the container **17** is mounted. The container support **70** has a coupling **72** which engages the manifold **30**. A vent lumen **73** includes a one-way valve **76**, such as an umbrella valve **78**, which permits air into the fluid container **17** to make up for the volume of fluid lost as explained below.

[0088] The pump **32** has a first part **80** and a second part **82**. The first part **80** reciprocates between a stored position (FIG. **13**) to a partial stroke position (FIG. **14**) and to a forward stroke position (FIG. **15**) at the greatest displacement. The first part **80** returns to the stored position to complete a cycle which delivers a volume of fluid to the chamber. The second part **82** also reciprocates between a stored position to a forward stroke position at a greatest displacement and back to the stored position each cycle. The first part **80** has an extension **84** extending from a main body **86**. The main body **86** has an end **88** facing an end **90** of a main body **89** of the second part **82**. The extension **84** on the first part **80** extends toward and interlocks with an extension **85** extending from the main body **89** of the second part **82**. The first part **80** is driven and in turn drives the second part **82** through each cycle by engagement of the extensions **84**, **85** and/or the ends **88**, **90** of main bodies **86**, **89** with one another. A cavity **92** is formed between the first part **80** and the second part **82** with the size of the cavity **92** changing as the first and second parts **80**, **82** move toward and away from one another. The cavity **92** increases in size when the first and second parts **80**, **82** move away from one another which draws fluid into the cavity **92** during the forward stroke. The cavity **92** decreases in size when the first and second parts **80**, **82** move toward one another which delivers the fluid from the cavity **92** to the chamber **16** during the return stroke. The cavity **92** has a volume commensurate with volume of the fluid being delivered which may be 7-12 microliters.

[0089] The fluid is drawn into the cavity **92** during the forward stroke of the first part **80**. The first part **80** and the second part **82** are movable from a stored position of FIG. **13**, to the partial forward stroke position of FIG. **14** and finally to the full forward stroke position of FIG. **15**. The first and second parts **80**, **82** move to the full stroke position with the first part **80** pulling the second part **82** upward due to the interlocking extensions **84**, **85** engaging one another. In the full forward stroke position the pump **32** is ready to deliver the fluid through the tube **56** and into the enclosure **18**.

[0090] When the first and second parts **80**, **82** reach the partial stroke position of FIG. **16** during the return stroke the fluid has been delivered from the cavity **92** to the chamber **16**. The first and second parts **80**, **82** complete the cycle by moving to the partial reset position of FIG. **17** and to the fully reset position of FIG. **13** again. An additional optional step may be to purge any fluid left downstream of the chamber **16** with a separate displacing medium. The tube **56**, the chamber **16** and the flow splitting chamber **66** represent a total downstream volume which is substantially free of fluid prior to delivery of the fluid. The volume of fluid delivered by the pump **32** may be 40-70% of the total downstream volume so that the tube **56** and flow splitting chamber **66** can be substantially empty when the fluid has been delivered to the chamber **16**. As mentioned above, the fluid may be ejected at a relatively high velocity of at least 0.5 m/s (or with the pump delivering the fluid at a pressure of at least 200 psi) to “fire” the droplet into the chamber **16** and which may permit surface tension forces to gather and hold the small volume of fluid together.

[0091] The pump **32** may also deliver make up air into the container **17** to make up for the volume of fluid lost. The pump **32** draws air into a make-up chamber **94** during the forward stroke and forces the air from the make-up chamber **94** toward the fluid container **17** so that air enters and vents the fluid container **17** during the return stroke. The first and second parts **80**, **82** each have an opposing end **97** positioned opposite the ends **88**, **89** which face each other to form the cavity **92**. At least one of the opposing ends **97** of the first and second parts **80**, **82** may forms part of the make-up chamber **94** (such as the opposing end **97** of the second part **82**) so that movement through a full cycle also draws air into the make-up chamber **94** during the forward stroke and expels air during the return stroke. Air is forced through the one-way valve **76**, through the vent

needle **40** and into the container **17** to make up for the volume of fluid lost (delivered). When the first and second parts **80**, **82** reach the fully reset position the make-up air has been delivered and the pump **32** is in the stored position again with the first part **80** of the pump **32** blocking the main inlet **52** to the enclosure **18**. O-rings are used to seal junctions and spaces between the first and second parts and the manifold and along the vent and fluid delivery paths.

[0092] Referring to FIGS. **4**, **6** and **18-23** together, a drive mechanism for the pump **32** is shown. The drive mechanism includes the first actuator **94** (which may be a button **95**) coupled to a first side **96** of a lever **98**. The lever **98** rotates about pivot P in the direction of arrow A as the button moves downward. A second side **100** of the lever **98** is coupled to a support plate **102** of the first part **80** of the pump **32** so that the first part **80** moves upward with the first side **96** of the lever **98** from the stored position of FIGS. **18** and **21** to the forward stroke position of FIGS. **19**, **20** and **22** in which fluid has been drawn into the cavity **92**. The lever **98** may provide a mechanical advantage of about 11/6 due to the difference in lever arm length. Of course, a powered system using the battery **19** may also be used to move the fluid without departing from other aspects. A ratchet **104** prevents back-travel as the button **95** is depressed until reaching the necessary downward displacement (full forward stroke) at which point the ratchet **104** is released to permit the return stroke.

[0093] The first actuator **94** (such as the button) also loads the pump return spring **95** (and may load two pump springs **95**) during the forward stroke. The loaded pump return spring(s) **95** drives the pump **32** back to the default or stored position during the return stroke. The pump return spring **95** may act on the first actuator **94**, the lever or directly on part of the pump **32** itself such as on the first part **80** as shown. The first actuator **94** (button **95**) is also returned to the stored position. In the stored position the main body of the first part **80** blocks flow through the lumen **54** in the tube **56** and the main body of the second part **82** blocks the vent path and the fluid delivery path. In this sense, the pump **32** acts a valve **104** and the present invention may be practiced with a dedicated valve closing the lumen **54** to the tube **56** and fluid being moved in another manner without departing from various aspects of the present invention.

[0094] Referring to FIGS. **25-31**, the device **1** also includes a shutter **105** having an aperture **107** through which the fluid is delivered. The shutter **105** blocks and covers the vibrating element **4** in the stored position and may serve as an “off” switch (or defines the “off” condition) when using a position sensor **110** to detect the position of the shutter **105** (specifically the circled area of the shutter **105**). A shutter spring **109** is also loaded as the first actuator **94** is moved through the forward stroke. Unlike the pump return spring **95**, the shutter spring **109** is locked in the loaded position of FIG. **26**. The position sensor **110** (which may be an optical, electromagnetic, electrical or mechanical sensor) determines when the shutter **105** is in the firing position in which the aperture **107** is aligned with the fluid openings **6**. For example, the sensor **110** may be an optical sensor coupled to the control unit **11** (and the reusable second housing) which senses a marker on the shutter. Fluid ejection is prevented when the position sensor determines that the shutter **105** is blocking (or will block very soon) delivery of fluid. The fluid is delivered upon actuation of a second actuator **106** (which may be a firing or dose button **108**) which is unlocked when the shutter **105** is in the position of FIG. **26** and the device is ready for delivery of the fluid. In use as described below, the firing button **108** mechanically releases the shutter **105** and the fluid ejector is activated by the control system **11** while the aperture in the shutter **105** is aligned with openings **6** in the vibrating element **4** as determined by the position sensor **110**.

[0095] The shutter **105** motion is now described in more detail. Referring to FIGS. **4**, **18** and **23**, the shutter **105** is in the stored position. The shutter **105** is moved downward by the first actuator **94** so that a tab **109** slides downwardly in a slot **111** and is locked in a ready state of FIGS. **19** and **26**. The device is now in an “on” state by activation of a switch (not shown) when the dose is loaded. During the shutter locked state, another sensor (not shown) may determine the device has loaded fluid and is ready to dispense a dose. Activation of the dose button **108** and the subsequent

activation and deactivation in accordance with the position sensor's **110** determination of the shutter **105** position is the mechanism by which the dose/ejection is triggered and terminated. Of course, numerous other methods of timing delivery may be used and, furthermore, the fluid may be delivered in a manner independent of the shutter **105** operation.

[0096] A shutter lock **115** is displaced by the firing button **108** to the position of FIG. **27** so that the tab **109** on the shutter **105** moves upward in a release slot **117** having a ramp **119**. The firing button **108** is mounted to a resilient arm **121** having a pair of hooks **123** which engage the shutter lock **115** and pulls the shutter lock **115** back to the stored position in part due to the resilient nature of the arm **121**. A button return spring **125** (see FIG. **17**) is compressed upon actuation and returns the button **108** to the ready state and may also serve to return the shutter lock **115** to the stored position.

[0097] Use of the device to handle and deliver a dose of the fluid is now described. The fluid container **17** may be mounted prior to use or may be pre-loaded or loaded from a prior use. When loading the fluid container **17** for the first (and optionally only) time, the fluid container **17** is mounted in a cavity **92** and the button is placed over the fluid container **17**. The user then depresses the first actuator **94** to force the container **17** downward so that the vent needle **40** and the delivery needle **34** pierce the fluid container as shown in FIG. **7**. The fluid container **17** may be locked to prevent removal and replacement of the fluid container **17**. The device may be stored in this condition.

[0098] Immediately before deciding to deliver the dose, the fluid is delivered to the chamber **16** by actuating (depressing) the first actuator **94** (cap) which moves the pump **32** through a full cycle to load the fluid in the chamber **16**. Once the actuator **94** has returned to the default position, the fluid is contained in the chamber **16** and ready for delivery. The first actuator **94** may be any suitable actuator such as the button **95**, a lever, a slider, a twist knob or any other suitable mechanical or electro-mechanical actuator without departing from numerous aspects of the present invention. Of course, the fluid may be delivered to the chamber **16** during delivery of the fluid to the eye or immediately before and in a continuous process without departing from virtually all aspects of the present invention. After delivery of the fluid to the chamber **16**, the device may also clear the tube **56** of fluid. For example, the pump **32** may draw a volume of displacing medium and deliver the displacing medium into the tube **56** to displace any fluid in the tube **56** into the enclosure **18** prior to delivery.

[0099] When the user is ready, the user then actuates the firing button **108** to deliver the fluid to the eye. To aim and align the device, the user positions the device adjacent the eye and looks into the device through the aperture **107** in the shutter **105** and views the vibrating element **4**. A light emitting element **114**, such as a light tube **116**, illuminates part of the device, such as the vibrating element **4**, to visually aim and align the device. Of course, any other suitable aiming/aligning method may be used. Once the device is properly aimed, the firing button **108** is actuated to deliver the fluid to the eye. The second actuation may be with the same actuator or a different actuator such as the firing button **108**. Although the present invention has been described with a two-step actuation process the two steps may be combined in a single actuation which delivers the fluid to the chamber **16** then determines an appropriate time to deliver the fluid such as by optically differentiating the eyeball from the eyelid. The device delivers substantially all of the fluid and the device is ready for storage after a single actuation and delivery of a single dose or quantity to the eye.

[0100] All aspects of the methods and devices as claimed may be applied to the other methods and devices and such claim combinations are expressly incorporated. Furthermore, combinations of size range, ratio, angular or linear coverage, percentage or any other quantity are expressly incorporated into the claims even if the specific combination has not been previously expressly claimed. For example, the alternative ranges 75%, 95% and “all” are used to describe various values which may be used or substituted for one in combination with the other quantities. The

terms “first” and “second” shall be interchangeable in the claims since they are not used as terms of natural order but merely to distinguish one from the other. In addition, the claim terms “have” “having” “includes” “including” “comprises” and “comprising” (and all other forms of these terms such as “has”) are all open ended as used herein in that “A has B” or “A includes B” means A includes B but may also include other elements or method limitations. Finally, the present invention has been described with reference to some aspects, advantages or operating conditions which are difficult to quantify and directly due to the small volume and fast delivery time. Thus, direct observation and measurement are at times not feasible, however, qualitative information supports some of the assertions. For example, it has been observed that water at the interface of the lip **46** and vibrating element **4** outside the enclosure **18** is drawn into the enclosure **18** when fluid is ejected indicating that air may likely be admitted as well. Furthermore, the fluid is smoothly ejected even with no dedicated vent opening.

[0101] The present invention has been described with reference to preferred embodiments, however, various modifications may be made without departing from the features and aspects of the invention. For example, the pump **32** may be a syringe, the enclosure **18** may be a rigid dome or the enclosure **18** may be attached to the vibrating element **4** without departing from aspects of the invention.

Claims

1. A device for delivering a volume of fluid to an eye, comprising: a housing; a fluid ejector coupled to the housing, the fluid ejector having a vibrating element with a plurality of openings, the vibrating element having a fluid side and a delivery side with the plurality of openings extending from the fluid side to the delivery side, the fluid ejector ejecting fluid from the fluid side through the plurality of openings to the delivery side when the vibrating element is vibrated.

2. The device of claim 1, further comprising: an enclosure positioned adjacent the fluid side the vibrating element, the enclosure and the vibrating element forming a chamber, wherein the enclosure includes a wall having a lip positioned adjacent the fluid side of the vibrating element, the lip extending around the plurality of openings, the enclosure and the vibrating element together defining the chamber which holds a volume of the fluid to be dispensed.

3. The device of claim 2, further comprising: a pump having an outlet fluidly coupled to the chamber formed by the enclosure and the vibrating element; and a first actuator operably coupled to the pump, wherein actuation of the first actuator activates the pump to deliver the volume of fluid to the chamber.

4.-**207**. (canceled)

208. A method of delivering a volume of fluid to an eye, comprising: activating a device comprising: a fluid ejector comprising a vibrating element with a plurality of openings and a central axis, the vibrating element having a fluid side and a delivery side with the plurality of openings extending from the fluid side to the delivery side; an enclosure comprising a wall and a resilient lip positioned adjacent the fluid side of the vibrating element, the lip extending around the plurality of openings, the enclosure and the vibrating element together forming a chamber which holds the fluid in contact with the fluid side of the vibrating element; and a pump comprising a first part and a second part movably coupled to one another to change a size of a variable volume cavity of the pump to draw a discrete dose of liquid from a fluid container into the variable volume cavity; delivering the discrete dose of liquid into the chamber during a cycle of the pump; and vibrating the vibrating element so that the discrete dose of liquid in the chamber is ejected through the plurality of openings toward an eye.

209. (canceled)

210. The method of claim 208, wherein activating the device comprises: activating a first actuator of the device causing the discrete dose of liquid to be delivered into the chamber during the cycle;

and activating a second actuator of the device by the user after the first actuation to deliver the discrete dose of liquid to the eye.

211. The method of claim 210, wherein activating the first actuator comprises sliding a shutter from a stored position to a firing position; and wherein activating the second actuator comprises pushing a button.

212.-**217**. (canceled)

218. The method of claim 208, wherein the variable volume cavity of the pump holds a volume of 7-12 microliters, which is delivered to the chamber during the cycle.

219. The method of claim 208, the lip is spaced apart from the fluid side of the vibrating element by less than 250 microns.

220. The method of claim 208, wherein the lip is spaced apart from the fluid side of the vibrating element by less than 250 microns about an angle of at least 270 degrees when viewed along the central axis.

221.-**222**. (canceled)

223. The method of claim 208, wherein the vibrating element has a maximum amplitude which is less than an average separation distance between the surface of the lip and the vibrating element.

224.-**227**. (canceled)

228. The method of claim 208, wherein the vibrating element has a thickness measured from the fluid side to the delivery side of 100-180 microns.

229.-**232**. (canceled)

233. The method of claim 208, wherein the lip is biased against the vibrating element in a direction of the central axis to hold the fluid in the chamber.

234. The method of claim 208, wherein the lip of the enclosure exerts a force of no more than 3 gram-f on the vibrating element measured in the direction of the central axis.

235.-**249**. (canceled)

250. The method of claim 208, wherein the lip and the vibrating element are adjacent one another to prevent fluid from passing therebetween along a closed loop which encircles the plurality of openings.

251. The method of claim 208, wherein the lip is in contact with the vibrating element around at least 270 degrees of the plurality of openings when viewed along the central axis defined by the open end to hold the fluid in the enclosure.

252. (canceled)

253. The method of claim 208, wherein the lip is spaced apart from the vibrating element by a separation distance of at least 125 microns and no more than 250 microns around at least 270 degrees of the plurality of openings when viewed along the central axis of the vibrating element.

254. The method of claim 208, wherein the lip is configured to separate from the vibrating element to vent air from the chamber as the discrete dose of liquid is ejected into the chamber.

255.-**264**. (canceled)

265. The method of claim 208, wherein further comprising loading the fluid container with the device, wherein the fluid container comprises a vial, ampoule, bag, bladder, or fixed container that has a fluid carrying capacity which is at least 150 times the volume of the enclosure.

266. The method of claim 208, wherein the vibrating element defines an enclosed border positioned adjacent to a surface of the lip, the enclosed border defining an enclosed feed area which is the area bounded by the enclosed border, the openings in the vibrating element encompassing a delivery area of the plurality of openings in the vibrating element.

267.-**283**. (canceled)

284. The method of claim 208, wherein the enclosure comprises a sidewall and a main inlet which receives fluid, the enclosure also having a first inlet and a second inlet through which fluid enters the chamber, the first inlet and the second inlet leading to the chamber and both oriented to direct fluid at a sidewall of the enclosure before being directed at the openings in the vibrating element.

285.-**304**. (canceled)
305. The method of claim 208, wherein the first part of the pump reciprocates between a stored position to a forward stroke position at a greatest displacement and back from the forward stroke position to the stored position each cycle, and wherein the second part of the pump also reciprocates between a stored position to a forward stroke position at a greatest displacement and back to the stored position each cycle.
306.-**321**. (canceled)
322. The method of claim 305, wherein the discrete dose is ejected from the cavity into the chamber at a pressure that is at least 200 psi.
323. The method of claim 208, wherein: the delivering is carried out with the fluid delivered through the lumen to the enclosure at a velocity of at least 0.5 m/s.
324.-**330**. (canceled)
331. The method of claim 208, further comprising a piezoelectric element coupled to the vibrating element.
332.-**361**. (canceled)
362. The method of claim 208, wherein the lip has a PTFE coating adjacent to the vibrating element to reduce friction therebetween, the coating extending around at least 270 degrees of the lip when viewed along the central axis of the vibrating element.
363. The method of claim 208, wherein the vibrating element has a PTFE coating adjacent to the lip to reduce friction therebetween, the coating extending around at least 270 degrees when viewed along the central axis of the vibrating element.
364. The method of claim 208, wherein the inner surface of the enclosure is hydrophobic over at least 70% of the inner surface in contact with fluid.
365.-**377**. (canceled)