Optimization of a cavitating jet for removing dental plaque from the surface of the screw of an implant and its practical application

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Abstract
Dental plaque on the surfaces of implants causes peri-implantitis and periodontitis. Although the plaque needs to be removed from the surfaces, it is difficult to clean it from the screw section of an implant, as this is roughened to improve biocompatibility. Recently, a method using a cavitating jet was proposed to clean dental plaque. In this paper, the geometry of a Venturi type nozzle for a cavitating jet is optimized by measuring the cavitation impact using a PVDF (Polyvinylidene Fluoride) sensor. The cleaning performance of a cavitating jet using this nozzle is compared with that of a normal water jet. The results show that the optimum divergence angle is 15 deg or 20 deg, depending on the injection pressure. The effect of temperature on the impact power was also investigated, and it was found that the impact power increases with water temperature and saturates at 40-50 °C. It was demonstrated that a cavitating jet using the optimized Venturi type nozzle can remove dental plaque from the screw section of an implant and that the area cleaned by the cavitating jet is greater than that cleaned by a normal water jet.

Keywords: Cleaning, Implant, Dental plaque, Cavitation, Jet, Nozzle

1. Introduction
Dental implants are widely used for replacing lost teeth. The success and long term health of the implant largely depends on the biological process of osseointegration where the implant material forms a direct structural connection with the bone of the jaw. For that purpose, the surface of the screw section is usually roughened to improve its biocompatibility (Quirynen et al., 1990; Gatewood et al., 1993; Rimondini et al., 1997). However, micro pits and gingival crevices resulting from the roughened surface provide ideal places for the growth of dental plaque (Teughels et al., 2006), which often causes peri-implantitis and periodontitis (Heitz-Mayfield, 2008; Lindhe and Meyle, 2008). Normally the screw section of implant is buried in the alveolar bone, however, as the peri-implatitits proceeds, it is exposed (Renvert and Giovannoli, 2012). In this case, although the dental plaque in the exposed screw section need to be removed, the micro texture on the roughened surface makes it very difficult to remove it by conventional means such as oral brushing, ultrasonic scaling and rubber cup cleaning (Schmage et al., 2014). Therefore, we need to develop a technique for cleaning dental plaque from a rough surface.

One of conventional methods of implant cleaning is cleaning by using titanium wire brush which is shown in Fig 1. Figure 2 reveals typical surface of screw part of implant. As shown in Fig. 1 (b), diameter of the wire of the brush is larger than 50 µm. On the other hand, size of dent of the surface of the implant is smaller than 10 µm. Namely, the conventional titanium wire brush cannot clean the rough surface of the implant. Although ultrasonic scalers with carbon
or plastic tip are using for cleaning of implant surface (Kawashima et al., 2007; Mann et al., 2012), it was reported that remnants of tips are reported (Yang et al., 2015). Generation of cavitation bubbles were observed at the time of using ultrasonic scalar with metallic tip in the submerged condition (Vyas et al., 2016), however the metallic tip cannot be used for the cleaning of the implant fixture in order to avoid the damage due to metal contact between the tip and the fixture. Recently, the use of a cavitating jet for dental cleaning has been proposed and encouraging results were obtained (Kikuchi et al., 2014), as there is no contamination problems nor damages. Note that there was no damage on the gums and mucous membranes at the cleaning by using the cavitating jet (Soyama et al., 2012a). It was experimentally demonstrated that the area of residual dental plaque on a titanium plate with a roughened surface decreased to 21 % after five minutes exposure to a cavitating jet. Note that the cleaning of dental plaque on the rough surface by the cavitating jet was confirmed by scanning electron micrograph observation (Soyama et al., 2012a). Cavitation is a phase change phenomenon from liquid to vapor occurring when the local pressure is decreased below the saturated vapor pressure by increasing the flow velocity in compliance with Bernoulli’s equation. When the velocity decreases, the pressure recovers and the vapor bubbles become liquid, and the micro jet of cavitation bubbles and/or shock wave produces impacts as the bubbles rebound. The size of the bubbles is of the order of a micrometer and the dynamic change happens within microseconds. One of the distinctive features of cavitation is the huge pressure and temperature generated during bubble collapse (Flint and Suslick, 1991; Brennen, 2013). If the number and intensity of the cavitation impacts are controlled, the removal of dental plaque from a roughened surface by a cavitating jet has been shown to be very effective (Kikuchi et al., 2014).

The intensity of a cavitating jet is normally evaluated by the mass of the specimen lost through erosion. However, the injection pressure is set to be small in order to avoid damage to the implant material when removing dental plaque. Therefore, assessing the intensity in this way is not suitable in this case. A feasible alternative for measuring the cavitation impact energy is to use a PVDF (Polyvinylidene fluoride) sensor (Momma and Lichtarowicz, 1995; Soyama et al., 1998). The cavitation force measured by the sensor is converted into an electrical signal. The high natural frequency (10 MHz for 110 µm thickness), high piezoelectric constant (-3.39 × 10⁻⁵ (V/m)/Pa) and high signal to noise ratio of the sensor make it ideal for dynamic cavitation intensity measurements. Besides, the PVDF film is pliable and can easily be made in various shapes. These advantages make it a reliable method for measuring the cavitation intensity (Soyama and Kumano, 2002).

Previous research has shown that the outlet geometry of the nozzle significantly affects the cavitation intensity.
(Johnson et al., 1984; Soyama, 2011; Soyama, 2013). In utilizing cavitation for cleaning dental plaque, a Venturi type nozzle is adopted to form the cavitating jet. The pressure field in a Venturi type nozzle changes with the nozzle geometry. Therefore, the influence of the nozzle geometry on cavitation intensity is largely the result of the different pressure fields generated inside nozzles with different structures. However, there have been few reports on the effect of the geometry of a Venturi type nozzle on cavitation intensity or discussions related to the mechanisms for this. The overall treatment provided by a cavitating jet is strongly affected by the water temperature, as both the saturated vapor pressure and the free gas content are functions of temperature (Lienhard and Stephenson, 1966; Hattori et al., 2013).

The surfaces of the screw sections of dental implants are roughened to get better biocompatibility, and the cleaning of this is very important in order to prevent peri-implantitis and periodontitis. As cavitation is a hydrodynamic phenomenon, the cleaning capability is strongly affected by the shape of the target being cleaned. A demonstration of the capability of a cavitating jet for removing dental plaque from the surface of the screw section of a dental implant is needed in order for this to be considered for practical applications.

In this paper, laboratory experiments were conducted to optimize the nozzle geometry and to determine the water temperature required for dental plaque cleaning using a cavitating jet passing through a Venturi type nozzle. Using the optimum geometry, a demonstration of the capability for cleaning plaque from the screw section of an implant was carried out.

2. Experimental apparatus and procedure

2.1 Cavitating jet apparatus

Figure 3 displays the cavitating jet apparatus used to evaluate cavitation impact. The ion-exchange water used in the apparatus was stored in an incubator for at least 24 hours before being used in the experiments in order to keep the distribution of cavitation nuclei in the water constant. A chiller was used to keep the water temperature constant during the experiments. The water is pressurized in the Venturi type nozzle by a diaphragm pump to form the cavitating jet. Figure 5 shows the relation of the frequency characteristics of the pump with the injection pressures. The PVDF sensor was placed at the bottom of the test section and connected to an analog pulse processing system. The upstream pressure of the nozzle was controlled by the rotational speed of the pump motor and measured by the pressure gage, while the downstream pressure was taken to be the constant atmospheric pressure. The standoff distance \( s \) was defined by the distance from the outlet of the nozzle to the surface of the target, i.e., the sensor or the implant.

The geometry of the Venturi type nozzle, which is made of acrylic resin, is shown in Fig. 4. The upstream section of the nozzle was preset with a convergent angle of 20 deg and throat diameter of 0.5 mm. The diameter and length of the throat are 0.5 mm and 1 mm, respectively. For the experiments, the injection pressure \( p \) was varied between 0.3 MPa and 0.5 MPa. The parameters optimized were the divergent angle \( \theta_d \) and the divergent length \( l_d \). The water temperature \( T \) investigated was in the range of 10 °C – 60 °C. The values of the test variables are given in Table 1.
2.2 Impact energy measurement by the PVDF sensor

The cavitation impact energy, $E_i$, for an individual bubble collapsing was calculated from the acoustic power, $I_i$, the duration, $\tau_i$, and the area, $A_i$, of the impact using the following expression:

$$E_i = I_i \cdot \tau_i \cdot A_i$$  \hspace{1cm} (1)

The acoustic power $I_i$ can be expressed by the following equation if the pressure wave propagates spherically:

$$I_i = \frac{P_i^2}{2\rho C}$$  \hspace{1cm} (2)

where $P_i$, $\rho$ and $C$ are the sound pressure, density and acoustic velocity of water, respectively. The impact force $F_i$ is measured directly by the PVDF sensor, thus the pressure can be calculated from impact area $A_i$ and impact force $F_i$ as follows:

$$P_i = \frac{F_i}{A_i}$$  \hspace{1cm} (3)

Substituting Eq. (2) and Eq. (3) into Eq. (1), the individual impact energy can be expressed as:

$$E_i = \frac{F_i \cdot P_i \cdot \tau_i}{2\rho C} = k F_i^2$$  \hspace{1cm} (4)

where $k$ is a proportionality constant.

Besides the cavitation pressure from bubble collapse, the signal measured by the PVDF sensor may contain noise, such as fluctuation of the stagnation pressure of the jet. Thus, the signal from the sensor was first processed through a high frequency pass filter, which filters out signals with frequencies below 5 kHz. The cavitation impact counter counted the number and amplitude of pulses whose magnitude is larger than a certain preset threshold value $F_{th}$. For the experiments, the threshold value $F_{th}$ began with the smallest value, 0.25 N, which was then followed by values increasing in steps of 0.25 N. Then, for the range over 5 N, the step was changed to 0.5 N. Two measurements were taken and these

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**Table 1  Values of the test variables for the cavitating jet**

| Parameter                      | Values               |
|-------------------------------|----------------------|
| Standoff distance $s$ [mm]    | 0.5, 1.0, 2.0, 3.0, 4.0 |
| Injection pressure $p$ [MPa]  | 0.3, 0.4, 0.5        |
| Divergent angle $\theta_d$ [deg] | 10, 15, 18, 20, 22, 25 |
| Divergent length $l_d$ [mm]   | 3.5, 4.5, 5.5        |
| Water temperature $T$ [°C]    | 10, 20, 30, 40, 50, 60 |

**Fig. 5 Relationship between the frequency of diaphragm pump and injection pressures**
The PVDF sensor was calibrated by the dropping ball technique (Soyama et al., 1998). For this, a steel ball was dropped onto the sensor from height $h_1$ before rebounding to height $h_2$. The rebound height was recorded by a camera. The average force on the sensor was calculated from the following equation:

$$F_{av} = \frac{m(1 + \sqrt{e})\sqrt{2gh_1}}{\tau}$$  \hspace{1cm} (5)$$

where the conservation of momentum is taken into account and where $m$, $g$ and $h_1$ are the mass of the ball, the acceleration due to gravity and the initial height, respectively. The duration of the impact, $\tau$, was determined by observing the output pulse signal on an oscilloscope. The coefficient of restitution $e$ is the square root of the ratio between the rebound height $h_2$ and initial falling height $h_1$:

$$e = \sqrt{\frac{h_2}{h_1}}$$  \hspace{1cm} (6)$$

Experiments were conducted with three steel balls with masses of 2.0 g, 5.1 g and 8.2 g being dropped from heights of 0.15 m, 0.2 m and 0.25 m. The potential energy loss of the ball $E_p$ was assumed to be the same as the input energy $E_i$, and this is given by Eq. (7). The average force measured by the PVDF sensor $F_{av}$ was taken to be equivalent to the impact force, $F_i$, as shown in Eq. (8) where $E_{PVDF}$ is referred to as the impact energy from the PVDF sensor:

$$E_i = E_p = mgh(1 - e^2)$$  \hspace{1cm} (7)$$

$$E_{PVDF} = kF_{av}^2 = kF_i^2$$  \hspace{1cm} (8)$$

Thus, the proportionality constant $k$ was determined from $F_i$ and $E_p$ by referring to Eq. (4) and Eq. (7). There should be a certain threshold force, $F_{th}$, where the cavitation impact is too weak to remove the plaque. Thus, Eq. (8) can be rearranged to Eq. (9) in order to consider this threshold level. In the present paper, $E_{PVDF}$ at measurement of cavitation impact was shown as energy per unit time, i.e., power.

$$E_{PVDF} = k\sum F_i^2$$  \hspace{1cm} (9)$$

2.3 Cleaning the dental plaque

The protocol for the cleaning test of the dental plaque was approved by the ethics committee of the School of Dentistry, Showa University, and written informed consent was obtained from all participants (No. 2011-013). The implant screw under test was a commercially available implant fixture (GENESiO Plus $\Phi$4.4mm, GC Corporation, Japan). The fixture was cut longitudinally to make two specimens. Dental plaque was formed on the specimens, which were kept in the mouths of four male volunteers for 72 hours at the buccal sites of molar and premolar teeth on custom-made stents (Riondini et al., 1997). The specimens were kept in the oral cavities except when eating and brushing. In order to demonstrate cleaning of the dental plaque, the specimens were dyed and then exposed to the cavitating jet, followed by observation using a microscope.

3. Experimental results and discussion

3.1 PVDF calibration

The output voltages for different impact forces in the dropping ball calibration are shown in Fig. 6(a). As the output voltage is nearly proportional to the force generated by the impact from the ball, the relationship between the peak voltage $V$ and the average impact force $F_{av}$ can be described by a linear relationship $F_{av} = 24.7V$ after least squares fitting. As the constant of proportionality is slightly affected by a time constant (Soyama et al., 1998), the slope of the relationship is a little less steep for larger forces. In the following, the impact force is obtained from the output voltage from the PVDF sensor using the linear relationship given above. The impact energy is determined from Eq. (8) and is plotted against $E_p$ in Fig. 6(b). The proportionality constant $k$ is calculated to be $k = 1.8 \times 10^7$ J/N$^2$ by performing least squares fitting between $E_p$ and $E_{PVDF}$. It follows from these relationships that the impact force is proportional to the square of the impact energy, and the cavitation intensity generated by the cavitating jet through the Venturi type nozzle can be evaluated by the impact energy measured by the PVDF sensor.
3.2 Effect of nozzle geometry

The cavitation impact energies per unit time, i.e., impact power with a Venturi type nozzle with various divergent angles $\theta_d$ and divergent lengths $l_d$ under different injection pressures $p$ and standoff distances $s$ were measured. Typical experimental results ($\theta_d = 20 \, \text{deg}, \, l_d = 4.5 \, \text{mm}$) are shown in Fig. 7 where the impact power $E_{PVDF}$ is shown as a function of the threshold impact force $F_{th}$. This clearly shows that the total impact power decreases with increasing $F_{th}$ since the rate at which large impact forces occur decreases. For injection pressures of 0.3 MPa, 0.4 MPa and 0.5 MPa, the measured largest impact forces in Fig. 7 are about 3 N, 11 N and 13 N, respectively. Therefore, it was concluded that the cavitation intensity of a cavitating jet produced after passing through a Venturi type nozzle depends strongly on the injection pressure. Especially, the differences in terms of the spread in impact power for various standoff distances increase significantly when $F_{th}$ is larger than 6 N.

To obtain the optimum standoff distance $s_{opt}$ where the impact power is largest, the impact power with $F_{th} = 2 \, \text{N}$ as a function of standoff distance was investigated. When the largest impact force was less than 2 N, 1 N was adopted as $F_{th}$. The optimum standoff distances for all the experimental conditions are shown in Table 2. The optimum standoff distance $s_{opt}$ may depend on the size of the cavitation cloud. That is, a larger cavitation cloud can travel further downstream and this may give larger $s_{opt}$. On the other hand, the size of the cavitation cloud depends on the divergent length $l_d$ and the divergent angle $\theta_d$ in the same way as a cavitating jet depends on the bore length and bore diameter of a simple nozzle (Soyama, 2011). Of course, when the divergent length $l_d$ is larger, $s_{opt}$ is smaller, as the standoff distance is defined by the distance from the nozzle exit to the surface of the target and the cavitation is developed in the divergent region. This is why $s_{opt}$ varies with $l_d$ and $\theta_d$. Thus, $s_{opt}$ at various $l_d$ and $\theta_d$ was obtained experimentally. In the following, the values of $E_{PVDF}$ at $s_{opt}$ for each $l_d$ and $\theta_d$ were examined to find the optimum geometry of the nozzle.

Figure 8 shows the dependency of the impact power $E_{PVDF}$ on the divergent angle $\theta_d$ for divergent lengths of 3.5 mm, 4.5 mm and 5.5 mm. $E_{PVDF}$ increases with increasing injection pressure for all conditions in Fig. 8. In Fig. 8(a), with $l_d = 3.5 \, \text{mm}$, the largest values of the impact power $E_{max}$ of $E_{PVDF}$ as a function of $\theta_d$ was obtained with $\theta_d = 15 \, \text{deg}$, with $E_{max} = 0.7 \, \text{mW}, 2.0 \, \text{mW}$ and $3.3 \, \text{mW}$ for $p = 0.3 \, \text{MPa}, 0.4 \, \text{MPa}$ and 0.5 MPa, respectively. In Fig. 8(b), with $l_d = 4.5 \, \text{mm}$, $E_{max}$ also occurs with the divergent angle $\theta_d = 15 \, \text{deg}$ for all three injection pressures. The values obtained are 0.2 mW, 2.0 mW and 4.8 mW for $p = 0.3 \, \text{MPa}, 0.4\text{MPa}$ and 0.5 MPa, respectively. Notice that other peaks appear at $\theta_d = 20 \, \text{deg}$ with $p = 0.4$ and 0.5 MPa, even though these peaks are smaller than the peaks at $\theta_d = 15 \, \text{deg}$ with $l_d = 3.5 \, \text{mm}$ and 4.5 mm. Finally, in Fig. 8(c), with $l_d = 5.5 \, \text{mm}$, the peak at $\theta_d = 20 \, \text{deg}$ is considerable, and the values of $E_{max}$ at $\theta_d = 20 \, \text{deg}$ are $0.04 \, \text{mW}$ at $p = 0.3 \, \text{MPa}, 4.3 \, \text{mW}$ at $p = 0.4 \, \text{MPa}$ and 5.9 mW at $p = 0.5 \, \text{MPa}$. Thus, the maximum impact power from all the test conditions is with $l_d = 5.5 \, \text{mm}, \theta_d = 20 \, \text{deg}$, and $p = 0.5 \, \text{MPa}$.

Figure 9 shows the relationship between impact power and injection pressure for each nozzle geometry. From these the optimum combination of $\theta_d$ and $l_d$ for each injection pressure can be found. With $p = 0.3 \, \text{MPa}$, the largest impact power obtained is with $\theta_d = 15 \, \text{deg}$ and $l_d = 3.5 \, \text{mm}$; however, with $p = 0.4$ and 0.5 MPa, it is with $\theta_d = 20 \, \text{deg}$ and $l_d =
5.5 mm. Thus, it was found that the optimum outlet geometry for the nozzle, i.e., $\theta_d$ and $l_d$, depends on the injection pressure.

In order to understand the reasons for the differences in optimum outlet geometry with the injection pressure, the flow field inside the Venturi type nozzle was considered. Cavitation phenomena in a divergent part of Venturi-type nozzle was investigated in the previous paper and it was shown that a flow pattern was changed with divergent lengths (Sato et al., 2015). Therefore, in this paper, it is suspected the divergent lengths and angles of the Venturi-type nozzle affects the flow pattern inside the nozzle. The fluid flowing inside the nozzle has several different patterns in different sections of the nozzle. In the throat, flow separation occurs and low pressure zones are formed. As a result, the vortex formation frequency decreases and the bubble cloud collapses. Thus, the divergent length should be large enough to maintain flow separation and to provide enough space for development of the vortex, but this has to be controlled for a certain length in order to prevent reattachment occurring in the diverging section. When $\theta_d$ is

![Fig. 7 Cavitation impact power distribution for various threshold force for divergent angle $\theta_d = 20$ deg and length $l_d = 4.5$ mm under inject pressure $p$ of (a) 0.3 MPa, (b) 0.4 MPa, (c) 0.5 MPa.](image)

![Fig. 8 Effects of the geometry of the nozzle outlet on the impact power under injection pressure of 0.3 MPa, 0.4 MPa and 0.5 MPa at the divergent lengths, $l_d$, of (a) 3.5 mm, (b) 4.5 mm and (c) 5.5 mm as a function of the divergent angle, $\theta_d$. At $l_d = 3.5$ mm and 4.5 mm, the impact power has a maximum at $\theta_d = 15$ deg. On the other hand, at $l_d = 5.5$ mm, the impact power has a maximum at $\theta_d = 20$ deg.](image)
near 20 deg, the flow attaches to the wall on one side while total separation occurs on the other. The phenomenon where the flow is drawn to the wall and attaches itself to it is the Coanda effect. On the side where separation occurs, cavitation bubbles develop, promoted by the vortexes, and large bubble clouds are formed. In this case, more vortexes are formed in a wider area when the divergent length is longer, and larger bubble clouds are formed because the flow doesn’t change and the separation is stable. Therefore, with $\theta_d = 20$ deg the maximum impact power is obtained when $l_d$ has the largest value, 5.5 mm. With further increases in the divergent angle, flow separation occurs on both sides. When $\theta_d$ is too large, for example, 25 deg, the flow velocity decreases due to the sudden pressure rise in the downstream section, which suppresses the intensity of the vortex as well as the formation of large cavitation bubbles. The peak at $\theta_d = 20$ deg in Fig. 8(b) is caused by the variation in impact power due to the repeated attachment and separation of the jet, because the flow is not stable and a transition occurs at $\theta_d = 15 – 20$ deg. Therefore, it is concluded that the condition for large cavitation impact power is a stable flow field with constant separation.

3.3 Effect of water temperature

In this section, the effect of water temperature is investigated. The optimum nozzle, with $\theta_d = 20$ deg and $l_d = 5.5$ mm, obtained from the experiments on nozzle geometry was used. First, the optimum standoff distance $s_{opt}$ for different temperatures was obtained as shown in Table 3. The optimum standoff distance is defined as the distance where the

| $\theta_d$ [deg] | $l_d$ [mm] |
|----------------|-----------|
| $p$ [MPa]      | 10        | 10        | 10        | 15        | 15        | 15        | 18        | 18        | 18        |
| 0.3            | 1         | 3         | 3         | 4         | 1         | 1         | 2         | 1         | 1         |
| 0.4            | 2         | 2         | 2         | 3         | 4         | 4         | 4         | 4         | 2         |
| 0.5            | 2         | 2         | 4         | 1         | 1         | 2         | 4         | 4         | 2         |

Table 2 Optimum standoff distance for each of the nozzle parameters

Fig. 9 Relationship between the peak impact power for each nozzle geometry and injection pressure. The optimum geometry depends on the injection pressure.
impact power $E_{PVDF}$ has a maximum when the threshold impact force $F_{th}$ is 3 N. From Table 3, $s_{opt}$ decreases with increasing water temperature $T$ for the injection pressures $p = 0.3$ MPa and 0.4 MPa.

Figure 10 shows the relationship between impact power at the optimum standoff distance and water temperature for each injection pressure when $F_{th}$ is 3 N. The value of $E_{PVDF}$ varies in the range from 0.68 mW to 14.8 mW for the various values of $T$ and $p$ employed. It was found that $E_{PVDF}$ increases with increasing $T$ and saturates at about 40 °C or 50 °C. Specifically, when $p$ is 0.5 MPa, the maximum value of $E_{PVDF}$ is 14.8 mW at $T = 40 \, ^\circ\text{C}$, and with $p = 0.3$ MPa and 0.4 MPa, $E_{PVDF}$ is 5.9 mW and 10.4 mW at $T = 50 \, ^\circ\text{C}$, respectively. Previous research has shown that the maximum cavitation erosion occurs at a water temperature in the range of 40 – 50 °C (Plesset, 1972; Hattori et al., 2005), which agrees well with the present results.

The water temperature affects the impact power, as the amount of air in water changes with water temperature. The air in the water can absorb and attenuate the cavitation impact in the form of a cushioning effect. When the temperature is low, the cavitation impact power is low because the air content is high and the cushioning effect is strong. Therefore, the impact power increases with increasing water temperature, since the air content, which reduces the cavitation impact, is decreased. However, the saturated vapor pressure also increases with water temperature, which raises the frequency of bubbles collapse. The residual bubbles have the same effect as vapor bubbles at relatively high temperature. As the vapor generation due to the reduction in difference between the static pressure of the water and the vapor pressure. As a result, the impact power decreases with increasing temperature beyond the optimum range of 40 – 50 °C. The optimum temperature with $p = 0.5$ MPa is 40 °C, which is smaller than that with lower injection pressures. When the temperature is high with $p = 0.5$ MPa, the cavitating jet is accompanied by small residual bubbles which are left after cavitation cushioning effect due to these residual bubbles is relatively larger at $p = 0.5$ MPa, the maximum value of $E_{PVDF}$ is obtained at a relatively lower temperature than that at the other injection pressures.

### 3.4 Cleaning dental plaque on the screw section of an implant

In order to demonstrate cleaning of a biofilm from the roughened surface of the screw section of an oral implant using a cavitating jet, Fig. 11 shows examples of specimens after exposure to the cavitating jet for (a) 0 s, (b) 30 s, (c) 60 s, and (d) 180 s, and also a specimen after exposure to (e) a normal water jet for 60 s. The optimized Venturi nozzle, i.e.,

![Table 3 Optimum standoff distance for each pressure and temperature](image)

| $p$ [MPa] | 10 | 20 | 30 | 40 | 50 | 60 |
|-----------|----|----|----|----|----|----|
| 0.3       | 4  | 3  | 4  | 4  | 3  | 2  |
| 0.4       | 4  | 3  | 4  | 1  | 1  | 1  |
| 0.5       | 1  | 1  | 1  | 1  | 1  | 1  |

![Fig. 10 Relationship between the impact power at the optimum standoff distance and the water temperature for each injection pressure. The impact power increases with temperature and saturates at between 40 °C and 50°C.](image)
$d = 0.5 \text{ mm}, \ l_d = 5.5 \text{ mm} \text{ and } \theta_d = 20 \text{ deg}, \ s = 1 \text{ mm}$ was used for the cavitating jet at $p = 0.5 \text{ MPa}$. In the case of the water jet, a nozzle with an equivalent throat diameter without a divergent section was used at the same injection pressure. In the previous paper, it is shown that the impact of the cavitating jet is stronger and affects in wider area than that of the water jet (Soyama, H. and Gong, F., 2012b). For the demonstration, dental plaque covering the screw sections of the implants was dyed. In Fig. 11, the gray areas are the areas cleaned by the cavitating jet and the water jet. Although the nozzle throat diameter and the injection pressure were equivalent, larger areas were cleaned by the cavitating jet than by the water jet. When Fig. 11(a) – (c) are compared, the gray area becomes larger with increasing exposure time. Thus, it can be concluded that the cavitating jet can clean the dental plaque on the roughened surface of the screw section of the implant.

As shown in Fig. 11(a) – (c), the bottom of the thread is cleaner than the top. Cavitation bubbles develop in high speed regions, i.e., in relatively low pressure regions, and collapse in low speed regions, i.e., relatively high pressure regions. Thus, bubbles are more likely to collapse at the bottom of the thread than at top. This is why the bottom of the thread is cleaner than the top. However, the top of the thread can be cleaned by the other methods, such as laser cleaning, so that the ability to clean the bottom of the thread is a great advantage of the cavitating jet.

4. Conclusions

In order to optimize the geometry of a Venturi type nozzle for a cavitating jet used to remove dental plaque, the impact power for nozzles with various divergent angles and divergent lengths at various injection pressures was measured using a homemade PVDF sensor. The effect of the water temperature on the impact power was also examined. In the present experiments, the nozzle throat diameter was kept constant at 1 mm. The removal of dental plaque from the screw section of an implant using the cavitating jet through the optimized Venturi type nozzle was demonstrated. The main results obtained in this paper are summarized as follows.

1. A cavitating jet using an optimized Venturi type nozzle can clean oral plaque on the surface of the screw section of an implant, especially the plaque at the bottom of the thread.

2. The impact power generated by cavitation collapse in a cavitating jet produced after passing through a Venturi type nozzle depends on the divergent angle, $\theta_d$, and the divergent length, $l_d$, of the nozzle, the injection pressure $p$, the

![Fig. 11](a) cavitating jet 0 s
(b) cavitating jet 30 s
(c) cavitating jet 60 s
(d) cavitating jet 180 s
(e) water jet 60 s
standoff distance $s$, and the fluid temperature $T$.

3. The optimum geometry for the nozzle outlet varies with injection pressure $p$. At $p = 0.3$ MPa, the optimum geometry is $\theta_d = 15$ deg and $l_d = 3.5$ mm. On the other hand, at $p = 0.4$ MPa and 0.5 MPa, the optimum geometry is $\theta_d = 20$ deg and $l_d = 5.5$ mm. In these experiments, the maximum impact power was obtained with $p = 0.5$ MPa, $\theta_d = 20$ deg, $l_d = 5.5$ mm, and $s = 1$ mm.

4. The impact power increases with water temperature and saturates at 40 – 50 °C.

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