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Testing for flow rates and pressure surges during the motion of surgical bone reamers

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ABSTRACT: In order to gain experience in fluid-structure interaction in the fluid mechanics laboratory, students in the junior year designed multi-bladed propellers and utilised them to simulate the motion of surgical bone reamers in tubes filled with water. Using a test stand, they had built to test actual reamers from manufacturers, they investigated the effect of the rotation and translation of multi-bladed propellers on the flow rates and the pressures generated during surgical operations. Their results show that the rotation of a propeller reduces the rate of fluid flow in the radial direction, creates a transient surge of pressure, and causes the steady-state pressure in the surrounding fluid to fall below the baseline value, defined here as that which existed before rotation was initiated. These results were consistent with what is reported by orthopaedic surgeons.

INTRODUCTION

Nowadays, reaming is considered to be a controversial procedure in orthopaedic surgery because it is associated with adverse effects: it leads to the impairment of vessels and to increases in intramedullary pressures, among other things [1]. The latter are considered very detrimental because they are linked to necroses and pulmonary dysfunction [2][3].

However, increases in intramedullary pressures during reaming operations are not solely due to the movement of the reamers [4]. Mueller and Rahn demonstrated this by using 9 mm reamers to investigate the effects of draining the medullary contents of the femoral medullary cavity on increases in pressures on a pair of human femora before reaming, or inserting unreamed nails [5]. They measured pressures in the mid diaphysis and in the metaphysis and found that, when medullary fat was removed, the pressures registered during reaming were lower than those for cases in which the fat had not been removed. Such reduction was observed during the insertion and during the withdrawal of reamers. Mueller and Rahn recommended the development of new instruments that would be used for the removal of the medullary contents before starting reaming procedures or inserting unreamed nails [5]. These observations lead one to wonder whether or not it is possible to separate the mechanical effects that arise from the motion of a reamer from those due to the presence of medullary fat and other particles [6].

THE PROJECT'S OBJECTIVES

In order to investigate how the effect of the motion of the reamer could affect the flow rates and pressures inside bones, students in a fluid mechanics laboratory designed two propellers, Prop2B and Prop4B, and attached them to small cylindrical shafts and inserted the resulting assembly into a small graduated cylinder filled with water at room temperature.

They then set the propellers into motion in order to simulate the movement of bone reamers. Propeller 2B had two blades, and propeller 4B had four blades; their physical dimensions are summarised in Table 1.

Students used a test stand, shown in Figure 1 that had been designed to test commercial reamers [7]. The objective was to measure the effects of the motion of a reamer on the flow rates and the pressures generated during surgical operations [8][9].

Table 1: Physical dimensions of the two propellers.

	Propeller 2B	Propeller 4B
Length of the shaft	11in (279.4cm)	11in (279.4cm)
Shaft diameter	1/4 in (6.35mm)	1/4 in (6.35mm)
Number of blades	2	4
Length of blade	3.5 in (88.9mm)	3.5 in (88.9mm)
Width of blade	1.5 in (38.10mm)	1.5 in (38.10mm)
Thickness of blade	1/32 in (0.794mm)	1/32 in (0.794mm)
Max. blade angle with the horizontal	68°	68°
Mass of impeller	84 grams	92 grams

TESTING THE FLOW RATES

A vertical cylinder was used as a container. It was fitted with an orifice on its side and located near the bottom of the cylinder. Three tests were carried out. In all the tests, the container was filled and the fluid was allowed to exit from the orifice. The exit flow rate was measured while maintaining the level of fluid in the container constant (see Figure 1).

Test F1 entailed the container being filled with fluid and, after waiting for all motion to come to rest, the fluid was allowed to exit from the orifice. The exit flow rate was measured by taking 12 consecutive samples.

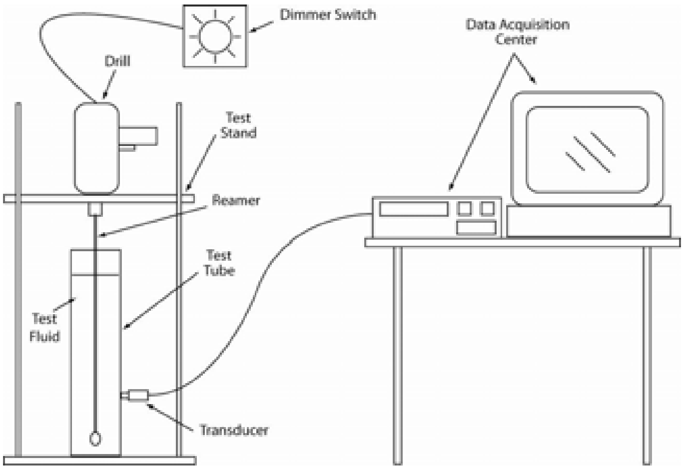

Figure 1: Experimental set-up (from [7]).

Test F2 involved an impeller being inserted into the container until its blades were two inches above the exit orifice; it was then set into rotation in the forward direction at 400 rpm. After that, the test was repeated.

Test F3 involved Test F2 being repeated, but with the propeller set to rotate in reverse. All three tests were carried out at two different elevations of the liquid's free surface: 4.5 in (11.43cm) and 10.5 in (26.67cm).

In each test, the results showed that the rotation of the propeller caused the exit flow rate to fall below the baseline value, defined as the exit flow rate that existed before rotation was initiated. This pattern was observed to hold during forward, as well as reverse, rotations of the propellers. It was also found to hold at both heights of the free surface of liquid in the cylinder. The decreases in exit flow rates were much larger when the propellers rotated in reverse than when they were in forward motion. This was true for both propellers and at both elevations of the free surface.

In all tests, the four-bladed propeller generated larger decreases in flow rates than the two-bladed propeller. For example, at a height of 10.5 inches, in both the forward and the reverse rotations, the decreases created by the four-bladed propeller were more than twice as large as those due to the two-bladed propeller.

However, at a height of 4.5 inches, the decrease created by the four-bladed propeller were still twice as large as those created by the two-bladed propeller, but only in forward rotation; in reverse rotation, they were only 19% larger. These results are shown in Tables 2 and 3, and illustrated graphically in Figure 2.

Table 2: Flow rate changes (h = 4.5 in).

Propeller Rotation	Prop 2B (symbol: 2B4H)	Prop 4B (symbol: 4B4H)
Forward	4.72% decrease	9.43 % decrease
Reversed	19.81% decrease	23.60% decrease

Table 3: Flow rate changes (h = 10.5 in).

Propeller Rotation	Prop 2B (symbol: 2B10H)	Prop 4B (symbol: 4B10H)
Forward	2.53% decrease	6.33% decrease
Reversed	10.76% decrease	29.11% decrease

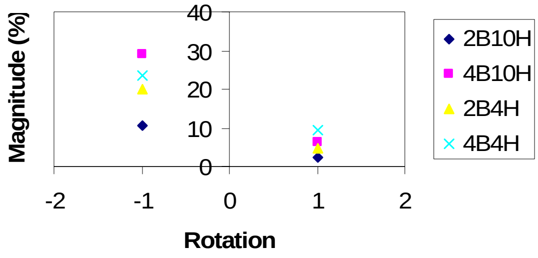

Figure 2: Reductions in the flow rates.

TESTING THE PRESSURE SURGES

The set-up in these tests was the same as that used to test flow rates with one major difference: the exit orifice was used to hold the sensing head of a pressure transducer to the container, rather than to let water out of the container (see Figure 1). Three tests were carried out.

Test P1 entailed the container being filled with fluid and, after waiting for all motion to come to rest, the pressure at the exit orifice was measured and recorded.

Test P2 covered an impeller being inserted into the container until its blades were two inches above the exit orifice; it was then set into rotation in the forward direction at 400 rpm and the pressure at the exit orifice was measured and recorded as a function of time. The impeller was then moved up 2 inches at a time so that the propeller blades were positioned at 4, 6, 8 and 10 in above the exit orifice, respectively. The test was then repeated at each position.

Test P3 involved Test P2 being repeated in its entirety, but with the propeller blades rotating in the reverse direction for each trial.

When the propeller blades rotated in the forward direction, the surges were positive. In all tests, the results showed that a forward rotation of the propeller caused an initial surge in pressure that was positive. The surge was followed by a progressive, but oscillatory, decrease in pressure with time, until steady state-conditions were achieved. The surges created by the four-bladed propeller were always larger than those created by the two-bladed propeller. Also, the magnitude of the surge increased as the blades got closer to the exit orifice and it decreased as they moved farther away from that orifice. These results are illustrated in Figure 3.

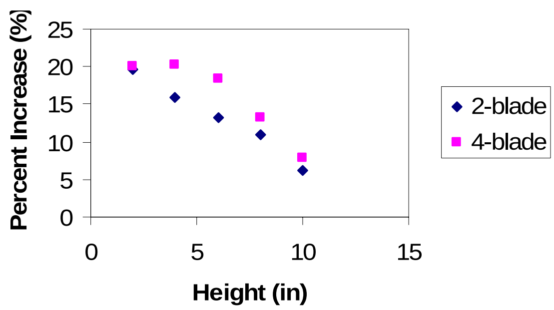

Figure 3: Pressure surges during forward rotation.

In order to demonstrate the effect of the distance between the blades and the exit orifice on the magnitude of the surge, the propeller blades were moved back and forth in the cylinder at constant speed. Pressures increased with forward translation until it stopped; and they decreased with backward translation until it stopped. Repeating this cyclic motion generated a graph of pressure versus time that was periodic, as shown in Figure 4. When the speed of translation increased, the magnitude of the surge was observed to increase as a consequence, and vice versa, Figure 5.

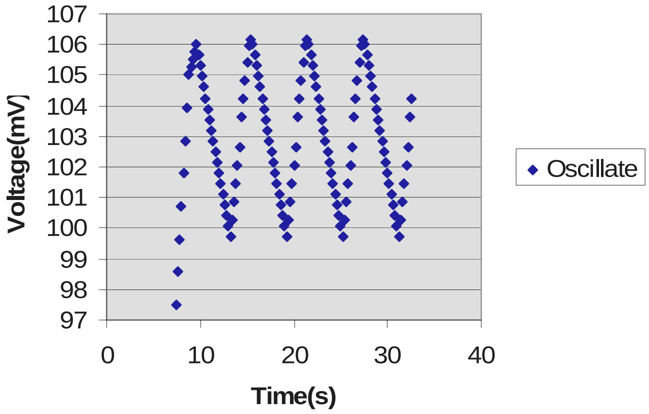

Figure 4: Pressures from the movement of Prob4B.

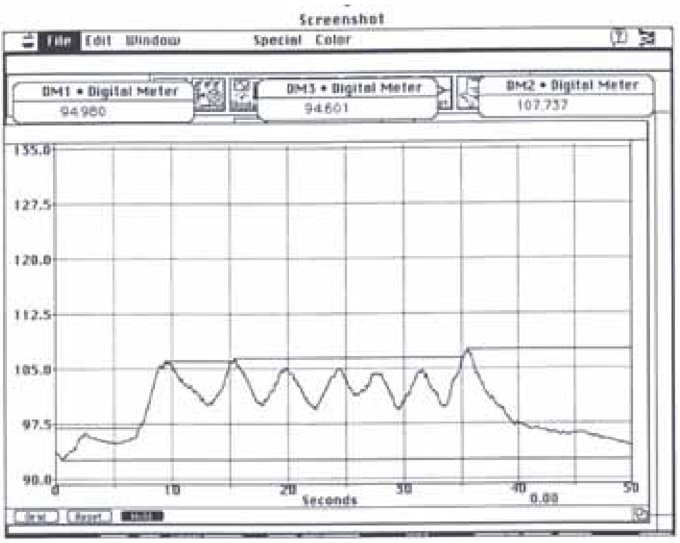

Figure 5. Variable-speed output from the transducer.

When the propeller blades rotated in the reversed direction, the results were as follows: the surges were negative; for the same rate of rotation, it was observed that the magnitudes of the negative surges were greater than those of the positive surges. Also, when the blades were moved at constant speed, no surge was observed. Instead, the magnitudes of pressures seemed to decrease, more or less, continuously until a minimum value was reached.

Regardless of the direction of rotation of the propellers, it was observed that steady-state pressures were less than the baseline pressures that corresponded to the static height of liquid in the cylinder before rotation was initiated. When the pressure was oscillatory, the envelopes of the pressure versus time curves were determined from the data. A pair of such envelopes is shown in Figure 6. Both envelopes shown were obtained with blades spinning from a level that was 2 inches above the exit orifice.

It can be seen from Figure 6 that the rise time from initiation of motion to peak pressure is larger for forward rotation than for reversed rotation of the propeller blades.

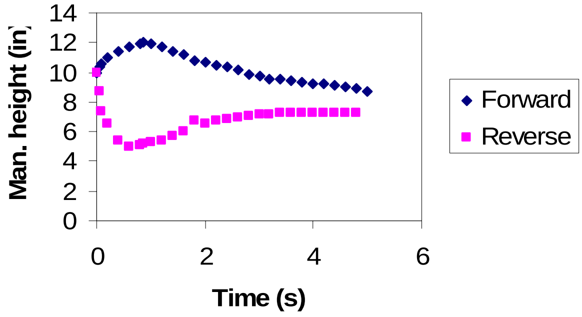

Figure 6: Envelopes of the pressure curves.

CONCLUSIONS

The measured data from using the rotation of multi-bladed propellers indicate that the rotation of propeller blades reduces the radial flow of fluid and generates pressure surges. When the rotation is forward, the surge wave was positive.

However, it was negative when the blades rotated in reverse. The steady-state pressures achieved during steady rotation of propellers were observed to be less than the hydrostatic pressures that were measured before the initiation of rotation.

These results suggest that increases in intramedullary pressures during reaming operations may be due to surge waves associated with the acceleration of rotating reamers.

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