Accuracy of Pressure and Flow Capacities of Four Arthroscopic Fluid Management Systems

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Purpose: The present study was conducted to evaluate 4 different fluid delivery systems: Arthrex AR-6450, Stryker 1.5L High Flow Pump, Arthro FMS 4, and Acufex InteliJet. Their flow and pressure capacity, as specified by the manufacturer, and their accuracy, as measured in a standardized fashion, were compared with directly measured pressure values. Type of Study: Experimental study.

Methods: Two experiments were performed: (1) the achieved pressure was measured with the pressure sensor within a ball and compared with the preset pressure values. The pressure was increased constantly while the flow was kept constant. (2) maximum flow per minute was tested using a beaker and a stopwatch. Results: The highest measured pressures for the Arthrex and the Stryker pumps were 115 mm Hg (46% of published maximum pressure) and 113 mm Hg (57% of published maximum pressure), respectively. The highest measured pressures for the Arthro FMS 4 and the InteliJet pumps were 251 mm Hg (101% of published pressure) and 132 mm Hg (88% of published maximum pressure), respectively. The maximal flow values for the Arthrex and Stryker pumps were 900 mL/min (56.3%) and 675 mL/min (48%), respectively. The Arthro FMS 4 and InteliJet pumps reached a maximal flow of 450 mL/min (56%) and 1,250 mL/min (62.5%). Conclusions: In the simpler pumps (Arthrex AR-6450 and Stryker 1.5L High Flow Pump), the pressure on the display must be set to higher values compared with the outflow-controlling pumps (Arthro FMS 4 and InteliJet) to achieve the same intra-articular pressure. All pumps were able to maintain a pressure of 60 mm Hg very accurately. Therefore, a surgeon can trust all of the pumps when the pressure is set below 60 mm Hg. Key Words: Arthroscopic fluid delivery systems—Infusion pumps—Pressure characteristics—Flow characteristics—Experimental study.

Good visualization is of key importance in arthroscopic surgery. In recent years, vast improvements have been made in the optical as well as the pump systems. Previous studies have reported improving mechanisms for pressure and flow control. In 1977, Gillquist et al. first reported a threshold pressure of 28 mm Hg as necessary for good visualization during knee arthroscopy. Ewing et al. found that a pressure of 70 mm Hg was necessary for consistent and sustained capsular distension. Arangio and Kostelnik investigated the minimum adequate pressure required for arthroscopic diagnostic procedures and surgery of the knee. Their results showed that with an average pressure of 55 mm Hg, arthroscopy could be performed in all knee positions studied. Furthermore, a positive correlation between this pressure and the diastolic blood pressure was found. During arthroscopy in a closed system, pressures in excess of 200 mm Hg can be generated in flexion and extension maneuvers. Excessive fluid pressures may result in subcutaneous extravasal diffusion, leading to possible major complications. The aim of this study was to...
test 4 different fluid delivery systems used in routine arthroscopic surgery and to investigate the accuracy of their flow and pressure capacities.

METHODS

A knee model utilizing a thin-walled, hollow, spherical rubber cavity with a volume of 700 mL was used for this investigation. Two small holes were made in the ball and 2 commercially available cannulas (8.25-mm diameter, AR 6535; Arthrex) were twisted into the ball to guarantee a watertight placement. The first was used for the outflow and to introduce a flat sensor (developed at the Vienna University of Technology) that consists of a pressure-measuring element embedded in a capsule, working on the basis of the semiconductor technique. The hydrostatic surrounding of the measuring element allows a transformation of the inhomogeneous pressure engagements into a uniformly distributed pressure acting on the measuring element. Furthermore, the capsule protects the measuring element against intruding liquid. The pressure limit for the sensor is 5,250 mm Hg. The resolution of the sensor was 0.75 mm Hg. The second cannula was used to introduce a 5-mm wide-angle arthroscope and to direct the inflow through the metal sheath (Fig 1).

Device representatives were asked to be responsible for the setup of their pumps to guarantee that it was as suggested by the manufacturer. The knee model and the devices tested were placed at the same height. The investigation consisted of 2 parts: In the first part, the achieved pressure was measured with the pressure sensor within the ball and compared with the preset pressure values. From the lowest value, the pressure was increased constantly while the flow was kept constant. In the second part, the maximum flow per minute was tested using a beaker and a stopwatch. A measuring amplifier (DMC Plus; Hottinger Baldwin Messtechnik, Darmstadt, Germany) and an iMac DV Computer (Apple Computer, Cupertino, CA) were used for data storage and analysis.

Four different fluid management systems were investigated: (1) Arthrex AR-6450 (Arthrex Medical Instruments GmbH, Karlsfeld, Germany), (2) Stryker 1.5L High Flow Pump (Stryker Osteo GmbH, Muelheim, Germany), (3) Arthro FMS 4 (Future Medical Systems S.A. Geneva, Switzerland), and (4) InteliJet (Acufex, Smith & Nephew, Andover, MA).

The Arthrex AR-6450 pump allows flow rates of up to 1,600 mL/min at pressure levels to 255 mm Hg. It has a 1 roller pump and the pressure is controlled continuously with a sensor. The flow rate was set to 70% and the pressure was increased from 40 to 240 mm Hg in increments of 20 mm Hg according to the device’s display. Outflow was placed to gravity.

The Stryker 1.5L High Flow Pump allows flow rates of 100 to 1,500 mL/min at pressures up to 200 mm Hg. It has 1 roller pump and 3 programs to save 3 different settings. With a flow rate of 1,500 mL/min, the pressure was increased at the same rate (20 mm Hg) from 40 to 160 mm Hg according to the device’s display. Higher pressures on the display could not be reached. Outflow was placed to gravity.

The Arthro FMS 4 pump is a computer-assisted dual pump system with 2 roller pumps, providing precise control over both irrigation and suction. The integrated suction pump manages both shaver and cannula suction. The pump has a performance of 100 to 800 mL/min at pressure levels between 10 and 150 (these pressure values represent fictitious numbers and are unit-less). The investigation started at a pressure level of 10 and was increased by tens till the pressure level was 100 at a flow rate of 94 mL/min. According to the manufacturer, a value of 10 should be comparable to a pressure of 37 mm Hg, and a value of 150 corresponds to a pressure of 368 mm Hg.

The InteliJet pump has a centrifugal pump that allows flow rates in excess of 2,000 mL/min. The outflow is controlled, conserving saline. Gravity inflow serves as a backup to the system. Pressure management is achieved through direct measurement at the cassette. The system is adjustable from 10 to 150 mm Hg. Using a flow of 30% to 40%, the investiga-
tion started at a pressure of 40 mm Hg and was increased by increments of 20 mm Hg to a maximum of 150 mm Hg according to the device’s display. The flow was tested with the outflow placed to gravity, suction, and then the suggested original inflow cannula was used instead of the sheath for the arthroscope with the outflow placed to suction.

RESULTS

The highest measured pressures for the Arthrex and the Stryker pumps were 115 mm Hg (46%) and 113 mm Hg (57%), respectively. In the beginning, the measured values were almost in accordance with the values shown on the display of the devices. Pressures up to 60 mm Hg were measured adequately by the pressure sensors of the 2 devices. The higher the pressure was set on the device the greater the deviation found.

The highest measured pressures for the Arthro FMS 4 and the InteliJet pumps were 251 mm Hg (101%) and 132 mm Hg (88%), respectively. Both devices measured the given pressure very accurately. While the Arthro FMS 4 pump measured accurately throughout all ranges, the InteliJet pump prevailed only at lower pressure values (Fig 2).

The maximal flow values for the Arthrex and Stryker pumps were 900 mL/min (56.3%) and 675 mL/min (45%), respectively. The Arthro FMS 4 and InteliJet pumps reached a maximal flow of 450 mL/min (56%) and 1,250 mL/min (62.5%). With suction, the knee model collapsed despite full flow and maximum pressure using the InteliJet pump when the original inflow cannula was not used. By using the original inflow cannula, the maximal flow per minute was increased only by 100 mL (Fig 3).

DISCUSSION

In 1989, Dolk and Augustini compared 3 irrigation systems for motorized arthroscopic surgery. Using a joint model, pressure measurements were performed simultaneously within the chamber with a standard dome transducer and in the bag with a transducer-tipped catheter. With the Arthro pump, intra-articular pressure was 30 to 35 mm Hg lower than the preset values at standard speed and a flow rate of 70 to 90 mL/min. With a higher flow rate and suction or shaver suction turned on, the pressure fell by 70 to 80 mm Hg compared with preset values. Also, the pressure recorded with the 3-M arthroscopy pump was 10 to 20 mm Hg lower than the preset values. The aim of this study was to investigate whether present fluid management systems for arthroscopic surgery really reach the high-pressure values as suggested on their displays in an artificial setting. In our study, the experimental setup chosen was similar to that of routine arthroscopic procedures with regard to the flow. The manufacturers’ representatives suggested the flow rate usually necessary for good visualization during arthroscopy. While all other variables were kept constant, the pressure was increased continuously.

Considering the possible complications related to high pressures, such as synovial pouch rupture, fluid extravasation, and compartment syndrome, it is difficult to understand why all devices allow pressure values far above 100 mm Hg. Moreover, Sperber and Wredmark investigated the capsular reaction to high intra-articular pressures. They concluded that, in order

![Figure 2](image-url)  
**Figure 2.** Comparison of the pressure reached by the 4 devices.

![Figure 3](image-url)  
**Figure 3.** The use of the original inflow cannula increased the maximum flow per minute of the InteliJet by only 100 mL.
to avoid capsular damage, knee arthroscopy should be done at intra-articular pressure levels below 120 mm Hg. According to Burgaard et al., the intra-articular pressure should be as low as possible and should never exceed 150 mm Hg. In this cadaver study, 10 knees were filled at 35° of flexion to a pressure of 100 mm Hg, were subsequently extended and flexed, and all knees ruptured during this maneuver. Also using a cadaveric model, Noyes and Spievack measured the intra-articular and thigh pressures during arthroscopy. Intra-articular pressures ranging from 180 to 240 mm Hg produced synovial pouch rupture in all knees studied. Conversely, in a clinical study, Ewing et al. measured a mean maximal pressure value of 268.5 mm Hg (±138.9; range, 90 to 750 mm Hg) without observing massive extravasation or rupture of the synovial pouch. They explained that the differences between their results and those of Noyes and Spievack could be explained by differences between clinical subjects and cadaveric specimens or by different pressurization rates.

The 2 more sophisticated pump systems, the Arthrex FMS 4 and the InteliJet, were able to reach the preset pressure. For the 2 other pumps, Arthrex and Stryker, large and small divergences between the preset and measured pressure were observed. These more simply constructed pumps never reached a pressure exceeding 135 mm Hg with the outflow cannula open. Both the Arthrex and the Stryker pumps had problems with the testing method chosen. In this study, the reachable pressures when the outflow cannula was closed were not investigated because, in arthroscopic surgery, a continuous flow is necessary to remove blood and debris. Considering the fact that an intra-articular pressure of below 120 mm Hg was suggested by Sperber and Wredmark to avoid capsular damage, all pumps were able to reach this intra-articular pressure limit in our experimental setting.

With a positive pressure in the knee joint, no compartmentation occurs within the suprapatellar pouch or anteromedial or posteromedial compartments. Therefore, the hollow, spherical rubber cavity is a valid knee model, with 1 limitation: no flexion or extension maneuvers, which are done frequently and at high-angle velocity during arthroscopy, can be performed. However, there is evidence in the literature that, with a closed system and even low baseline articular pressures about 20 mm Hg, intra-articular pressures in excess of 200 mm Hg are generated by flexing the knee. During routine arthroscopy, rapid movements caused intra-articular pressure values up to 400 mm Hg.

To our knowledge there are no reports on experimental flow measurements in the literature. Interestingly, none of the investigated pumps reached their published maximum flow values. The devices reached flow rates of 45% to 62.5% with respect to the published values of up to 2,000 mL/min (Table 1).

Flow through a vessel or tube follows Poiseuille’s law. The most important flow-regulating factor is the diameter of the inflow line. In our model, the flow was led through the arthroscope despite the high resistance in the spigot and water canal. But even with the use of the original inflow cannula, the maximal flow of the InteliJet pump could be increased only by 100 mL/min, from 1,150 to 1,250 mL/min.

### Table 1. Comparison of Arthroscopic Fluid Management Systems

<table>
<thead>
<tr>
<th>Arthrex</th>
<th>Stryker</th>
<th>Arthro FMS 4</th>
<th>InteliJet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Published</td>
<td>255 mm Hg</td>
<td>200 mm Hg</td>
<td>150*</td>
</tr>
<tr>
<td>Shown on display</td>
<td>240 mm Hg</td>
<td>160 mm Hg</td>
<td>100†</td>
</tr>
<tr>
<td>Measured</td>
<td>115 mm Hg</td>
<td>113 mm Hg</td>
<td>251 mm Hg</td>
</tr>
<tr>
<td>Percent of published</td>
<td>46%</td>
<td>57%</td>
<td>101%</td>
</tr>
<tr>
<td>Maximum flow (mL/min) Published</td>
<td>1,600</td>
<td>1,500</td>
<td>800</td>
</tr>
<tr>
<td>Measured</td>
<td>900</td>
<td>675</td>
<td>450</td>
</tr>
<tr>
<td>Percent of published</td>
<td>56%</td>
<td>45%</td>
<td>56%</td>
</tr>
</tbody>
</table>

*According to the information provided by the company, a fictitious, unit-less value of 150 shown on the display corresponds to a pressure of 368 mm Hg.
†According to the information provided by the company, a fictitious, unit-less value of 100 shown on the display corresponds to a pressure of 249 mm Hg.
CONCLUSIONS

Our investigation found that all 4 pumps are able to create pressure values considered by some investigators to be high enough to damage the capsule of the knee. The 2 simpler pumps do not create pressures accurately and as high as set on the display, perhaps because these pumps are not able to control the outflow. In contrast, the 2 outflow-controlling pumps create pressures in a precise manner. None of them reached the maximum published flow values in our experimental setup. In the simpler pumps, the pressure on the display must be set to higher values compared with the outflow-controlling pumps, to achieve the same intra-articular pressure. Below a displayed pressure of 60 mm Hg, a surgeon can trust the arthroscopic pumps used. When higher pressures are set, a surgeon who is familiar only with simple roller pumps must be aware that outflow-controlled pumps, such as those tested in this study, reach the preset pressure very accurately with the possibility of capsular damage. The authors do not understand why manufacturers allow their pumps to generate pressure values, at least on the display, that are beyond the limits suggested in reports in the literature. Nor do we understand why fictitious, unit-less numbers are used by one of the manufacturers.

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REFERENCES