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rthroscopic procedures are associated with smaller incisions, less structural damage, improved intra-articular visualization, less pain in the immediate postoperative period, and potentially faster recovery. With any surgery, exposure is critical. In arthroscopy, maintaining adequate exposure throughout the procedure requires an optical system and good joint distension by a system that delivers and maintains a clear medium into the joint. Lack of adequate joint distention is probably the most common avoidable cause of poor visualization.

As the image quality and effectiveness of pump systems improve, arthroscopy has become the primary treatment modality to address various conditions previously treated with open techniques.

Since its inception, arthroscopic surgery has become widely adopted among orthopedic surgeons. It is therefore important to have an understanding of the basic principles of arthroscopy. Compared with open techniques, arthroscopic procedures are associated with smaller incisions, less structural damage, improved intra-articular visualization, less pain in the immediate postoperative period, and faster recovery for patients. Pump systems used for arthroscopic surgery have evolved over the years to provide improved intra-operative visualization. Gravity flow systems were described first and are still commonly used today. More recently, automated pump systems with pressure or dual pressure and volume control have been developed. The advantages of automated irrigation systems over gravity irrigation include a more consistent flow, a greater degree of joint distention, improved visualization especially with motorized instrumentation, decreased need for tourniquet use, a tamponade effect on bleeding, and decreased operative time. Disadvantages include the need for additional equipment with increased cost and maintenance, the initial learning curve for the surgical team, and increased risk of extra-articular fluid dissection and associated complications such as compartment syndrome. As image quality and pump systems improve, so does the list of indications including diagnostic and treatment modalities to address intra-articular pathology of the knee, shoulder, hip, wrist, elbow, and ankle joints. This article reviews the current literature and presents the history of arthroscopy, basic science of pressure and flow, types of irrigation pumps and their functions, settings, applications, and complications. [Orthopedics. 2016;39(3):e474-e478.]
Over the years, the use of arthroscopy has progressed to include the knee, shoulder, hip, wrist, elbow, and ankle. Orthopedic surgeons commonly perform arthroscopy procedures, and it is important to understand the equipment that is used.

**History**

The earliest reference for exploration of body cavities using arthroscopy was found in the ancient Hebrew literature. More recently, in the 19th century, the development of endoscopic devices was spurred by the desire to explore the bladder. The first use in orthopedic surgery occurred in 1918 when Dr Kenji Takagi described endoscopy of a cadaver knee joint using a Charrier number 22 cystoscope. He later modified his instrumentation to develop the first joint arthroscope. Arthroscopy of the knee gained worldwide attention in 1958 when it was introduced at the Internal Society of Orthopaedic Surgery and Traumatology conference. With the advancement of arthroscopy, it quickly became apparent synovial fluid was not the preferred medium for visualization. Saline rapidly became the standard to replace synovial fluid to enhance visualization of key structures and pathology.

Pump systems used for arthroscopic surgery have evolved over the years to provide improved visualization. Gravity flow systems were used first and are still commonly used, followed by automated pump systems. Gravity flow systems simply use gravity to control inflow by positioning a bag of fluid higher than the joint to provide enough pressure for insufflation. The development and use of an automated pump for arthroscopy began in Sweden in the 1970s. Currently, there are 2 basic types of automated pump systems. The first type is a pressure-control pump, which controls pressure via inflow only. More recent automated pump systems maintain pressure by controlling inflow and outflow independently, thus termed pressure and flow control pumps or dual systems.

**Basic Science**

**Pressure**

Forty years ago, little was known regarding intra-articular pressure during arthroscopy. Questions regarding minimal pressure required for good visualization, pressure necessary to rupture the synovium, pressure changes caused by positioning, and even average pressures attained by the gravity flow method remained unanswered.

In 1977, Gillquist et al first reported that a threshold pressure of 28 mm Hg was necessary for good visualization during arthroscopy of the knee. Ewing et al corroborated this finding in 1986 and reported that 30 mm Hg was the average threshold pressure required to cause tamponade of small intra-articular vessels. They also stated that a pressure of 70 mm Hg was necessary for consistent and sustained capsular distention.

In 1986, Bergstrom and Gillquist performed a study on 45 knee arthroscopy using a mechanical pump with open outflow and flow rates of 45 cc per minute. They reported good visualization for all of the procedures with intra-articular pressures ranging between 40 and 60 mm Hg and noted that pressure never rose above 60 mm Hg. In 1992, Arangio and Kostelnik investigated the minimum adequate pressure required for arthroscopic procedures of the knee. Their results showed that with an average pressure of 55 mm Hg, arthroscopy could be performed in all knee positions studied and that pressure required for adequate joint distention ranged from 30 to 60 mm Hg.

As technology advances, the pressure gradient of an inflow system produced by an automated pump is totally controlled by the pump and is not dependent on the fluid reservoir height, volume, or gravity. Automated pumps have the capability of producing predictable continuous flow rates with an open system. In addition, they are able to generate intra-articular pressures that exceed those possible with gravity inflow systems. Advocates of the pump system believe they generate better visualization and clearing of joint debris during arthroscopy.

**Flow**

Flow through a tube follows Poiseuille’s law:

\[
\text{Flow} = \frac{\text{Pressure gradient}}{\text{Resistance to flow}}
\]

A gravity-fed system is related to the height difference between the fluid reservoir and the joint (ie, raising the inflow bag and not the amount of fluid in the bag). Also, with a gravity system in which outflow is closed, flow will occur until the joint is distended to an intra-articular pressure equal to the inflow pressure gradient, at which time, flow will cease.

Regardless of whether inflow comes from a gravity or pump system, intra-articular flow requires that fluid must come into and out of the joint at 2 separate points (inflow-outflow system). The primary need for fluid flow is to clear the joint of cloudy fluid caused by blood or debris to allow improved visualization. When good visualization is achieved, there is no need for continuous flow. If flow rates become exceedingly high, turbulence is created, which can interfere with visualization. Conversely, there are times when flow may be a hindrance, such as during loose body removal or when performing microfracture and checking for backbleeding.

If the rate of fluid outflow exceeds the capacity of the inflow system, a negative fluid balance exists, which leads to loss of joint distention and loss of visibility. This situation commonly occurs with outflow through a motorized suction shaver where outflow occurs by a negative pressure suction line attached to the shaver. Use of a mechanical pump in this setting can increase flow rates proportional to the outflow to a point where a fluid balance exists, thus avoiding loss of joint distention. With a gravity-fed system, this problem may be circumvented by intermittently clamping the suction line to the shaver, thus giving inflow time...
to catch up with the negative fluid balance.

The 2 most common access routes for inflow during knee arthroscopy are through the sheath that houses the arthroscope or through a separate cannula, usually placed in the suprapatellar pouch. Many surgeons prefer to lead inflow through the arthroscope, despite high resistance created at the inflow spigot and the water canal between the arthroscope and the sheath that encases it.\textsuperscript{15,16} Inflow through the arthroscope is advantageous for a number of reasons. Inflow through the suprapatellar route frequently is impeded by knee flexion and the “figure of four” position, leading to poor visualization. In addition, suprapatellar portal incisions can be painful and slow to heal.

Furthermore, in arthroscopy of other joints (eg, wrist, elbow, ankle, hip), the number of possible access portals is limited. Thus, inflow on the scope obviates using one of few portals for inflow, giving the surgeon increased flexibility for operative instrument placement. With inflow from the arthroscope, fluid entering the joint cleanses the area that coincides with the surgeon’s field of view.

**Components of an Irrigation System**

There are 5 basic components to creating an irrigation system for joint arthroscopy: (1) saline bag; (2) inflow tubing; (3) a pressure gradient supplied from gravity or an automated pump; (4) intra-articular joint space; and (5) outflow tubing with or without pressure-sensing feedback to an automated pump.

One of the advantages of a gravity flow system is the ease of setup and maintenance. Saline bags are simply attached to an intravenous (IV) pole a few feet above the level of the joint being operated on, then one end of the sterile inflow tubing is attached to the bags and the other end is attached to the arthroscopy instrumentation. To change the amount of inflow/pressure during the case, an operating room nurse will need to raise or lower the height of the IV pole. If outflow is necessary for better visualization, then another portal can be created with a stopcock instrument, which allows the amount of outflow desired to be adjusted manually. The surgeon may attach outflow tubing to the stopcock so that it drains into a catch basin or bag.

When using an automated pump system, the setup will depend on the type and brand of pump used. The basic concepts are inherently the same for each system, with a few differences. Multiple commercial irrigation pump systems are available. The system components include transparent safety covers, irrigation roller pump, tension rocker arm, power pad, display, and adjustment. First, the saline bags are attached to an IV pole the same as for the gravity system. However, the height of the IV pole is irrelevant. Outflow with a pressure control pump is set up in the same manner as for a gravity system. If a pressure and flow control pump is used, the sterile outflow tubing is attached through the roller pump designated for outflow. The Table provides industry examples of pressure levels with and without tourniquet in various joints.

Automated pump systems have an impeller pump power by an electronic controller. Solution flows from the bags through the tubes around the roller pump and through the pressure chamber, where the pressure is read by a built-in pressure transducer. The controller determines the speed of the impeller pump, which drives the flow of irrigant and determines the resultant static pressure.

The dual system functions similarly to the pressure control pump, except that it also has a separate outflow roller connected by tubing back to the pump that allows for outflow control. Solution flows from the outflow tubing around the roller, through a separate chamber where pressure is measured. Computer-integrated inflow and outflow control helps to maintain constant pressure in the joint. The device also has the capability to increase pressure and flow independently to eliminate debris and control bleeding. It interfaces directly with the shaver to automatically control shaver suction, and thus no wall suction or manual adjustments are necessary.

For automated systems, the surgeon then will have to ensure that the settings are correct. The inflow pressure is set for the pressure control pump, and both the inflow and outflow pressures are set for the dual system. There may be a foot pedal control with the automated systems that allows for transient increases in pressure and flow to improve visualization.

**Discussion**

The effectiveness of an arthroscopic pump system is based on the visualization

<table>
<thead>
<tr>
<th>Joint</th>
<th>With Tourniquet</th>
<th>Without Tourniquet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder</td>
<td>-</td>
<td>50-60</td>
</tr>
<tr>
<td>Acromioplasty</td>
<td>-</td>
<td>50-60</td>
</tr>
<tr>
<td>Knee joint</td>
<td>30-35</td>
<td>65</td>
</tr>
<tr>
<td>Wrist</td>
<td>30-40</td>
<td>65</td>
</tr>
<tr>
<td>Elbow, ankle</td>
<td>30-40</td>
<td>65</td>
</tr>
<tr>
<td>Hip</td>
<td>40-45</td>
<td>65</td>
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</table>
afforded to the surgeon during the procedure while maintaining patient safety. Visualization stems from a combination of camera image quality and maintaining a clear fluid medium. The irrigation system controls the fluid medium environment by regulating fluid volume used via inflow and outflow and the intra-articular vs set pressure. Patient safety relies on maintaining low intra-articular pressures and low levels of fluid extravasation.

The advantages to using a gravity flow system are the ease of setup and maintenance as well as a low complication profile since the pressure rarely reaches dangerous levels. Gravity flow systems have been used in Sweden for approximately 14 years without significant complications.\(^8,11\) The drawback associated with using a gravity-fed system is that it requires manual adjustments throughout the case to change the amount of inflow and outflow necessary for good visualization. This can be troublesome for long cases, especially if the tourniquet cannot be used.

Ewing et al\(^10\) stated that an ideal automated pump should deliver necessary flow rates, keep the intra-articular pressure at adequate levels for visualization, and include safety features such as pressure monitors that sound a warning when the pressure is too high. Use of these pumps set to deliver a constant intra-articular pressure slightly above end capillary diastolic filling pressure should allow one to perform arthroscopic surgery in a clear field of view without the use of a tourniquet. When an automated pump meets all of these criteria, then this product would offer many advantages over the gravity-flow methods.\(^10\)

More recently, evidence suggests that dual systems provide better visualization than pressure-control systems, which may lead to decreased operative times. Ogilvie-Harris and Weisleder\(^18\) prospectively compared pressure-controlled pumps vs pressure and flow control pumps for multiple types of arthroscopic procedures. Visualization and technical ease were assessed subjectively via observations of the video monitor and given a score based on the amount of impairment of visualization. They concluded that the adequacy of visualization and technical ease significantly improved with the pressure and flow control system compared with the pressure system alone. They also compared surgical times for the 2 pumps based on the duration of the surgery. They reported an increased number of surgeries less than 1 hour using the pressure and flow control units and concluded that the increased number of shorter duration surgeries was due to improved visualization.

Ampat et al\(^19\) prospectively compared these 2 types of pump systems (Aquaflo2 pump vs Fluid Management System [FMS; DePuy, Mitek, Raynham, Massachusetts]) for shoulder arthroscopic surgery based on visual clarity, presence of bleeding vessels, and total red blood cell loss for subacromial decompressions of 20 shoulders. The surgeon assessed the visual clarity and presence of bleeding vessels subjectively. Total red blood cell loss was determined by multiplying the volume of fluid that was used and the cell count in the effluent. There were no significant differences in relation to visual clarity, presence of bleeding, or red blood cell loss, and they concluded that there was no difference between the pumps in straightforward shoulder procedures.

The studies by Ogilvie-Harris and Weisleder\(^18\) and Ampat et al\(^19\) compared visualization based on subjective measures, and neither study set out to measure the amount of operative time saving. Tuinjhoft et al\(^17\) compared a gravity pump with a pressure and flow control pump using objective data and demonstrated time saving for the latter system.

Sieg et al\(^20\) sought to perform a direct comparison in terms of operative times in anterior cruciate ligament (ACL) reconstructive surgery using these 2 automated pumps. This retrospective study evaluated all ACL reconstructive surgeries performed by 3 surgeons during an 8-month period. During the first 4 months, a pressure-driven pump was used, and during the second 4 months, a pressure and flow control pump was used. Fifty-eight ACL reconstructions were performed; 21 procedures were performed using the pressure-control system, and 23 procedures were performed using the dual system. Average operative time using the pressure-control pump was 126 minutes vs 111 minutes for the dual system. There was an average 15-minute decrease in surgical time ($P=.04$) in favor of the dual system. The authors concluded this was likely due to the improved visualization provided by the independent control of pressure and flow.

**Complications**

Automated pressure-sensitive pumps monitor intra-articular pressure and automatically shut down if preset pressure levels are not maintained. In normal operation, they automatically maintain flow and pressure independent of one another to maintain joint distention and improve irrigation.\(^13\) However, if the pressure sensor fails, automated pumps may not shut down, and intra-articular pressures can rise to dangerous levels.

High intra-articular pressures may pose a risk to fluid extravasation, compartment syndrome, and synovial pouch rupture. Studies have reported synovial pouch rupture when intra-articular pressure rises in the range of 120 to 150 mm Hg.\(^21,22\) Despite known possible complications related to high pressure, many commercial devices allow pressure values far above 100 mm Hg.\(^8\)

Complications rate of 1% have been described in the literature, with complications including fluid extravasation (intra-peritoneal and extraperitoneal accumulation), synovial pouch rupture (distension of compartments of the leg and thigh), and compartment syndrome.\(^15\) There are reported cases for termination of knee arthroscopy due to distention of the anterior and posterior compartment of the leg and
thigh, and compartment syndrome with no palpable pulses of posterior tibial or dor-salis pedis arteries requiring fasciotomies. Noyes and Spievack\textsuperscript{23} reported excessive fluid extravasation in 4 of 300 cases during a 9-month period. Other complications that have been reported include mas-sive intraperitoneal and extraperitoneal accumulation of irrigation fluid during hip arthroscopy and compartment syndrome after knee arthroscopy for examination of a tibia plateau fracture.\textsuperscript{24,25}

**CONCLUSION**

Advantages of mechanical fluid irrigation system over gravity irrigation are: consistent flow; greater degree of joint distention; improved visualization, especially when motorized operative instruments are used; decreased need for tourniquet use; a tamponade effect on bleeding; and decreased operative time.\textsuperscript{13} Disadvantages include the need for additional equipment with increased cost and maintenance, initial learning curve for the surgical team, and extra-articular fluid dissection.\textsuperscript{23,26} Although significant advances have been made in arthroscopic equipment, few investigations exist that compare different pump systems. Even though improvements in visualization have been noted with dual systems, more research is necessary to determine the clinical significance.

**REFERENCES**