Incomplete Leg Exsanguination: A Possible Cause of Post Total Knee Arthroplasty (TKA) Cognitive Deficit (CD)

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Abstract

Introduction & Aims: Mild to moderate CD after TKA is a common side-effect of an otherwise successful procedure. Despite improvement in the majority of the cases within weeks to a few months, this is a source of concern and disappointment. This analysis presents a possible mechanism for post-TKA cognitive changes.

Method: We reviewed the literature on the hemodynamic events around limb exsanguination, tourniquet placement and release during TKA. The majority of this literature is in anesthesia journals, with only a few in orthopedic journals (e.g., Berman, *JBJS*, 1998, 389-96). Once the data were collected, we scrutinized it for validity and in order to identify a plausible etiology that links between the TKA operating procedure and CD.

Results: Limb elevation, Esmarch bandage, or Rhys-Davis exsanguinators are used prior to tourniquet inflation. Blond et al, (*Acta Orthop Scand*. 2002; 73:89–92) showed that at best, 70% of the limb's blood was exsanguinated. Miller et al. (*Ann. Surg*. 1979; 190: 227-230) demonstrated that blood remaining inside the vessels of an occluded limb coagulates. Parmet et al (*Lancet*. 1993; 341:1057-8) observed a shower of echogenic material in the right atrium approximately 30 seconds after tourniquet release in ALL patients. Berman et al., (*JBJS*, 1998, 389-96) documented that this echogenic material consisted of fresh thrombi and not fat, bone marrow or cement. These thrombi partially occlude the pulmonary circulation, elevating the pressure in the right heart. As such, the blood pressure balance across the septum of the right atrium reverses. For patients with patent foramen ovale, blood flows from right to left. This brings echogenic material to the cerebral circulation in over 50% of TKA patients as detected by transcranial Doppler ~50 seconds after tourniquet release (Sulek, *Anesthesiology* 1999; 91:672–6). These cerebral emboli were associated with new brain infarcts detected by pre- and post-TKA MRI imaging (Koch, *J Neuroimaging*. 2007 17:332-5). The last step in this chain-of-evidence analysis is the statistics of CD post-TKA (Rodriguez, *J Arthroplasty.* 2005 20:763-71.)

Conclusions: The disproportionate prevalence of CD post-TKA as compared to other surgical procedures performed under similar types of anesthesia and in similar patients is worrisome. This hemodynamic analysis invokes a hypothesis that links incomplete limb exsanguination with cognitive dysfunction. Prospective studies where near-perfect exsanguination is applied in comparison with the current methods should be performed.

Bloodless Surgical Field

Most surgeons exsanguinate the leg and use a tourniquet to occlude blood flow as a routine method of maintaining a bloodless surgical field during total knee arthroplasty. Some prefer using it for the entire duration of the operation, while others only block the arterial flow into the leg for cementing of the implanted knee. In any event blood flow is stopped for anywhere between 30-120 minutes (maximum). This brief review is focused on the practice of limb exsanguination and the consequences of the incomplete removal of the blood from the vessels in the leg.

Exsanguination

The current methods of limb exsanguination before application of the tourniquet include the following methods:

1) Esmarch bandage wrapped tightly from distal to proximal;
2) Limb elevation;
3) Rhys-Davies exsanguinator (Woodville Polymer Engineering, Derbyshire, UK)[1] and the Pomidor roll-cuff (Pomidor AB, Varnamo, Sweden);
4) an elastic exsanguination tourniquet (HemaClear®, OHK Medical Devices, Haifa, Israel).[2]

In a series of studies, Blond et al.[3] used Tc99-tagged red blood cells to measure the extent of blood removal from a limb by applying each of the first three methods listed above.

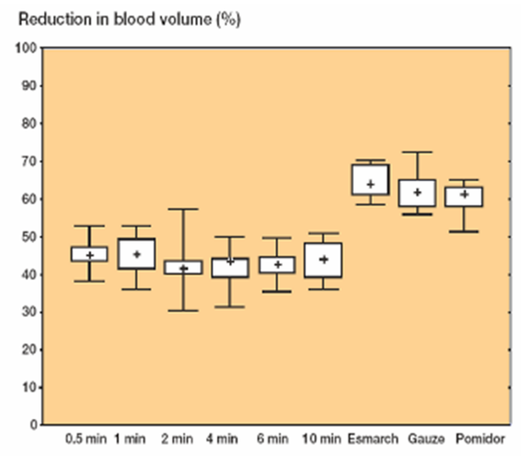

Figure 1. Results of various exsanguination methods in 12 subjects expressed as median (+), range and inter quartile percentage reduction in blood volume calculated from counts before and after exsanguination. Limb elevation achieved less than 50% count reduction. Esmarch about 65%.[4]

Figure 1 summarizes Blond's findings. They found that the best level of exsanguination was obtained with the Esmarch bandage. It was able to remove nearly 70% of the blood. The Pomidor, a device that is similar to, but smaller than the Rhys-Davies, was found to have removed slightly over 60% of the blood. Limb elevation was the least effective with no more than 45% of the blood was removed irrespective of the duration of holding the limb up.[5] As such, these studies clearly indicate that a substantial (eg. 30-55%) amount of the blood remains in the limb at the time the tourniquet is applied and blood flow ceases. No similar studies have been done so far with the elastic exsanguinating tourniquet, but multiple clinical studies have indicated that the exsanguination is near perfect (Fig. 2).[6]

Figure 2. A nearly bloodless surgical field when using silicone exsanguinating ring.

Intravascular Coagulation

When blood stops flowing or becomes stagnant, it tends to coagulate and form fresh thrombi. Clot formation during tourniquet application has been demonstrated in 1979 in subhuman primates.[7] There are several factors that promote coagulation during total knee arthroplasty. These include reduced temperature, hypoxia and seepage of activated complement components from the incision site.

The time it takes for blood to coagulate from the onset of tourniquet application is under 6 minutes and is certainly less than 30 minutes[8]. With more than a pint of blood in the vessels of a normal sized leg. Incomplete exsanguination as outlined above will leave behind 120-250 mL of blood in the leg. When this residual blood clots, there is a certain degree of separation between the plasma and the clot so that the actual clot volume is probably 50-120 mL, depending on the pre-operative hematocrit.

The Events at Tourniquet Release

When tourniquet pressure is reduced ("tourniquet down"), blood floods into the limb first into the arterial side and shortly thereafter blood starts flowing in the veins. The blood flow sweeps with it the fresh thrombi from the veins into the inferior vena cava and into the right atrium. Multiple studies where the right atrium was monitored with trans-esophageal Doppler have identified a shower of echogenic material in the atrium in all the patients. Several of these studies are worth mentioning more in detail. In 2002, Hirota et al.[9] did a quantitative analysis of the extent of the material traveling across the atrium. They found a peak density of about 20% of the atrium cross sectional area. This peak occurred approximately 30 seconds after the release of the tourniquet and gradually subsided over the next 10-15 minutes.

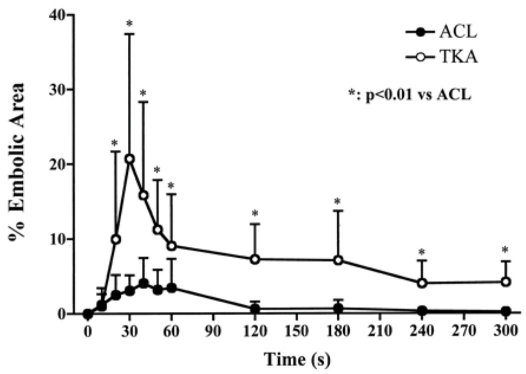

Figure 3. Time course of emboli formation in the right atrium (RA) after tourniquet release in the anterior cruciate ligament (ACL) and total knee arthroplasty (TKA) groups. *P < 0.01 versus ACL. All data are mean ± sd.

Another important publication is a study by Berman et al. in the JBJS in 1998.[10] In addition to documenting the fact that all the patients had echogenic material passing through their right atrium, they specifically evaluated the nature of the material. They inserted catheters into the femoral veins in the right atria in some of the patients that participated in the study, and aspirated blood immediately after the release of the pneumatic tourniquet. All the aspirates that contained solid material consisted of soft thrombus and did not contain fat, marrow, or cement material. The ongoing existing controversy on the nature of this echogenic material before the publication of this study was ended by these results.

Another study that shed light on this phenomenon was done by Parmet at al.[11] in 1998, where they compared the extent of the echogenic material in patients undergoing total knee arthroplasty with and without a pneumatic tourniquet. They found a 5.3 fold increase in the amount of material at the time of the tourniquet release in the tourniquet group compared to those patients where a tourniquet was not used. As such, it is clear from this study that the presence of thrombi is directly and unequivocally related to the stagnation of the blood in the leg.

Some of the studies attempted to correlate the duration of the application of the tourniquet with the extent of the thrombi recognized by the trans-esophageal Doppler. These studies did not show any statistically significant correlation. However, it should be noted that in all the studies tourniquet time was substantially greater than typical clotting time of blood. As such, one would not expect to see a correlation if in all patients clotting had already occurred. To date, no studies have yet been published on the extent of the echogenic material at the release of newer elastic exsanguination tourniquet.

Hemodynamic Effect of Thrombi Migration into the Right Heart

The clots that sweep through the right atrium continue into the right ventricle and the pulmonary arteries, and eventually lodge in the more distal arteries and arterioles in the pulmonary circulation. There they occlude the blood flow, thereby diverting the blood into other parts of the lung. Pulmonary vascular resistance goes up and the afterload of the right ventricle increases. In most normal patients the right ventricle reacts by increasing its end systolic pressure, as well as the end diastolic pressure. However, the pulmonary blood flow may be impeded to a degree, leading to a transient reduction in the venous return into the left atrium and ventricle. It is safe to assume that the Frank-Starling mechanism will reduce the left ventricular contractility and cardiac output. The negative inotropic effect is compounded by the effect of the acidic blood coming from the legs' veins, which may also include high levels of carbon dioxide and potassium. During the period of occlusion of blood flow there is tissue hypoxia and a buildup vasodilator. These dilate the arterioles causing a decrease in vascular resistance. When tourniquet is released and perfusion is restored, blood flow is elevated leads to reactive hyperemia. The reactive hyperemia results in a washout of the acidic blood

The accumulated effect of these factors cause a sudden drop in systolic and diastolic blood pressure which is very familiar to anesthesiologists who care for patients undergoing TKA. The common practice is to infuse 560-1000 mL of fluids just prior to tourniquet release in anticipation of this pressure drop. As such, one may conclude that the effect of the pulmonary emboli at the time of the tourniquet release is not associated with the detrimental cardio pulmonary consequences of any lasting importance. However patients with preexisting conditions, such as pulmonary hypertension, COPD, congestive heart failure and related illnesses, should be given special attention to these effects.

Right-Left Shunt and Thrombi into the Arterial Circulation

In about 20%[12] of the population, the foramen ovale is closed by a detachable flap that prevents blood from moving from the higher pressure left atrium into the right atrium. This flap can open like a one way valve when the pressure in the right atrium rises above that on the left. This happens when emboli occlude the pulmonary circulation, as described in the previous section. This circumstance causes the right to left flow of blood which is saturated with thrombi from the limb clot. Once in the left side, the thrombi readily move into the left ventricle and are pumped into the arterial system. With the carotid arteries being the first branches out from the aortic arch in a straight line orientation, it is not surprising that at least some of these clots move into the cerebral circulation. This has been documented by trans-cranial Doppler in a number of studies that showed nearly 60% prevalence of echogenic material in the Circle of Willis with a peak at 50 seconds after the pneumatic tourniquet is released.[13] Other paths of the right-left shunt of blood and clots are through AV connections in the lungs that open up when pulmonary blood pressure rises.

Brain Infarcts Post Total Knee Arthroplasty

The first publication on cerebral emboli post TKA[14] failed to document cerebral infarcts by brain CT. However, a subsequent study by Monk et al[15] in 2005 clearly showed by MRI before and after TKA that 5 from 22 patients had new brain infarcts. The difference between the two papers is probably explained by the fact that small brain infarcts surrounded by edematous brain tissue are more readily detected by MRI than CT scan.

Post TKA Cognitive Dysfunction

The entity of reduced cognition after elective TKA is well known and well documented. The prevalence has been researched in a number of studies with observations that more than 40% of the patients have cognitive dysfunction seven days after surgery and more than 15% still had cognitive dysfunction 3 months after surgery. The percentages are much higher than observed in other procedures by general surgeons with similar types of anesthetics. As such, the notion that this cognitive dysfunction has to do with the performance of the anesthesiologist is not supported by the evidence. On the contrary, it is quite plausible and at least indirectly documented that these cognitive changes are the result of cerebral emboli infarction.

Summary

A flow diagram below summarizes the events leading from incomplete limb exsanguination to cognitive dysfunction during TKA.

Conclusions

Prevention of blood stagnation in the exsanguinated limb seems to be the critical element in this chain of events described above. This can be done by avoiding the use of the tourniquet all together or by using a technology that exsanguinates the blood better than with the current methods (Esmarch, limb elevation, Rhys-Davis). HemaClear® is one such device that exsanguinates the entire blood from the limb (except the blood within the bone marrow).

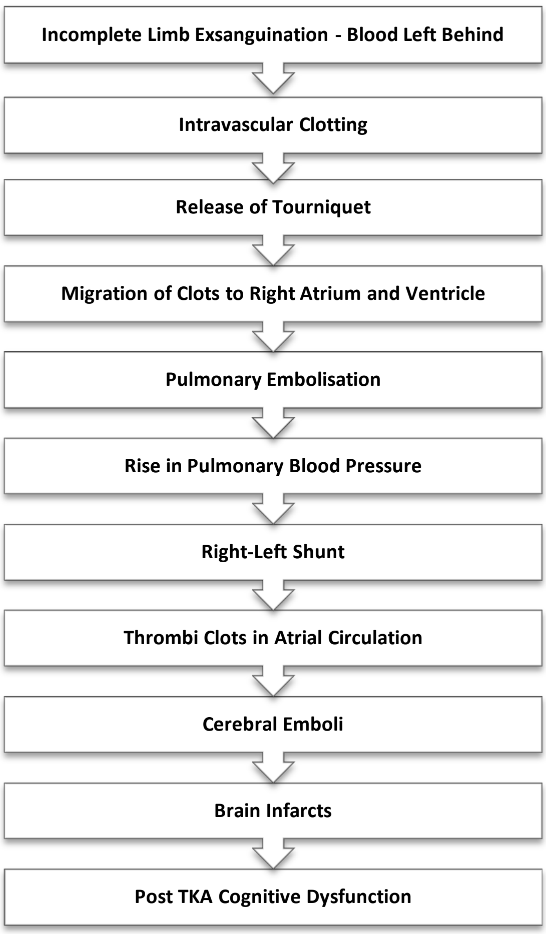

Figure 4. Cascade of events that link post TKA CD with incomplete leg exsanguination. See text for details.

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