The Hydrodynamic Effect of Bare Platinum Coils versus Hydrogel-Coated Platinum Coils

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Summary

HydroCoils (HES) were designed to obtain a better initial aneurysm occlusion and increased durability of endovascular treatment. We compared the immediate hydrodynamic effects of HES versus bare platinum coils (Guglielmi detachable coils, GDC). Intra-aneurysmal pressure and flow were measured with a 0.014 inch guide-wire mounted transducer in silicone aneurysms mounted onto a pulsatile flow phantom before and after consecutively coiling with GDC and HES. We evaluated flow using the thermodilution technique along with changes in steady pressure and sudden increases in pressure. We also considered the effect of the coils on the transmission of pressure from the parent artery to the dome of the aneurysm.

Intra-aneurysmal pressure remained unchanged after maximal packing with either GDC or HES. Sudden increases in pressure were less attenuated within the aneurysm after coiling with HES. In spite of HES obtaining a much higher percentage filling volume in the aneurysms, GDC equivalently virtually abolished intra-aneurysmal flow apart from in one instance where there was significant persistent flow after coiling with GDC. The effects of HES in terms of pressure and flow attenuation within the aneurysm could hence not be proven superior to GDC.

Introduction

The treatment of a cerebral aneurysm aims at the complete exclusion of the aneurysm from the circulation. This can be achieved by surgical clipping over the neck of the aneurysm, by endovascular filling of the aneurysm with embolization material, or by parent artery occlusion. With perfect clip placement, surgical clipping provides an immediate and permanent occlusion of the aneurysm, though this approach is highly invasive. Endovascular embolization of the aneurysm is less invasive but carries a significant rate of persisting intra-aneurysmal flow or recanalization. The chance of incomplete endovascular exclusion of the aneurysm from the circulation increases in large and/or wide-necked aneurysms being as high as up to 60%¹. With persistent circulation into the aneurysm, it may grow and/or cause delayed hemorrhage in approximately 4%¹. These numbers were obtained using bare platinum coils like Guglielmi detachable coils (GDC) but could be reduced when coiling with hydrogel-coated platinum coils², the so-called HydroCoil embolic system (HES). In HES, the bioactive polymer hydrogel-coating expands when in contact with liquid, being expandable quickest in a warm solution with a pH close to 7.35. Apart from their immediate effect of a

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larger percentage filling volume³, HES coils are reported to increase neointimal coverage of the aneurysm neck and promote infiltration of the coil mass with mature vascularized fibrous tissue, thereby improving the long-term outcome of coiled aneurysms⁴. On the other hand, a more favorable percentage filling volume is not a guarantee for abolished circulation within the aneurysm³. Clinical studies evaluating the efficiency of HES employed angiographic criteria for the grade of aneurysm occlusion^{2,3,5}, but they could not measure flow within the aneurysm directly. Evaluation of intra-aneurysmal flow following coiling with GDC versus HES as the acid test for complete aneurysm obliteration was our current goal. Concomitantly, changes in static intra-aneurysmal pressure and the more dynamic attenuation of sudden pressure waves obtained by GDC versus HES were investigated. To this end, we designed a controlled experimental setting where silicone aneurysms were consecutively coiled with GDC and HES and the coils immediate hydrodynamic effect studied.

Methods

The Flow Phantom

We used a custom-made system comprising a molded silicone replica of the aortic arch and brachycephalic vessels⁶ (MicroVention, Inc., Aliso Viejo, CA 92656). Fitted to segments representing the internal carotid arteries and vertebral arteries were connections leading to a basin into which silicone molded aneurysms of different shapes could be placed and connected to the "systemic" arterial and venous circulation. The chamber into which the aneurysms were mounted could be filled and perfused with isotherm physiologic solution using a circuit that was not connected to the vascular component of the phantom. The flow phantom included an electromagnetic flow pump (LMI Milton Roy, Acton, MA 01720, USA) that allowed pulsatile flow with simulated heart rates varying between 40/min and 100/min. Moreover, the systemic pressure could be varied using an adjustable clamp mounted on the main inflow connection to the phantom. The amplitude of the pulsatile excursions could be controlled by the liquid-level in an accumulator chamber and was kept constant throughout the experiment in every aneurysm investigated. Although the pulse rate and pressure were adjust-

ed, flow in the parent artery was kept constant by setting the stroke-volume in the electromagnetic pump in such a way that flow remained constant at $230\text{ml}\cdot\text{min}^{-1} \pm 10\%$. To control the correct setting of stroke – volume, flow was measured using an intra-operative flow probe that was clamped around the parent artery as far proximal to the aneurysm as possible (CardioMed CM-2008 flowmonitor, CardioMed A/S, Oslo, Norway). The model was perfused with 0.01 mol/L phosphate-buffered saline with a pH at approximately 7.35. A constant temperature of 37°C was achieved with a heater unit and was controlled by a thermostat/heater control unit built into the reservoir of the model.

Hydrodynamics

A 6 French guiding catheter was positioned in the vessel connected to the aneurysm parent artery (tip positioned 6-8 cm proximal to the aneurysm). A 0.014" guide-wire mounted pressure-temperature sensor (PressureWire™ Sensor, RAD Medical Systems, Uppsala, Sweden) was calibrated with the zero pressure corresponding to the barometric room pressure, and the zero temperature corresponding to room temperature at 20°C. The pressure-temperature sensor was advanced through the guiding catheter and placed adjacent to the wall of the aneurysm on the zenith of the dome, with the flexible tip past the sensor assuring a stable position of the sensor. After having been calibrated in an identical manner, another identical pressure-temperature sensor was placed in the parent artery approximately 3 cm proximal to the neck of the aneurysm. Using a commercially available angiographic injector (Angiomat 3000, Liebel-Flarsheim Company, Cincinnati, Ohio, USA), saline at room temperature was injected through the guiding catheter at a rate of $5\text{cc}\cdot\text{s}^{-1}$ over two seconds. The injection had a dual function: firstly, it induced abrupt and reproducible increases in intra-vascular pressure⁷, and secondly, it allowed assessment of flow by taking advantage of the thermodilution principle. Thermodilution is a variant of an indicator dilution technique, where a defined volume of cool injectate is used as the indicator. The injectate mixes with the circulation and the resulting local change in temperature is proportional to the volume flow-rate at the site of measurement. The normal saline within the perfusion phantom was maintained at 37°C which could be cooled down maximally to

Figure 1 Pressure in the parent artery (blue) and at the dome of the aneurysm (red) at steady state and during injection of 5cc.s-1 over two seconds with saline (arrow) after coiling of the aneurysm with Guglielmi detachable coils (GDC, upper) or with HydroCoil embolic system (HES, lower). The green line is the ratio of the pressure in the parent artery by the pressure in the aneurysm (transmission index). With unperturbed pressure transmission the index equals 1. During the saline injections, the pressure wave is attenuated at the dome of the aneurysm after coiling with GDC and HES, but to a smaller extent in the latter.

room temperature by the injectate. As we calibrated the temperature sensors to zero at room temperature, the sensor measured values around 17°C in the 37°C warm flow phantom and would, upon injection of room temperature saline cooled to between 17°C and 0°C – depending on the local volume flow. After each injection the temperature in the flow model was allowed to return to 37°C prior to the next injection. The intravascular pressures and thermodilution curves were recorded simultaneously using the RADIANalyzer™ (RADI Medical Systems, Uppsala, Sweden). These registrations were then transferred into a computer for storage and off-line analysis using the RadiView 1.00 2xT Software (RADI Medical Systems, Uppsala, Sweden).

Pressure was analyzed with respect to comparing the pressures at the dome of the aneurysm versus the pressure in the parent artery.

The ratio of the pressure in the parent artery by the pressure in the aneurysm was calculated automatically online by the four channel RADIANalyzer (Figure 1, green line). With unperturbed pressure transmission this ratio equals 1. Hence, changes in that ratio indicate a change in pressure transmission between the parent artery and the aneurysm and we denoted this ratio for the transmission index.

The thermodilution curve was analyzed using the following three parameters⁸:

1) ΔT which is the maximum drop in temperature obtained by the saline injections

2) The pressure-flow shift ϵ which is the time gap between the observed increase in pressure and the start of decrease in temperature upon saline injection. The shift ϵ is an expression for the dissociation of pressure and flow which ex-

ists in all oscillating systems; pressure and flow are only in phase when the frequency equals zero.

3) The dilution interval; i.e. the duration of the temperature change obtained by the injection. This parameter is comparable to the wash-out or “turn-over” at the site of measurement.

Flow within the aneurysms was calculated by applying a modified Stewart-Hamilton-Equation:

$$\text{Flow} = V (T_S - T_I) k / T_S(t)^{\text{dt}}$$

where V represents the volume of the injectate, T_S the temperature of the saline circulating in the flow phantom, T_I the temperature of the injectate, k being a constant varying with the model being used, and $T_S(t)^{\text{dt}}$ symbolizing the change in temperature as a function of time.

The Aneurysms

We examined four aneurysms; two bifurcational and two side-wall aneurysms. Their geometrical characteristics are listed in Table 1. For each aneurysm, its specific hydrodynamic profile was delineated employing injections with room temperature saline at various pulse rates (40/min, 60/min, 80/min and 100/min) within three different pressure levels (50 mmHg, 100 mmHg, and 140 mmHg), resulting in 12 pulse rate/pressure combinations (baseline values). For every possible combination of pulse rate and pressure two injections were performed and averaged during off-line analysis.

Thereafter, with the pressure/temperature sensors in place, the aneurysm was coiled with either GDC (Boston Scientific, Inc., Fremont, CA, USA) or HES (MicroVention, Inc., Viejo, CA, USA), (a coin decided on which embolization material to use first) in a bi-plane angiographic suite according to clinical criteria.

When coiling with HES, standard coils were used to create a “basket” which then was filled with HES (Table 2). The percentage filling volume was calculated as described previously in the HEAL study⁹. After completion of coiling, injections corresponding to those performed for baseline values were carried out. After that, the pressure/temperature sensor was carefully retracted and placed alongside the pressure/temperature sensor in the parent artery. The pressures obtained from the two sensors were checked for equality and an injection with saline was performed to assure that both sensors acquired uniform thermodilution curves. The coil material was thereafter carefully removed. The pressure/temperature sensor was replaced at the exact same site within the dome, and the aneurysm coiled once more with either GDC or HES, depending on which coil material was used initially. Subsequently, all saline injections were carried out in an identical manner described for the baseline values.

Data Analysis

For statistical analysis we used SPSS 13.0 for Windows®. For comparison between pressure and flow parameters in aneurysms coiled with GDC versus HES we used the paired samples T-test. Results were considered significant if $p < 0.05$.

Results

Coiling of the Aneurysms

One aneurysm was coiled with GDC first, whereas the three other aneurysms were first coiled with HES (Table 1). The material used and percentage of filling volume obtained is listed in Table 2. We needed a total of 36 GDCs versus 32 HES (corresponding to 4.75 m GDCs

Table 1 Geometric properties of the aneurysms.

Aneurysm #	type	depth (mm)	height (mm)	Volume (mm ³)	neck size (mm)	Coil sequence
1	Bifurcational	8	7	235	5	GDC-HES
2	Side-wall	8	12	402	5	HES-GDC
3	Side-wall	7	8	205	3	HES-GDC
4	Bifurcational	10	9	471	4	HES-GDC
GDC: Guglielmi detachable coils; HES: HydroCoil embolic system

Figure 2 Angiographic result of coiling with Guglielmi detachable coils (GDC, above) or with HydroCoil embolic system (HES, below) in the four silicone aneurysms. The 0.014" guide-wire mounted pressure-temperature sensors are in place within the aneurysm and the parent artery.

and 4.00 m HES). The filling volume obtained was considerably higher with HES; in aneurysm 3, the calculated filling volume suggested a significant over packing.

The angiographic result of the coiling procedures is shown in Figure 2. Despite over packing in aneurysm 3 with HES, there was no coil prolapse into the parent artery. There were neck remnants in several aneurysms both after coiling with GDC and HES.

Adequate function without drifting of the zero calibration was verified in all pressure/temperature sensors after retraction from the coiled aneurysms. One wire was damaged and discarded when it had hooked to the coils and stretched at the flexible tip; the sensor itself was still working correctly.

Pressure in the Aneurysms

The mean pressure in the aneurysms was 100.83 ± 34.38 mmHg before coiling and changed to 100.33 ± 35.81 mmHg after coiling with

GDC (NS), and 99.82 ± 34.04 mmHg with HES (NS), respectively. Also in aneurysm 3 that was filled in excess with HES, the mean pressure did not increase. Corresponding to these intra-aneurysmal pressure changes, the transmission index was 0.98 ± 0.096 when we had coiled with GDC and 1.01 ± 0.02 when HES was used.

During the sudden increases in pressure created by the saline injections, the transmission index increased from 0.86 ± 0.08 to 0.95 ± 0.05 ($p < 0.001$) in the bifurcational aneurysms when the aneurysms were coiled with GDC. In contrast to that, the transmission index was 1.02 ± 0.03 when using HES for coiling and did not change significantly during the saline injections (1.01 ± 0.04 , NS).

In the side-wall aneurysms, GDCs increased the transmission index to 1.03 ± 0.05 and 1.11 ± 0.06 ($p < 0.001$) during the saline injections; i.e. there was a relatively marked pressure wave attenuation. The same pattern was also seen when the side-wall aneurysms were coiled with

Table 2 Material used for coiling and percentage filling volume obtained.

	GDC	Percentage filling volume	HES	Percentage filling volume
Aneurysm 1	8 mm x 20 cm GDC-10 7 mm x 10 cm GDC-10 6 mm x 20 cm GDC-10 5 mm x 15 cm GDC-10 5 mm x 15 cm GDC-10 5 mm x 10 cm GDC-10 4 mm x 10 cm GDC-10 4 mm x 10 cm GDC-10	24%	7 mm x 16 cm MicroPlex Complex 2D tracker -18 4 mm x 10 cm 4 mm x 10 cm 4 mm x 10 cm 4 mm x 10 cm 4 mm x 10 cm 4 mm x 10 cm	102%
Aneurysm 2	12 mm x 30 cm GDC-18 7 mm x 30 cm GDC-10 5 mm x 20 cm GDC-18 5 mm x 15 cm GDC-10 5 mm x 15 cm GDC-10 5 mm x 15 cm GDC-10 5 mm x 15 cm GDC-10 5 mm x 15 cm GDC-10 4 mm x 10 cm GDC-10	27%	8 mm x 30 cm MicroPlex Helical tracker -18 6 mm x 10 cm 6 mm x 10 cm 6 mm x 10 cm 6 mm x 10 cm 6 mm x 10 cm 6 mm x 20 cm	73%
Aneurysm 3	7 mm x 30 cm GDC-18 6 mm x 20 cm GDC-10 6 mm x 20 cm GDC-10 5 mm x 20 cm GDC-18 4 mm x 10 cm GDC-10 3 mm x 8 cm GDC-10 3 mm x 8 cm GDC-10	44%	8 mm x 30 cm MicroPlex Helical tracker -18 8 mm x 30 cm MicroPlex Helical tracker -18 4 mm x 10 cm 5 mm x 10 cm 5 mm x 10 cm 6 mm x 20 cm 5 mm x 10 cm 5 mm x 10 cm 4 mm x 10 cm 4 mm x 10 cm	195%
Aneurysm 4	8 mm x 30 cm GDC-18 4 mm x 6 cm GDC-10 4 mm x 8 cm GDC-10 3 mm x 8 cm GDC-10 3 mm x 8 cm GDC-10 3 mm x 8 cm GDC-10 3 mm x 6 cm GDC-10 3 mm x 4 cm GDC-10 3 mm x 4 cm GDC-10 3 mm x 4 cm GDC-10 3 mm x 4 cm GDC-10 2 mm x 8 cm GDC-10 2 mm x 8 cm GDC-10	15%	6 mm x 13 cm MicroPlex Complex 2D tracker -18 5 mm x 10 cm 4 mm x 10 cm 4 mm x 10 cm 4 mm x 10 cm 3 mm x 7 cm 3 mm x 7 cm 3 mm x 7 cm	51%
GDC: Guglielmi detachable coils; HES: Hydrocoil

Figure 3 Thermodilution curves at the dome of the aneurysm (red) and in the parent artery (blue) after coiling with Guglielmi detachable coils (GDC, upper) or with HydroCoil embolic system (HES, lower) in aneurysm 4 (left) and aneurysm 2 (right). The flatter the thermodilution curve the more abolished is flow at the site of measurement. In aneurysm 4 there is considerable remaining flow at the dome of the aneurysm after coiling with GDC, whereas intra-aneurysmal flow is equally well reduced in aneurysm 2.

HES, but less distinct (from 1.00 ± 0.03 to 1.05 ± 0.03 during saline injection).

Flow in the Aneurysms

As expected, all aneurysms had their own typical flow characteristics (Table 3). Flow was reduced significantly with both GDCs and HES coils, both in terms of calculated flow and in terms of the thermodilution parameters ΔT , ϵ , and the dilution interval. The reduction of flow seemed to be stronger after coiling with HES (Table 3). Analyzing bifurcational and side-wall aneurysms separately, this difference was mainly present in the bifurcational aneurysms, whereas the flow reduction in side-wall aneurysms was more similar between GDC and HES. Considering every aneurysm individually, delineated in fact only aneurysm 4 as disclosing quite different flow characteristics

after coiling with GDC compared to after coiling with HES (Figure 3). In this aneurysm there was a considerable residual flow (32.40%) after coiling with GDC, whereas flow was virtually abolished after coiling with HES. This aneurysm had the poorest filling volume for both GDC (15%) and HES (51%).

In aneurysms 1 and 3, GDCs obtained a similar to HES and almost complete reduction in flow although the filling volumes were very different (24% versus 102% and 44% versus 195%). In aneurysm 2, there was a statistically - but maybe not clinically - significant difference in flow reduction between GDC and HES, as GDCs caused a powerful reduction in flow of 95.08% versus 98.37% after coiling with HES (Figure 3).

The pressure-flow shift ϵ was the only parameter that was convincingly more affected by

HES in all instances; i.e. there was a larger dissociation of pressure and flow after coiling with HES.

Discussion

The present study investigated immediate hydrodynamic changes induced by the insertion of HES versus GDC into silicone aneurysms. As flow into an aneurysm is not only defined by the geometry of the aneurysm sac and neck but also by the circulation pulse rate and systemic pressure we tested our aneurysms during various combinations of pulse rates and systemic pressures. We could thereby minimize possible confounding from the circulatory state of the flow phantom on the measured intra-aneurysmal pressures and flow. Therefore, we also kept the systemic flow constant.

Regarding flow, our core finding was a close to abolished intra-aneurysmal flow after both GDC and HES in three out of four aneurysms. The *raison d'être* to develop the HES was a higher percentage filling volume than that obtainable with platinum coils and thereby prevent persistent circulation and/or recanalization within the aneurysm. Several clinical studies^{3,9,10,11} and an experimental study¹² have confirmed the fulfilment of higher packing attenuation with HES compared to GDC. The percentage filling volume could be increased from around 30% in GDC to 60-85% in HES^{9,10,11}. This corroborates well with our present data, with an average percentage filling volume of 28% with GDC and 105% with HES (75% if the aneurysm with excessive overfill is excluded). Some authors had questioned the adequacy of aneurysm volume calculations as no natural aneurysm is perfectly spherical. This uncertainty could give rise to the difference in filling volumes between GDC and HES. In the present study, however, we coiled the very same silicone aneurysm with either coil material; i.e. the aneurysm volumes were identical for the GDC and HES group in contrast to the previous studies where the GDC and HES group consisted of matched controls. Since we found a difference in packing attenuation between GDC and HES in the same magnitude as in these studies, the diversity has to be caused by the characteristics of the coil material rather than by calculation errors. However, the calculation of packing volumes for the HES presumes complete coil expansion, which is un-

known whether archived or not. With our aneurysm that was filled to a theoretical volume of 195% without considerable dislodgement of the coil mass into the parent artery and without increase in intra-aneurysmal pressure, it seems very likely that the HES is not entirely expanding when it meets resistance in coil loops or the aneurysm wall. One could hence suspect that the packing volumes of HES tend to be overestimated.

Furthermore, the relationship between packing density and durability of the coil occlusion is not straightforward. Although the packing density obtained with HES was much higher than with GDC, the overall rate of recurrence was merely moderately reduced with HES^{2,11,13}, especially in large and giant aneurysms a real advantage of HES over GDC was difficult to prove. On the other hand, the recurrence rate could be significantly reduced when using HES as the finishing coil and not platinum in aneurysms coiled with HES. In HEAL¹⁴ the recurrence rate was 11% with a final HES coil versus 29% with a final platinum coil, and in the study by Gaba et Al.¹¹ it was 13% versus 22%, respectively. Angiographically confirmed aneurysm occlusion has hence been attributed to the ability to occlude the neck of the aneurysm rather than the percentage filling volume per se^{3,11,14}. In the present study, the aneurysms were coiled entirely with HES apart from the initial framework or "basket". This means all our final coils were HES in the HES group. Still, intra-aneurysmal flow was virtually abolished with both GDC and HES in three out of four aneurysms. In other words, the functional result of aneurysm occlusion; i.e. cessation of flow, was equally good regardless of the packing attenuation within the aneurysm. Furthermore, although the percentage filling volume in aneurysm 4 was lowest of all aneurysms coiled with HES, the reduction in flow was the best of all aneurysms. This finding supports the notion of the importance of aneurysm neck occlusion. Moreover, angiographically confirmed aneurysm occlusion may not necessarily correspond to functional occlusion. In aneurysm 4, the angiographic result of coiling after GDC was satisfactory, but a considerable amount of flow persisted within this aneurysm. With small amounts of contrast entering the aneurysm and a large number of coil loops obscuring the contrast, residual flow may be sometimes difficult to visualize, especially when the coil finish to-

Table 3 Flow characteristics in the aneurysms after coiling with Guglielmi detachable coils (GDC) versus HydroCoil embolic sustem (HES).

	All aneurysms	Bifurcational aneurysms	Side-wall aneurysms	Aneurysm 1 bifurcational	Aneurysm 2 Side-wall	Aneurysm 3 Side-wall	Aneurysm 4 bifurcational
Flow (ml.min-1)	95.32 ± 82.26	153.53 ± 78.38	37.11 ± 24.78	226.77 ± 32.13	61.33 ± 5.20	12.88 ± 1.84	80.29 ± 18.10
Flow after GDC (ml.min-1)	9.44 ± 11.08	17.30 ± 11.44	2.09 ± 1.82	6.84 ± 6.60	3.02 ± 2.25	1.20 ± 0.35	26.01 ± 5.84
Flow after HES (ml.min-1)	1.62 ± 1.70	2.16 ± 2.23	1.05 ± 0.40	3.61 ± 2.39	1.00 ± 0.41	1.11 ± 0.38	0.71 ± 0.21
<i>p</i> (GDC versus HES)	0.001	0.001	0.01	NS	0.01	NS	0.001
ΔT (°C)	8.13 ± 3.42	10.99 ± 1.71	5.27 ± 2.01	12.41 ± 0.46	7.17 ± 0.53	3.38 ± 0.67	9.57 ± 1.08
ΔT (°C) after GDC	2.29 ± 2.09	3.79 ± 2.13	0.91 ± 0.48	1.80 ± 1.17	1.21 ± 0.51	0.61 ± 0.15	5.45 ± 1.00
ΔT (°C) after HES	0.69 ± 0.47	0.81 ± 0.61	0.56 ± 0.19	1.23 ± 0.62	0.58 ± 0.20	0.54 ± 0.17	0.39 ± 0.12
<i>p</i> (GDC versus HES)	0.001	0.001	0.001	NS	0.001	NS	0.001
ε (sec)	0.64 ± 0.32	0.51 ± 0.19	0.77 ± 0.37	0.43 ± 0.13	0.45 ± 0.16	1.09 ± 0.22	0.59 ± 0.21
ε (sec) after GDC	2.50 ± 1.81	1.22 ± 1.17	3.67 ± 1.47	2.36 ± 0.70	4.45 ± 1.56	2.88 ± 0.85	0.27 ± 0.27
ε (sec) after HES	6.49 ± 2.26	4.99 ± 1.55	8.00 ± 1.83	3.62 ± 0.69	6.67 ± 1.44	9.33 ± 1.02	6.36 ± 0.70
<i>p</i> (GDC versus HES)	0.001	0.001	0.001	0.001	0.01	0.001	0.001
Dilution interval (sec)	11.84 ± 6.62	7.57 ± 3.12	16.11 ± 6.46	4.72 ± 0.54	9.98 ± 0.80	22.23 ± 2.49	10.43 ± 1.60
Dilution interval (sec) after GDC	33.39 ± 13.53	22.93 ± 7.97	43.19 ± 9.80	28.66 ± 8.44	42.06 ± 11.95	44.28 ± 7.29	18.15 ± 2.77
Dilution interval (sec) after HES	43.60 ± 12.86	39.83 ± 10.50	47.54 ± 13.98	32.54 ± 7.24	52.53 ± 17.57	43.00 ± 7.43	47.11 ± 7.88
<i>p</i> (GDC versus HES)	0.001	0.001	NS	NS	0.01	NS	0.001

wards the parent artery is good. In the present study, we exclusively examined the immediate hydrodynamic effects after GDC versus HES coiling and the impact on long-term patency of the coiling may only be guessed. The effect of blood clotting is eliminated. An earlier work showed that the insertion of GDCs in a canine aneurysm creates qualitatively similar reductions in flow when the aneurysm was either perfused by blood or by saline⁶. There is hence a strong hydrodynamic effect of the coils themselves, an effect also proven by Gobin et Al.¹⁵ in silicone aneurysms. In the presence of blood, flow would be quantitatively reduced somewhat more, depending on the amount of anticoagulative medication administered. Boecher-Schwarz et Al.¹⁶ found fewer changes in flow in coiled *ex vivo* rabbit aneurysms when they were perfused with heparinized blood than when they were perfused with saline. The initial blood clot between the coil loops may dissolve after some days and may allow recirculation into the aneurysm. Unless infiltration of the coil mass with vascularized fibrous tissue and neointimal coverage of the aneurysm neck occur, the patency of aneurysm occlusion would then rely mostly on the hydrodynamic wave-breaker effect of the coil package. We therefore assume our aneurysm model as valid in comparing the immediate effects of coiling, especially when evaluating two different types of coil material. One could further assume the immediate changes induced by insertion of coils to be crucial for the long-term success of aneurysm occlusion. In the present study both GDCs and HES obtained such a good attenuation of flow that additional thrombosis hardly would have had a supplementary effect. Regarding long-term outcome, one could assume these aneurysms to most likely remain occluded. Although HES reduced flow slightly more than GDC, this difference would most likely be irrelevant in a clinical setting. In aneurysm 4, however, there was such an amount of persistent flow after coiling with GDC that later coil compaction could be feared even in the presence of thrombus formation. On the other hand, in all our aneurysms, there was some degree of neck remnants with both GDCs and HES (Figure 2). The site of flow and pressure measurement was at the dome of the aneurysm; i.e. even with abolished flow at the dome, a significant neck remnant may give rise to coil compaction. It is unknown whether the

neck remnants would have been identical or smaller if our aneurysms had been perfused by blood and not by saline.

The pressure/flow shift ϵ was more effectively prolonged after coiling with HES in all aneurysms, i.e. there was a larger dissociation of pressure and flow. This effect is most likely attributable to the different physical characteristics of the coils with hydrogel filling almost all available space in the aneurysm and thereby increasing the impedance. It is uncertain whether this finding by itself would have had any clinical impact on the durability of the aneurysm occlusion, particularly in light of the cast of hydrogel not providing a superior attenuation of pressure-waves. As was to be expected, the attenuation of sudden pressure waves was poorer in HES than in GDC. As the GDCs were both longer and had a smaller diameter, pressure attenuation should be more effective as it varies directly with length and inversely with diameter. In addition, the number of curvatures and bends along the coils can be assumed to be larger in GDC than in HES, which would also be positive for pressure attenuation. Despite the dense packing volume with HES, the intra-aneurysmal pressure remained unchanged. This concurs with the findings of Canton et Al.¹⁷ who found unchanged pressures in silicone aneurysms packed with HES up to 93% density. They also showed that there was no extrusion into the parent artery by the coils despite the large filling volume¹⁷. The present study adds the observation of unchanged intra-aneurysmal pressure even at theoretical filling volumes exceeding the volume of the aneurysm.

Conclusions

Intra-aneurysmal pressure remained unchanged after maximal packing of silicone aneurysms with either GDC or HES. Sudden increases in pressure were attenuated slightly less within the aneurysm after coiling with HES. Although HES obtained a much higher percentage filling volume in the aneurysms, GDC equivalently virtually abolished intra-aneurysmal flow apart from in one instance where there was significant persistent flow after coiling with GDC. The effects of HES in terms of pressure and flow attenuation within the aneurysm could hence not be proven superior to GDC.

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