STENT CONFIGURATIONS AND ITS EFFECTIVENESS IN RENAL ARTERY ANEURYSM

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by

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LIST OF SYMBOLS

D	characteristic length
Re_d	Reynolds number
ρ	Density of the fluid
v	Velocity of the fluid flow
p	Fluid pressure
μ	Apparent viscosity
μ_p	Viscosity of the suspending fluid
k_0 and k_∞	Model parameters
$\dot{\gamma}$	Shear rate
$\dot{\gamma}_c$	Critical shear rate
$\emptyset$	Volume concentration of the dispersed phase
u	Displacement of the structural body
b^s	Body forces subjected to the structure
S	Second Piola-Kirchhoff stress tensor
ρ^s	Density of the structure
F	Gradient tensor of deformation
I_1 and I_2	1st and 2nd strain invariants of the Cauchy-Green deformation tensor
C_{ij}, C_{10}, C_{01}, C_{11}, C_{20}, C_{02}	material constants for Mooney–Rivlin hyperelastic model
δ_{ij}	Kronecker delta
Δx	particles displacement
Δt	time interval between the two consecutive images
σ_u	standard deviation of velocity

LIST OF ABBREVIATIONS

3D	3-Dimensional
AAA	Abdominal aortic aneurysm
Bpm	Beat per minute
CAD	Computer aided design
CFD	Computational fluid dynamic
CNC	Computer numerical control
CSS	Computational solid stress
CT	Computer tomography
EVAR	Endovascular
FD	Flow diverter
Fps	Frame per second
FSI	Fluid–structure interaction
ICU	Intensive care unit
L1 and L2	Lumbar spinal disc 1 and 2
LBM	Lattice Boltzmann method
LED	Light emitting diode
MRI	Magnetic resonance imaging
PIV	Particle image velocimetry
RAA	Renal artery aneurysm
TAA	Thoracic aortic aneurysm
UDF	User–define function
WSS	Wall shear stress

KONFIGURASI STENT DAN KEBERKESANANNYA PADA ANEURISME ARTERI BUAH PINGGANG

ABSTRAK

Aneurisme arteri buah pinggang (RAA) adalah penyakit di mana arteri buah pinggang mengembang pada satu kawasan tertumpu. Endovaskular, sebuah rawatan aneurisma dengan memasukkan stent (atau penyonsang aliran (FD)) ke dalam arteri adalah antara pilihan terbaik hari ini. Dalam kajian hemodinamik, tumpuan kajian kepada RAA masih kurang berbanding dengan penyakit aneurisme yang lain. Di dalam tesis ini, simulasi FSI dan eksperimen PIV bagi RAA dengan pelbagai konfigurasi FD telah dilakukan untuk mengkaji keberkesanannya dalam merawat RAA. Corak aliran, tegasan ricih dinding (WSS), perubahan bentuk dan tekanan von Mises dianalisis. Konfigurasi FD terbahagi kepada dua: (1) keliangan yang berbeza (65% hingga 80%); (2) ketebalan yang berbeza (0.05 mm hingga 0.09 mm). Tambahan itu, model rheologi Quemada digunakan untuk mewakili sifat darah. Model ini mengambil kira segala faktor penting yang mempengaruhi kelikatan darah termasuk kadar rincihan, kelikatan plasma dan sel darah merah. Perbandingan antara data simulasi dan eksperimen PIV menunjukkan persamaan dengan purata perbezaan peratusan sekitar 5%. Peredaran darah di dalam aneurisma berkurang dengan drastik apabila FD diletakkan dalam model RAA. Pengurangan sekitar 90% untuk WSS dan 40% untuk perubahan bentuk apabila FD tidak hadir. Di samping itu, tekanan von Mises yang dialami oleh RAA adalah lebih besar apabila tiada FD di dalam RAA. Keduanya ialah perbandingan FD dengan ketebalan yang berlainan. Untuk corak aliran, FD dengan ketebalan 0.05 mm mempunyai peredaran darah di dalam kubah aneurisme. Selain itu, WSS yang dicatatkan adalah yang terbesar di antara ketiga-tiga kes tersebut. Selanjutnya, apabila ketebalan FD meningkat, tegasan maksimum von Mises mengalami penurunan.

Kesimpulannya, FD dengan peratusan keliangan sebanyak 65% adalah mencukupi untuk menghasilkan hasil yang diinginkan setanding dengan FD dengan peratusan keliangan yang lebih besar. Dari ketebalan FD, ketebalan stent minimum yang dicadangkan untuk mengelakkan daripada peredaran darah di dalam kantung aneurisme adalah 0.07 mm.

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ABSTRACT

Renal artery aneurysm (RAA) is a disease in which the renal artery is dilated at a particular point. Endovascular, a treatment for aneurysm by inserting a stent (or flow diverter (FD)) in the aneurysm effected artery is the preferable choice today. In the hemodynamic study, the focus on RAA study is still lacking compared to other aneurysm conditions. In this thesis, FSI simulations and PIV experimental work of RAA condition for different configurations of FD were conducted to study its effectiveness in treating RAA. Flow patterns, wall shear stress (WSS), deformation and von Mises stress parameters were analysed. The FD configurations were divided into two: (1) different porosity (65% to 80%); (2) different thickness (0.05 mm to 0.09 mm). In addition, Quemada rheological model was used to represent blood material properties. This material model considers all the important factor that affect the viscosity of the blood including shear rate, plasma viscosity and red blood cells. Comparison between simulations and PIV experimental data showed good agreement with average percentage difference around 5%. The blood circulation inside the aneurysm reduced drastically when FD placed in the RAA model. A reduction around 90% for WSS and 40% for deformation when FD was not presence. Additionally, von Mises stresses experienced by RAA was larger stress when no FD placed inside the RAA. Secondly was comparison of FD with different thicknesses. For the flow pattern, FD with thickness of 0.05 mm had blood circulation inside the aneurysm dome. additionally, the WSS recorded for it was the largest among all three cases. Furthermore, as the FD thickness increased, the maximum von Mises stress experienced decreases. In conclusion, FD with porosity percentage of 65% is sufficient

to produce the desired and comparable results as with FD with greater percentage porosity. In terms of the FD thickness, the suggested minimum FD thickness to prevent from having blood circulation inside the aneurysm sac is 0.07 mm.

CHAPTER 1

INTRODUCTION

1.1 Overview

Chapter one is an introduction to the thesis. The research background, problem statements, research objectives and research scopes are discussed here. In section 1.2, the thesis discussed the background of renal artery, aneurysm and renal artery aneurysm (RAA). In addition, this section also reviewed briefly the treatment of RAA and how RAA could be analysed through the lens of engineering. Section 1.3 explains about the problem statements, the issues that lead to the importance of conducting the research. In section 1.4, the objectives of the research were stated. Section 1.5 is the research scopes, explaining the scopes that were being covered in this study. To close the chapter one is the thesis outline that described the structure of this thesis.

1.2 Research Background

1.2.1 Renal artery

Renal arteries is the arteries that supply blood to the kidneys. Renal arteries also connected the abdominal aorta with the kidneys. Usually, these arteries are located at level L1 or L2 relative to the intervertebral disk. They are located below the mesenteric artery and enter the renal hila to supply blood to the kidneys. Figure 1. 1 shows the renal arteries branches from abdominal aorta to the kidneys

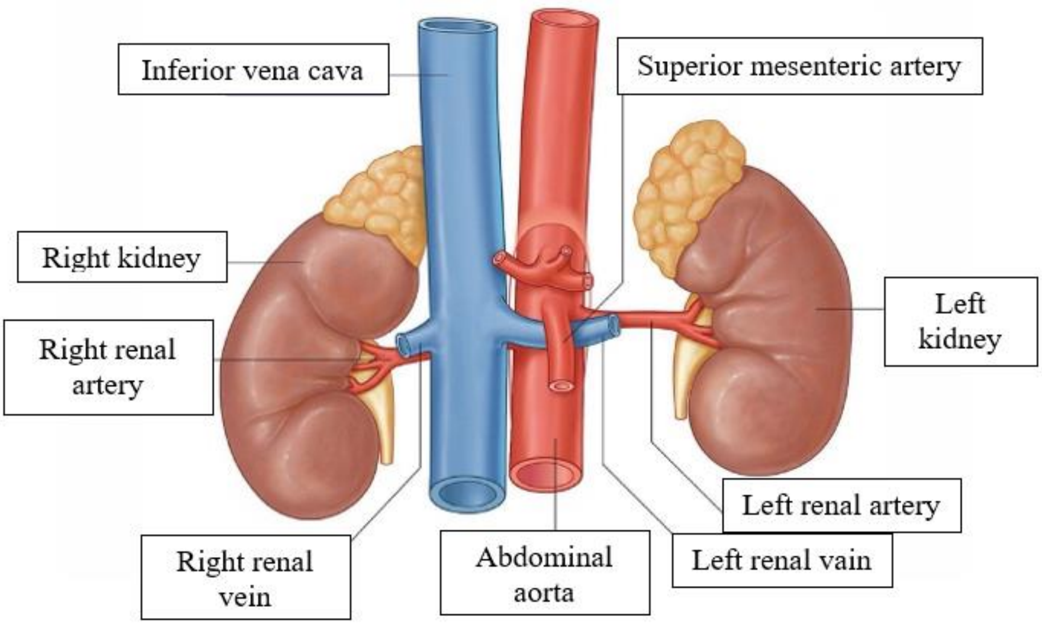
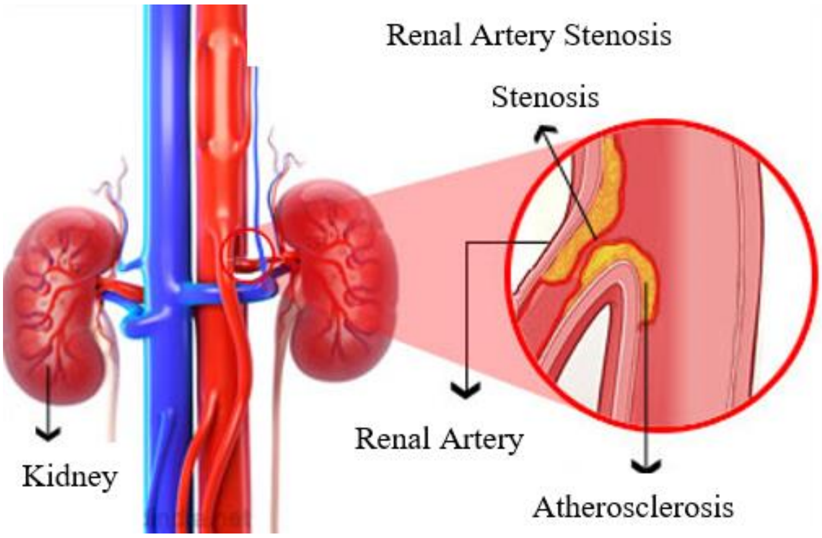


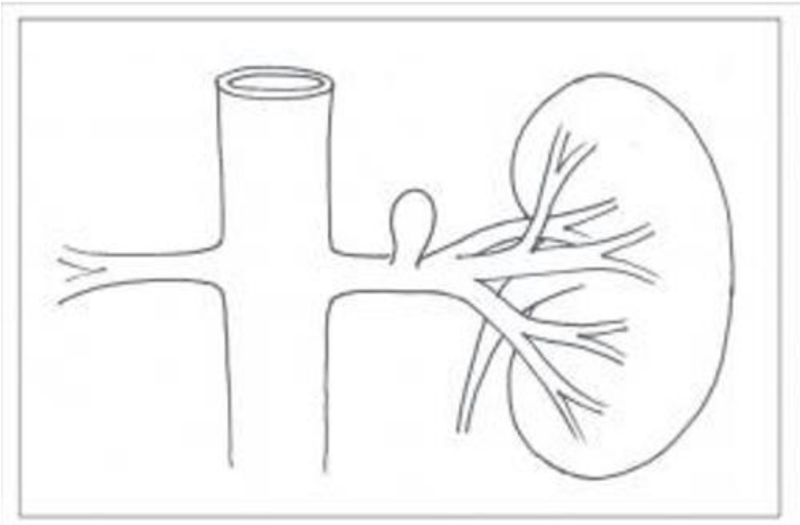
Figure 1. 1. Renal arteries configuration (X. Wang et al., 2011)

Typically, the left renal artery is shorter, more horizontally and arise slightly more than the right renal artery. On the other hand, the right renal artery located behind and passing through the vena cava and right renal vein to reach renal hilum. It is estimated that around 1200 ml/min blood flows through renal artery and both kidneys filter at least 115 litres of blood thus producing a minimum of 950 ml of urine (X. Wang et al., 2011). One of the importance of kidneys is to regulate blood volume and composition, blood pressure, pH level, and glucose level.

Among the diseases commonly related to renal artery are renal artery stenosis and renal artery aneurysm. Renal artery stenosis is the condition where there exist plaque build-up that obstructed the flow of the blood to the kidney. This will results in increased in blood pressure, which is also known as renovascular hypertension. Conversely, renal artery aneurysm (RAA) is the bulging of the renal artery wall due to the weakening of the muscle of artery. Figure 1. 2 (a) depicted the renal artery stenosis disease while Figure 1. 2 (b) depicted the renal artery aneurysm disease.



(a)



(b)

Figure 1. 2. (a) Renal artery stenosis disease (Tharu, 2015); (b) Renal artery aneurysm (RAA) (Gates et al., 2017)

1.2.2 Aneurysm

Aneurysm is a weakening of a localized region of the arterial vessel wall that causes a bulge. The increase in size of the bulge usually more than half of the diameter of the arterial vessel. There are three types of aneurysm, namely: (1) fusiform; (2) saccular; (3) pseudoaneurysm. Fusiform aneurysm is the expansion of the arterial vessel on both side of the arterial wall. Saccular aneurysm on the other hand is the bulging on only one side of the arterial wall. Saccular aneurysm is also known as 'berry' aneurysm. Pseudoaneurysm is a false aneurysm that occurs commonly due to trauma. It happens when there is a tear inside of the vessel, causing the blood to fill in the layer in between the blood vessel. Figure 1. 3 exhibits the three forms of aneurysm that could occurs.

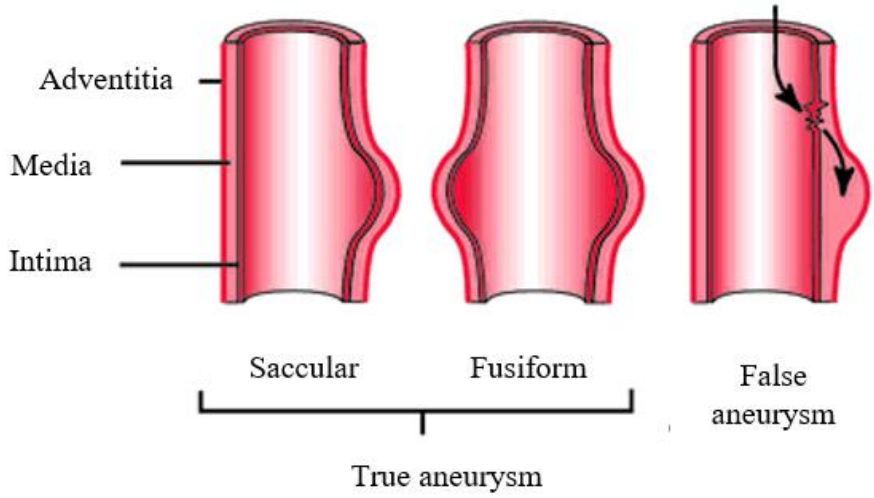


Figure 1. 3. Types of aneurysm: saccular, fusiform and pseudoaneurysm/false abeurysm. ("false aneurysm.," 2003)

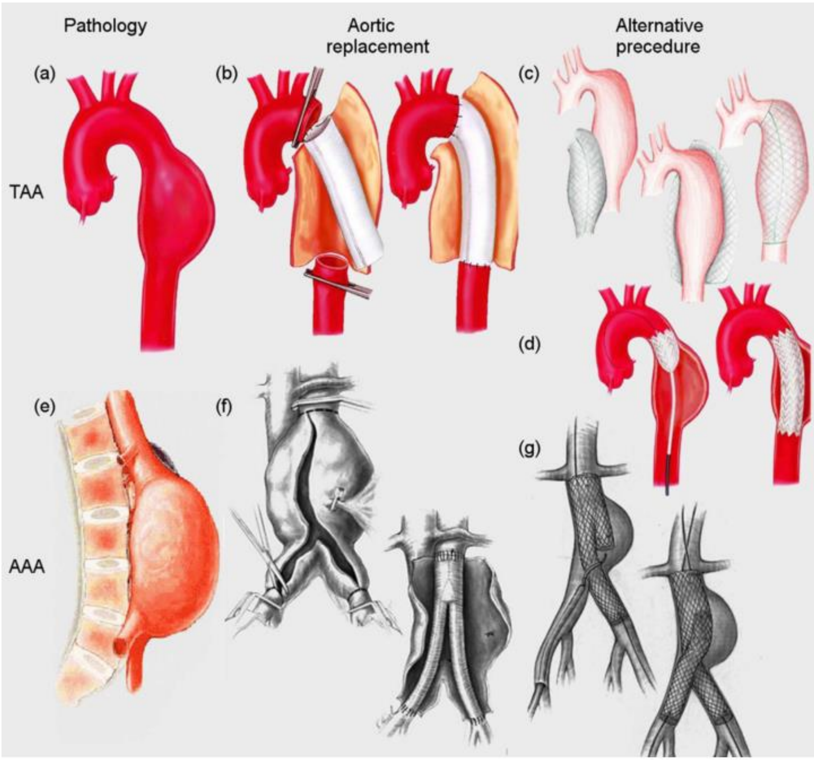
Aneurysm can occurs at several locations. Usually, the aneurysm will be named based on the location where it take place. Abdominal aortic aneurysm (AAA) happens in the aorta vessel. AAA is one of the common aneurysm condition and it usually occurs in abdominal region of the aorta. Thoracic aortic aneurysm (TAA) is the aneurysm that occurs in the chest portion of the aorta vessel. Cerebral aneurysm happens in the vessel of the brain. Generally, cerebral aneurysm ruptures could lead to stroke or worst, death. Renal artery aneurysm is a dilated renal artery wall that exceed 50% of the normal diameter. The patients suffering from RAA can either have symptoms or no symptom at all. Up until today, there are limited study on RAA compared to other aneurysm conditions mentioned previously.

1.2.3 Renal artery aneurysm (RAA)

As mentioned in the previous sub-section, renal artery aneurysm or RAA is a localized, blood-filled balloon-like segment in the wall of the renal artery that expand twice the size of the vessel diameter. RAA occurrence is not as common as any other aneurysm conditions. It is usually found unintentionally when performing MRI to investigate other condition. It is estimated that the prevalence of RAA is only 0.01% (Barros et al., 2014). However, in a study of RAA ruptured during pregnancy, Soliman et al. (2006) stated that the RAA condition has been detected more frequently in recent years because of the frequent use of angiography technology.

1.2.4 Treatment of RAA

There are two types of treatment for RAA patients namely surgery and endovascular treatments (EVAR). Figure 1. 4 (a) shows the surgical treatment for aneurysm condition located in aortic of thoracic artery. Another examples of open surgery is the aneurysm clipping. EVAR treatments includes insertion of stent-graft, coil-embolization and stent-assisted coil embolization. The current treatment intervention is when the size of the bulge is larger than 2 cm. Patient with symptom such as hypertension is also required to undergo treatment as well. The EVAR procedure is the preferable option today compared to conventional surgery. EVAR treatment is done by inserting either a mesh-like tube called stent or coils from the femoral artery to the desired location that is effected by aneurysm. The stent is carried by a guiding tube or catheter. For aneurysm with narrow neck opening, coil embolization technique is the preferable choice. However, for a large neck opening, also known as wide-neck aneurysm, stent or flow modulator/diverter is the suitable selection. Figure 1. 4 (b) depicts the insertion of flow diverter in RAA. The intervention is crucial because of the devastating outcomes that could occurred if the aneurysm ruptures. The most devastating outcome of RAA rupture is mortality especially for women in pregnancy period (Sherif Sultan et al., 2016). Another possible consequences are kidney failure and hemorrhage. Hemorrhage is the escape of the blood from the vessel causing the internal bleeding (Figure 1. 5).



(a)

Figure 1. 4. (a) Example of surgical treatment in TAA and AAA (a, b, c, e, f) and EVAR treatment (d,g)(Farotto et al., 2018); (b) The insertion of FD in renal artery (Sherif Sultan, Basuoniy Alawy, et al., 2016)

(b)

Figure 1. 4. (a) Example of surgical treatment in TAA and AAA (a, b, c, e, f) and EVAR treatment (d, g) (Farotto et al., 2018); (b) The insertion of FD in renal artery aneurysm (Sherif Sultan, Basuoniy Alawy, et al., 2016) (cont.)

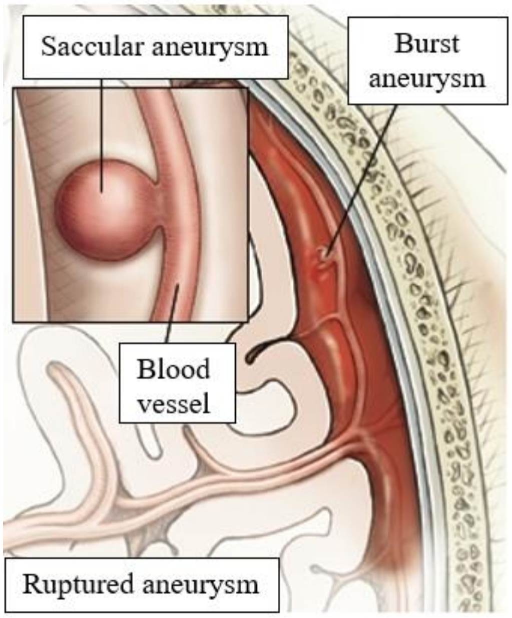


Figure 1. 5. Depiction of ruptured aneurysm that caused hemorrhage ("Subarachnoid Hemorrhage," 2018)

1.2.5 Engineering approach in RAA analysis

The current advancement in engineering can be translated with the advancement in the medical devices available today. In the treatment of aneurysm, devices such as coil embolization and stents have made a great impact in treating the disease. The progression in computational fluid dynamic (CFD) for instance, has increased our understanding of the aneurysm pathology. Characteristics such as stresses, wall shear and the blood flow patterns are important parameters in the study of aneurysm from engineering perspective. The significance of engineering approach in the study of aneurysm and renal artery aneurysm specifically will result in providing a proper solution to treat RAA effectively.

1.3 Problem Statement

The study of RAA is still lacking in comparison with other aneurysm conditions. It is said that RAA only happens about 0.1% of the general population of the world (Coleman et al., 2015). This low incidence rate may be a factor contributes to the lack of research of this disease. Although RAA incidence rate is not as significant as other RAA conditions, the effect of the aneurysm ruptures is as devastating as other aneurysm conditions.

It is noteworthy to mention that due to small dimension of renal artery as compared to other artery such as abdominal aorta could produce different flow circumstance which in turn would yield different effects if an aneurysm is presence in that artery. For instance, the abdominal aortic aneurysm size which requires proper intervention is at a size of 8.0 cm and above in diameter. In contrast, the intervention for RAA is needed when the aneurysm size reached a diameter greater than 2 cm (which is debatable) or patients with hypertension symptom. On this premises, a separate study regarding RAA is desired.

In addition, the lack of FSI study in RAA is also a major motivation for this thesis. The conventional FSI analysis in the study of RAA is incapable to formulate the exact viscosity of the blood. Most existing models only cosiders the shear rate factor when trying to model the blood viscosity. This will neglect the haematorcit factor in influencing the viscosity of the blood. The hyperleastic behaviour of the artery, shear rate–dependent viscosity of the blood are among the factors that FSI study is lack too.

1.4 Research Objectives

The objectives of this research are as follow:

- To study the flow pattern in the idealized, wide-neck, saccular renal artery aneurysm
    - Validate the FSI simulations with PIV experiment
- To determine the efficiency of flow diverter by changing its porosity and thickness

1.5 Research Scope

The research scopes consist of three elements, the design, simulations and experiments. Design elements is the creation of RAA model and FD to be used in the simulations and experiments parts. Due to the unavailability of CT data, the RAA model will be an idealized model based on a case study by Bracale et al. (2017) on a wide-neck renal artery aneurysm. There are two parameters that are vary when designing the FD, which are porosity percentage and thickness. For the porosity percentage, four FD with porosity percentage 65%, 70%, 75% and 80% are constructed. For the thickness parameter, three FD with thickness 0.05 mm, 0.07 mm