Journal of Orthopaedic Translation 24 (2020) 144–149

Contents lists available at ScienceDirect

Journal of Orthopaedic Translation

journal homepage: www.journals.elsevier.com/journal-of-orthopaedic-translation

Original Article

Biomechanical comparison of four tibial fixation techniques for meniscal root sutures in posterior medial meniscus root repair: A porcine study

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A R T I C L E I N F O

Keywords:
Meniscus–suture interface
Posterior medial meniscus root repair
Transtibial pull-out fixation

A B S T R A C T

Objective: This study hypothesized that the suture anchor of tibial fixation method of PMMR repair technique is the main factor which reduce the gap formation or over displacement of tear site in initial healing, and then investigated the fixation stability of 4 different tibial fixations through cyclic and ultimate failure load testing of meniscal root sutures.

Methods: Twenty-four porcine tibiae with intact medial meniscus roots were randomly assigned into 4 groups: transosseous suture, washer, suture anchor, or screw with washer. Each sample underwent cyclic loading followed by a load-to-failure test. Displacement, maximum load to failure, stiffness, and elongation at failure load were recorded.

Results: The maximum average load and displacement at failure for each of the repair groups were as follows: transosseous suture, 232.8 N and 12.16 mm; washer, 189.9 N and 21.5 mm; suture anchor, 140.6 N and 13.8 mm; and screw with washer, 167.9 N and 18.9 mm. The maximum stiffness values for each of the repair groups were as follows: transosseous suture, 19.5 $\pm$ 0.7 N/mm; washer, 21.5 $\pm$ 1.4 N/mm; suture anchor, 13.8 $\pm$ 0.7 N/mm; and screw with washer, 18.9 $\pm$ 3.9 N/mm. The mean elongation across the repairs for each of the repair groups after 1000 loading cycles was: transosseous suture, 3.74 $\pm$ 0.28 mm; washer, 3.04 $\pm$ 0.13 mm; suture anchor, 2.25 $\pm$ 0.33 mm; and screw with washer, 2.43 $\pm$ 0.19 mm. The mean elongation was significantly less with the suture anchor than with the other techniques ($p < .05$).

Conclusion: Under physiological loading, our results indicate that a slower rehabilitation program with limited flexion and only partial weight bearing is advised when using a suture anchor because of the lower maximum load and stiffness.

The translational potential of this article: Tibial fixation using a washer or a screw with a washer is an effective and cost-saving technique when an option is required with high stiffness and low displacement at failure.

Introduction

Radial tears of the posterior medial meniscus root (PMMR) are clinically common and are defined as those located within 10 mm of the posterior root attachment site of the meniscus. The incidence of tears in the medial meniscus is almost four times higher than that in the lateral meniscus, and up to 30% of medial meniscus tears appeared to be PMMR tears in one study [1]. Possible causes of PMMR tears include being forced into a deep squat among older adults or experiencing trauma among younger people [2].

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https://doi.org/10.1016/j.jot.2020.01.006
Received 16 September 2019; Received in revised form 15 January 2020; Accepted 20 January 2020
Available online 17 February 2020

PMMR tears can alter the biomechanics and kinematics of the knee joint, which may accelerate joint degeneration [3–5]. Although the appropriate treatment for PMMR tears remains controversial, most surgeons use operative management in active healthy individuals with minimal osteoarthritic change [6–8]. An effective fixation technique should provide sufficient tensile strength and resistance to gap formation to improve healing. The various techniques for repair of PMMR tears involve suturing around the root tear area, after which the sutures are pulled out and fixed on the medial tibial cortex [3,9–14]. Transtibial pull-out fixation is the most common technique, with recent short-term and medium-term follow-up results indicating favourable outcomes among patients with PMMR tears [8,13,15]. Furthermore, studies have found that poor prognostic factors after PMMR tears repair are modified outerbridge classification grade ≥3, chondral lesions, varus alignment >5°, older age, female sex, high BMI and medial meniscus extrusion [8, 16]. To improve the poor prognosis of PMMR tears repair, studies on transtibial pull-out fixation have focused on the meniscus–suture interface using different fixation techniques, such as the modified Mason–Allen technique or two simple sutures [17,18]. However, to date, few studies have examined tibial fixation methods in PMMR repair. We hypothesised that the suture anchor of the tibial fixation method of the PMMR repair technique is the main factor that reduces the gap formation or over displacement of tear site in initial healing. The present study investigated the fixation stability of four different tibial fixations through cyclic and ultimate failure load testing of meniscal root sutures.

Materials and methods

A total of 24 porcine tibiae with intact medial meniscus root were used and randomly assigned to four groups (6 specimens each). Fresh porcine hind limbs from adult hybrid Landrace–Yorkshire–Duroc pigs were obtained immediately after death from a local slaughterhouse; ethical approval was not sought for the present study. The mean age of the animals was 28–30 weeks, and the average weight was 130 kg. The skin and all muscles were removed. The femur site was removed after cutting the connecting ligaments and soft tissue, and the tibia site was left intact. The tibia was truncated approximately 15 cm below the joint line. Subsequently, a careful examination of all the experimental knees was performed to exclude the specimens that had poor quality medial meniscus roots. A 5-mm longitudinal incision was made through the red-red zone of the posterior medial meniscus with around 5 mm from the root tear site using a no. 15 blade scalpel.

The modified Mason–Allen suture technique using no. 2 sutures (FiberWire, Arthrex, FL, USA) was applied for all PMMR repairs, and different tibial fixations for root sutures were tested accordingly. The sutures were then positioned through a 5-mm diameter bone tunnel [19] and fixed to the anterolateral aspect of the tibia using a (a) transosseous suture, (b) washer, (c) suture anchor (PopLok Knotless Suture Anchors, 4.5 mm, ConMed Linvatec, Largo, FL, USA) or (d) screw with washer, respectively (Fig. 1). For the transosseous group, a transverse bone tunnel was drilled using 2.5 mm drill bit from medial to lateral cortex. Each end of the two sutures was shuttled through the bone tunnel and then tied on the lateral cortex to avoid knot irritation. For the screw with a washer group (4.5 × 40 mm screw and 13.0 mm diameter washer, Synthes GmbH, Solothurn, Switzerland) and washer (13.0 mm diameter) group, all the sutures were pulled out from the bone tunnel and then tied on the alternating post device using 5 half-hitches in the anterolateral cortex. For the suture anchor group, a 4.5-mm guide pin was punched into the anterolateral tibial cortex 1 cm distal to the bone tunnel. Two of the four free ends of the meniscal sutures were then passed through either eyelet of the suture anchor and tension was adjusted under knee arthroscopy to avoid the meniscus being cut by the tightening suture.

All tests were performed at room temperature (25 ± 1 °C), and the specimens were kept moist with saline solution. A material testing system (MTS Bionix 858, Eden Prairie, MN, USA) with a custom-made clamping device was employed for tensile testing. The clamping device was rigidly

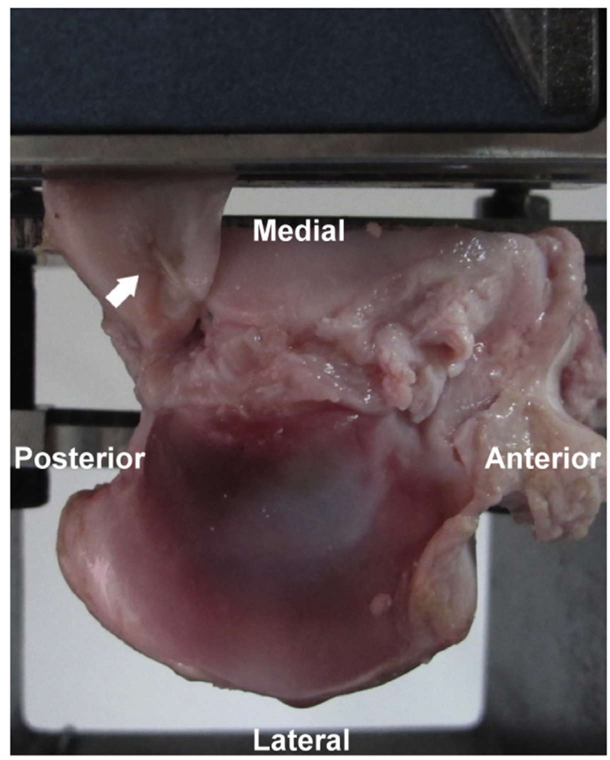

Figure 2. Biomechanical test setup. The clamp was equipped with corrugated jaw faces to prevent meniscus slippage, and the menisci were clamped medial to the sutures or grafts. The arrow indicates the modified Mason–Allen suture repair.

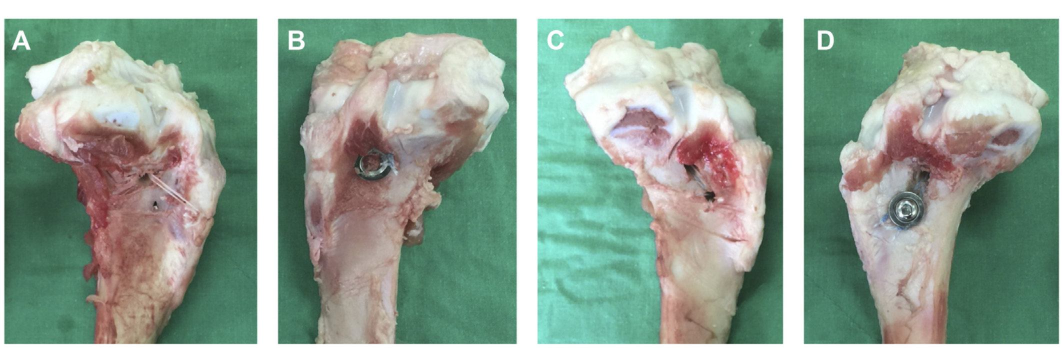

Figure 1. Illustration of the transtibial pull-out meniscal root repair technique for repair of the medial meniscus posterior root (PMMR) using a A) transosseous suture, B) washer, C) suture anchor (PopLok, ConMed Linvatec, Largo, FL, USA) and D) screw with washer on the anteromedial tibia, respectively.

mounted to the plate of the material testing machine, and the peripheral section of the medial meniscus using no. 2 sutures (Ethibond, Ethicon, Somerville, NJ, USA) with a whipstitch that promoted uniform load across each limb during testing was placed in a mechanical screw-action clamp. To prevent meniscus slippage, the clamp was equipped with corrugated jaw faces. To avoid interference with the stiffness analysis, the menisci were clamped 1 cm medial to the sutures of the meniscus (Fig. 2). After a preload of 2 N, all specimens were subjected to 1000 cycles of a load between 2 N and 20 N at a rate of 0.5 Hz. Table 1 details the displacement of four groups after cyclic load. Subsequently, the specimens were loaded to failure at a rate of 0.5 mm/s [19]. The failure of specimens was determined by either rupture or pullout of the suture, and the load was defined as the failure load. The number of cycles and the amounts of displacement and load were recorded by the software of the MTS system. The following parameters were analysed in all tests: (1) the displacement after 100, 500 and 1000 cycles and (2) the maximum load, stiffness and elongation at the failure load. Displacement was defined as the difference in the crosshead position from the peak of the first cycle to the peak of cycles 100, 500 and 1000. The stiffness was calculated as the steepest slope of the load–deformation curve spanning 30% of the data points collected between load initiation and the maximum load at failure. The elongation was measured as the total displacement of the sutures at maximum failure load. Additionally, the mode of failure was determined by visual inspection.

A Kruskal–Wallis test was used to test the group differences. The level of significance was set at $p < 0.05$. A *post hoc* power analysis was performed (alpha = 0.05, power = 0.80) and statistical analysis was also completed. All statistical analysis was conducted using SPSS software version 20.0 (IBM, Armonk, NY, USA).

Results

Table 1 shows that the suture anchor group had the lowest displacement values at different cycle points. The mean displacement after 1000 cycles for the suture anchor group versus the transosseous suture (*post hoc* power analysis = 100%), washer (*post hoc* power analysis = 100%) and screw with washer groups (*post hoc* power analysis = 21.1%) was calculated (all $p < 0.05$). The displacements of the four groups at 100, 500 and 1000 cycles were statistically different ($p < 0.01$).

Table 2 depicts that the results of the four groups showed that the suture anchor group had significantly lower maximum load and stiffness ($p < 0.01$). The maximum load for the suture anchor group versus the transosseous suture (*post hoc* power analysis = 100%), washer (*post hoc* power analysis = 100%) and screw with washer groups (*post hoc* power analysis = 79.3%) was calculated (all $p < 0.05$). The stiffness for the suture anchor group versus the transosseous suture (*post hoc* power analysis = 100%), washer (*post hoc* power analysis = 100%) and screw with washer groups (*post hoc* power analysis = 96.2%) was calculated (all $p < 0.05$).

For the four groups, all specimens were failed by sutures cutting through the meniscus along the sharp end of the incision site near the PMMR tears except for the suture anchor group (Figs. 3 and 4); the failure mode of each group is shown in Table 2. Suture loosening was noted in both the transosseous suture and suture anchor groups (Fig. 3a and c). In addition, there is no sample slipped during the test.

Table 1
Displacement during cyclic loading.

Group	Displacement (mm)		
	After 100 cycles	After 500 cycles	After 1000 cycles
Transosseous suture	2.12 ± 0.28	3.44 ± 0.24	3.74 ± 0.28
Washer	1.70 ± 0.02	2.62 ± 0.08	3.04 ± 0.13
Suture anchor	1.45 ± 0.34[a]	2.00 ± 0.30[a]	2.25 ± 0.33[a]
Screw with washer	1.56 ± 0.13	2.12 ± 0.16	2.43 ± 0.19

Note: data are presented as mean ± standard deviation.
[a] Significant differences between the four groups ($p < 0.05$).

Table 2
Maximum load, stiffness and elongation at failure load.

Group	Max. load (N)	Stiffness (N/mm)	Displacement at failure (mm)	Failure mode
Transosseous suture	232.8 ± 14.86	19.5 ± 0.66	12.16 ± 0.51	Sutures cutting
Washer	189.9 ± 17.45	21.5 ± 1.44	10.64 ± 2.20	Sutures cutting
Suture anchor	140.6 ± 7.98[a]	13.8 ± 0.69[a]	12.14 ± 1.23	Suture loosening
Screw with washer	167.9 ± 22.69	18.9 ± 3.92	9.29 ± 1.05[a]	Sutures cutting

Note: data are presented as mean ± standard deviation.
[a] Significant differences between the four groups ($p < 0.05$).

Discussion

There is no current consensus on PMMRT tibial fixation techniques. Different tibial fixation techniques such as those using a Hewson button [20], screw and washer [21] (post-tie technique using cortical screws), transosseous suture [9], 4.75-mm sliding knot and Bio-Composite SwiveLock anchor (Arthrex) [8,13] have been applied in PMMRT repair [22]. However, implant choice in tibial fixation in the literature has been based on surgeons' preferences, with no specific focus on fixation methods. In our study, we chose a knotless suture anchor PopLok for tibial fixation because of the difficulties in performing transosseous suture in the flat medial tibial cortex, of the fact that no skin irritation is caused by metal implants, there is no need for implant removal in the future and tension is adjustable intraoperatively. A guide pin enables the whole construct to be pushed into the dilated hole without resistance using the same axis to further avoid implant breakage. The PopLok Knotless Suture Anchors feature a suture-locking mechanism that traps the suture within the anchor for dependable fixation. They also place tension on the suture after the anchor is seated in the pilot hole.

Under cyclic load testing, the suture anchor exhibited the lowest displacement compared with the other techniques. The suture anchor group used for stabilisation is available double loaded with two sutures, allowing for more points of soft-tissue fixation with a single anchor, which means that surgeons can control anchor tension in root repairs. Compared with the suture anchor group, the other three fixation techniques had difficulty in achieving appropriate meniscus tension; thus, the suture anchor was able to reduce the occurrence of gap formation in the repair site during cycle loadings compared with the other three techniques. Moreover, this knotless suture anchor has the following advantages as compared to the other three techniques: (1) no metal implant retention and no need for implant removal; (2) decreased knot-induced skin irritation and (3) tension for suture fixation can be controlled under intraoperative knee arthroscopy.

Displacement for the suture anchor and screw with washer groups was less than 3 mm after all the cycles were tested. Previous studies have suggested that suture failure may occur once gap formation surpasses 3 mm [8,15,23–26], noted that gap formation could adversely affect meniscal repairs as it does in tendon repairs, which is why it is critical to minimise displacement or motion during the healing process. In this study, the transosseous suture group exhibited the largest displacement of all the tested groups under cycle loading. It exhibited greater than 3 mm of displacement after 500 and 1000 cycles of loading were tested. The reason for this loosening might be the difficulties of tightening up the tie on the tibial cortex or gradual loosening of the suture tie.

Poor prognosis is in part despite the superior repair efficacy of arthroscopic pull-out repair (transosseous suture). Moon et al. [8] reported that extrusion of the meniscus was found to have progression after arthroscopic pull-out repair after a mean follow-up of 33 months. The

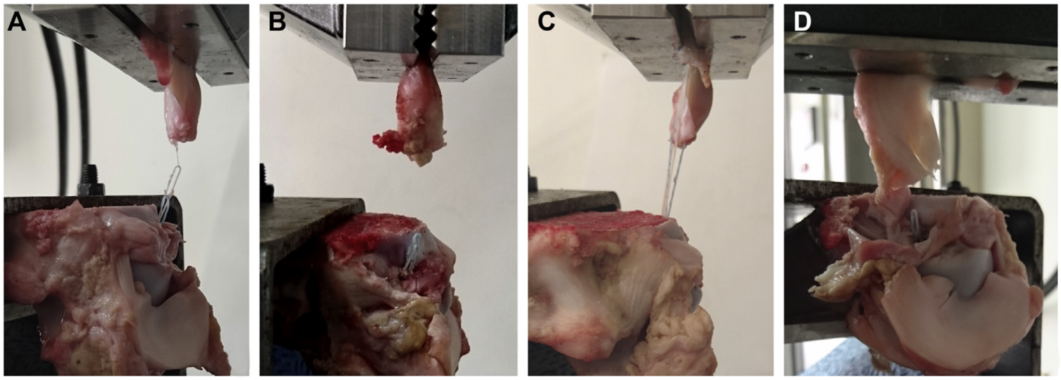

Figure 3. Failure modes of the A) transosseous suture, B) washer, C) suture anchor (PopLok, ConMed Linvatec, Largo, FL, USA and D) screw with washer groups.

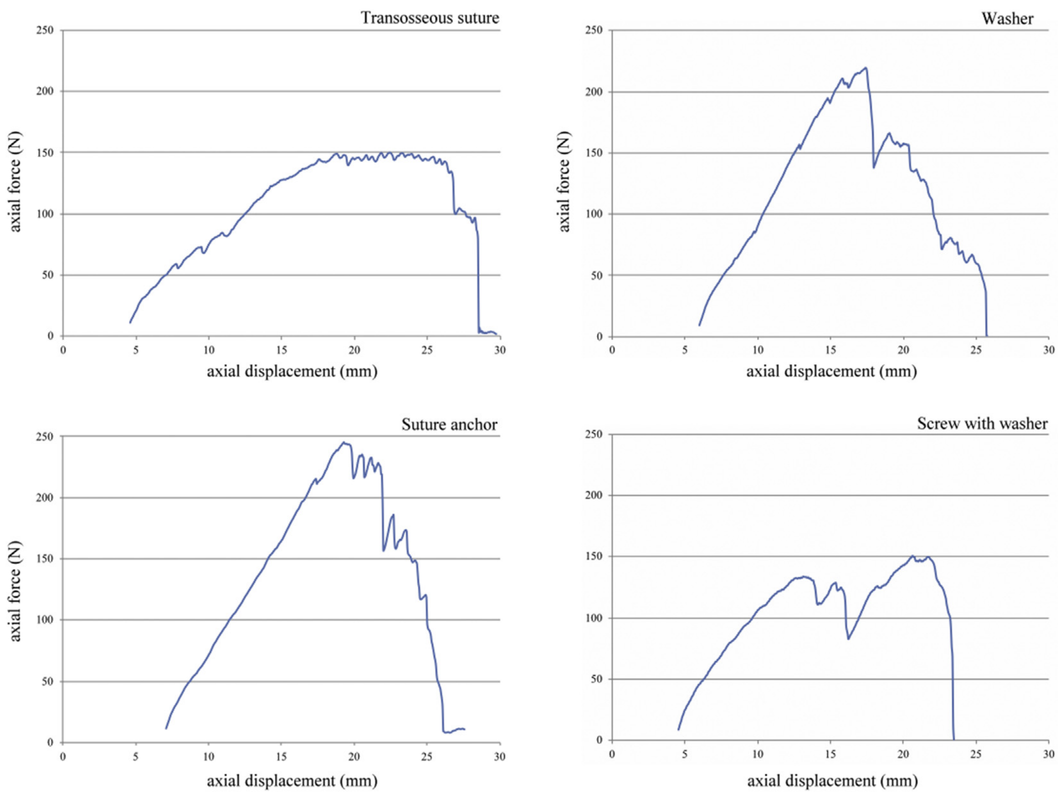

Figure 4. Axial force and displacement curve of four groups.

follow-up study of Seo et al. [16] showed similarly inferior results (no healing and progressed extrusion) after arthroscopic pull-out repair for PMMRT. These clinical results indicated that gap formation or over displacement in initial healing may be a factor in poor prognosis. A stiffer and simpler repair technique must be considered.

In the present study, the screw with washer group exhibited the least displacement, whereas the suture anchor group exhibited significantly lower stiffness and lower maximum failure load when compared with the other groups during the load-to-failure test. In addition, the failure mode of suture anchor fixation was suture slippage (i.e., suture loosening prior to the meniscus being cut by the suture) from the implant in the load-to-failure test. By contrast, the others were a result of suture–meniscus interface failure (Fig. 3c). Our results were similar to those of Feucht's *in vitro* porcine model study [19], which showed that the suture anchor repair technique did not reach the strength of the native PMMR. However, no suture slippage occurred in the suture anchor group in Feucht's study. That is a notable difference between the two studies. The PopLok device was designed to achieve a press-fit within the bone, and the ribs of the anchor increase frictional resistance to pull-out; this type of anchor may not perform as well as a screw-in anchor in osteoporotic bone, and the suture-retention strength relies heavily on a tight interference fit of the suture between the anchor and surrounding bone. Regarding insertion techniques, traditional suture anchors such as corkscrews are screwed into the bone directly without predrilling or tapping; however, PopLok insertion requires predrilling and punching. Predrilling and punching may decrease the interference strength between the anchor and surrounding bone, further reducing the suture-retention strength and increasing the risks of suture slippage. Wieser et al. [27] indicated that the use of knotless suture anchors appears to be a quick and easy method for performing rotator cuff repair; however, anchor systems cannot even reach half of the anchor pull-out strength from bone before suture slippage occurs. In another biomechanical study for rotator cuff repair, Klinge et al. [28] indicated that a press-fit anchor was prone to slippage failure, whereas an improved internal suture-locking mechanism for knotless suture anchors exhibited minimal slippage. In our study, suture slippage of press-fit PopLok installations was the primary failure mechanism in PMMR tears repair. However, different suture-retention mechanisms in knotless suture anchors used for PMMR tears repair were not assessed in this study. The effect of suture-retention mechanisms for PMMR tears requires further evaluation.

In a human cadaver study, Stärke et al. [29] recorded the tensile forces acting on repaired medial meniscal root lesions under a partial weight-bearing condition, which showed that the tension at the meniscal root area was related to the femorotibial load ($p < 0.001$). Compared with the highest root tension (60.1 ± 20.2 N) in the study of Starke [29], our results of maximum load indicate that all four repair techniques could offer sufficient strength for PMMR tear patients.

As a biomechanical experiment, this study did not evaluate healing of PMMR tears and no inferences can be drawn on potential outcomes or clinical performance. The mechanical differences in the four techniques were only observed, which was a limitation inherent to the study design. Another limitation of this study was its time-zero *in vitro* design. The main difference between this study and actual clinical situations was the use of a porcine knee model. Because human knees are generally difficult to obtain for practicing new techniques, an animal model was adopted to compare the initial mechanical characteristics of the four techniques in this study. Porcine knee models are often used to evaluate the mechanical characteristics of human knees due to their similarities in size, shape and bone quality as well as the consistency of tissue quality [29–33].

Conclusion

Tibial fixation using a washer or screw with washer is an effective and cost-saving technique when seeking an option with high stiffness and low displacement at failure. Under physiological loading conditions, the PopLok knotless suture anchor is an alternative for PMMR tears fixation.

Author contributions

Shen-Han Wu, Tsu-Te Yeh, Wei-Chun Hsu, Alexander TH Wu, Jia-Lin Wu contributed to the active discussion of experimental design, the performing of porcine study, wrote part of the content of this manuscript. Guoan Li, Chian-Her Lee, Chih-Hwa Chen contributed to critically revising the manuscript. Shen-Han Wu, Jia-Lin Wu contributed to drafting, critically revising the manuscript. All authors have read, approved the final submitted manuscript.

Acknowledgements

This study was supported by grants from the support by Taipei Medical University and National Taiwan University of Science and Technology through project no. 107-TMU-NTUST-107-08.

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