Biologic Orthopedic Journal

Original Article
DOI: 10.22374/boj.v3iSP1.39

OSTEONECROSIS OF THE FEMORAL HEAD: VASCULARISED AND NON-VASCULARISED GRAFTING TECHNIQUES

Mark Andrew Sohatee[1], Ajay Malviya[2]

[1]Sheffield Children's NHS Foundation Trust, Department of Trauma and Orthopaedics, Sheffield, England, UK
[2]Northumbria NHS Foundation Trust, Department of Trauma and Orthopaedics, Newcastle Upon Tyne, UK

Author for correspondence: Mark Andrew Sohatee: mark.sohatee@nhs.net

Submitted: 1 March 2022. Accepted: 7 July 2022. Published: 5 February 2023

Abstract

Avascular necrosis when occurring as osteonecrosis of the femoral head poses a challenge for hip surgeons due to the risk of collapse of the articular cartilage. The pathological process and its various stages have been classified using a number of systems to aid with diagnostic decision making and employing a variety of methods of operative intervention for appropriate indications. When there is such a plethora of management options, it highlights that there is no one "excellent" option for management of the condition. Having undertaken a scoping review, the authors conclude that surgical decision-making, based on the options available, should be tailored to patient factors (aetiology, age, collapse, etc.) and surgical skills set (microvascular surgery, pedicle grafting versus non-vascularised versus synthetic grafting). There are different hip preservation techniques in the literature with different success rates, however, from the current data available, it can be observed that vascularised techniques result in a lesser rate of conversion to arthroplasty but require greater time and technical abilities in microsurgery than non-vascularised techniques.

Keywords: *avascular necrosis*; *core decompression*; *hip*; *necrosis*; *vascularised grafting*

INTRODUCTION

Avascular necrosis (AVN) when occurring as osteonecrosis of the femoral head (ONFH) poses a challenge for hip surgeons due to the risk of collapse of the articular cartilage.

A number of classification systems have been devised to grade ONFH, related to the degree of collapse, including Ficat and Arlet,[1] Marcus and Enneking,[2] Steinberg,[3] ARCO,[4] Kerboul[5] and JIC.[6]

Management options are often based on the grade of disease and its associated subchondral collapse.

Broadly speaking, management strategies can be considered in terms of non-operative and operative modalities, with operative management being further subclassified as joint preserving or joint replacing.

Joint preserving treatment options are focused on a number of different goals, which include prevention of or further progression of subchondral collapse, structural support and restoration of blood supply to the femoral head. This article concentrates on grafting techniques and procedures, which are intended to achieve such outcomes.

Depending on the nature of the graft used, they are intended to reinstate a blood supply to the proximal femur and/or provide structural support. For this reason, they can be considered in the following way.

Whilst hip replacement is associated with good outcomes in greater than 90% of patients at 10 years,[7] it has been shown that revision for any cause in arthroplasty for AVN is more common than in osteoarthritis.[8] Furthermore, for younger patients, joint preservation may prevent the need for subsequent “revision” arthroplasty procedures later in life by deferring or ameliorating the need for an initial arthroplasty.

With this in mind, the authors feel it important to consider the role of such grafting techniques in the context of whether or not they are associated with favourable conversion rates to arthroplasty and whether such joint preserving grafting procedures are associated with good function and patient-reported outcomes. Furthermore, the authors look to compare and contrast these techniques with respect to these outcomes, to ascertain whether one technique may be more favourable than another.

METHODS

A scoping review was conducted looking into the joint preserving grafting techniques and surgical strategies utilised. This involved review of manuscripts from AMED, BNI, CINAHL, EMBASE, EMCARE, HMIC, Medline, PsycINFO and PubMed (via HDAS database), along with Google Scholar. Additional references were found via cross referencing.

Search terms included: Hip and Necrosis combined with grafting, “vascularised OR vascularized,” “non-vascularised OR non-vascularized,” “pedicle,” “Phemister,” “lightbulb,” “trapdoor,” or “Porous” and “Rod.”

Only studies including aseptic, predominantly atraumatic, ONFH were included. Some studies included overlap with femoral neck fractures; however, studies focusing solely at femoral neck fracture were not included. Articles incorporated, included fundamental science articles, prospective and retrospective clinical research. Systematic reviews and meta-analyses were not included.

Statistical analysis was undertaken on Minitab©. Chi-squared test was used to analyse categorical variables.

RESULTS

A number of studies were identified using the above search strategies and have been categorised as per the groupings described above.

Bone Grafting

Because bone grafting was first described in 1668 by Van Meekeren,[9] where a canine skull was grafted into the defective bone of a human soldier, the technique of bone grafting has continued to be used to treat bony defects, or facilitate healing of bones.

The means in which bone graft can be used to manage these pathologies are related to three specific physiological functions,[10] namely, osteoinduction, osteoconduction and osteogenesis. Of these three mechanisms, the one that is of particular relevance in ONFH is osteoconduction, whereby the bone graft acts as a structural scaffold. Given that the subchondral bone, within the femoral head, may undergo increasing levels of collapse with worsening stages of the pathology, this structural support may be important when considering hip joint preservation.

The use of bone graft as a treatment for ONFH can be subclassified based on the vascularity of the graft and the type of bone used or based on the technique used for insertion. At the broadest level, this bone graft can be considered either vascularised or non-vascularised.

Vascularised bone grafts

Vascularised grafts utilise an alternative source, to the normal anatomical vascular supply (Figure 1), to perfuse the femoral head in ONFH. This can

Graft/Support Type	Subtypes
Vascularised	• Pedicle grafting • Free grafting
Non-vascularised	• Autologous • Allogenic
Synthetic grafting/ structural support techniques	• Calcium-based composite • Porous rod

Figure 1. Subtypes of Graft

Bio Ortho J Vol 3(SP1):e35–e56; 5 February, 2023.

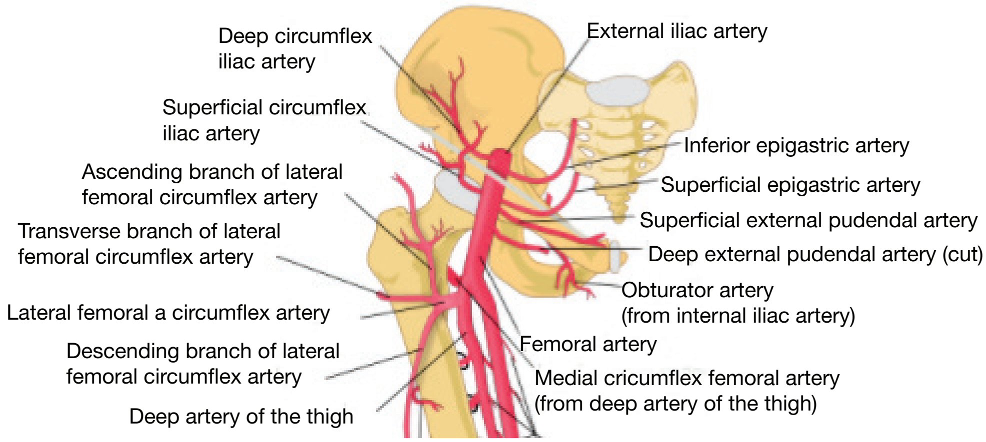

Figure 2. Vascular anatomy of the proximal femur. Image adapted from https://commons.wikimedia.org/wikiFile:Thigh_arteries_schema.svg#filelinks under creative commons license.

either be through the use of an alternative vascular pedicle being utilised locally, or through the use of a free vascular graft.

Pedicle-based grafts

Due to the problems posed by hip diseases and having seen such surgery utilised in canines, in the 1950s, Dr. Joe B. Davis published a work on the use of muscle pedicle bone graft.[11] At this time, it was used for achieving arthrodesis of the hip joint[11–13] and involved using vascularised iliac graft. Davis subsequently went on to report that muscle pedicle graft was an effective treatment for achieving hip joint arthrodesis, however, its indications spanned beyond this and was used for the treatment of AVN.[14]

Since the inception of pedicle-based grafting techniques to manage disorders around the hip, there have been multiple reports of the use of local vascularised grafts in ONFH, utilising either local vascular pedicle bone flaps or vascular muscle pedicle bone grafting techniques.[15–36]

Whilst there are a number of differences between described techniques, the primary aim of all of these procedures is to take a well-vascularised area of bone and/or muscle with its blood supply and incorporate it into the diseased proximal femur. In doing so, the healthy tissue promotes neovascularisation and allows reperfusion of the diseased femoral head. For this reason, it is generally believed that there should be no evidence of collapse for pedicle-based grafts to be indicated.[37] Furthermore, given the success of total hip arthroplasty (THA),[38] it is generally accepted that hip preservation procedures in ONFH are most appropriate for younger patients, with 50 years often referred to as an approximate, yet somewhat arbitrary age cut-off.[37] Ultimately, this represents the age where the lifespan of an implant may conceivably exceed the remaining lifespan of the individual.

The variations in the literature correspond to the differing vascular pedicles or vascular muscle pedicles used for grafting. The commonly used pedicles for bone flaps are summarised in Table 1, which include those arising from the deep circumflex iliac artery,[18–21,23,25–27,30] superficial circumflex iliac artery[17,28,39] and the ascending branch of the lateral femoral circumflex artery.[24,40] When muscle pedicle grafting is used, the uses of Tensor fascia lata,[22,31] Sartorius,[41,42] Quadratus femoris[43–45] and Gluteus Medius[46] have been described.

Considering the outcomes of pedicle flap-based studies, there was an overall conversion to arthroplasty calculated at a rate of 10.4%, after analysing the studies that reported the conversion rates (80 out of 772 cases). The percentage of conversion rates ranged from 0–75.8%.

Where mean follow-up was stated in a way that could be analysed, the calculated mean was 62.24 months.

Table 1. Characteristics and Outcomes of Studies on Pedicle-based Grafts

Year	Author	Study Type	Type of Pedicle Flap	Muscle Flap, Bone Flap or Vessel (Supplying Flap)	Number (Followed Up)	THA	Mean Follow-up	Good to Excellent/ Clinical Success or Mean Post-op Score	Classification
1978	Meyers[33]	NS	MPBF	Iliac graft with quadriceps muscle pedicle	23	NS	NS	56.52% (13/23)	Marcus–Enneking I – [1] II – [7] III – [4] IV [1]
1981	Lee[34]	Prospective	MPBF	Quadratus Femoris	10	1/10 (10.00%)	42.4 months	70% (7/10)	Stage 1 or 2 (Marcus et al. classification)
1993	Iwata et al.[17]	NS	PBF	Superficial circumflex iliac artery pedicle bone flap (deep circumflex iliac artery was additionally used in 2 cases)	23	1/23 (34.35%)	34.96 months	Mean post op JOA score 82.64*	JIC classification I-C - [19] II - [2] III-B [1]
1996	Wassenaar et al.[29]	NS	PBF	Vascularised iliac bone graft	12	1/12 (8.33%)	50 months	Mean post op HHS 88	Ficat and Arlet II - [5] III - [7]
1996	Leung[30]	Retrospective	PBF	Deep circumflex iliac artery pedicle bone flap	21	1/21 (4.76%)	4–12 years	77.78% (16/21)	Myer's classification: III - [6] IV - [8] V - [7]
1997	Ishizaka et al.[27]	Retrospective	PBF	Deep circumflex iliac artery pedicle bone flap	31	3/31 (9.68%)	6 years	77.42% (24/31)	Ficat and Arlet: II - [18] III - [13]

1997	Hasegawa et al.[28]	Retrospective	PBF	Superficial circumflex iliac artery pedicle bone flap (deep circumflex iliac artery was used in 8 hips)	31	1/31 (3.2%)	8 years	61.29% (19/31)	Inoue and Ono II - [28] IIIA - [3]
2001	Eisenschenk et al.[26]	Retrospective	PBF	Deep circumflex iliac artery pedicle bone flap	82	NS (82 with grafting + 8 with THR)	5 years	86.6% (71/82)	ARCO I-II - [62] III - [1] IV - [19]
2002	Stein et al.[35]	NS	MPBF	TFL – long longitudinal artery	37	4/36 (11.11%)	NS	NS	NS
2004	Nagoya et al.[25]	Retrospective	PBF	Deep circumflex iliac artery pedicle bone flap	35	NA	103 months	NS	ARCO II - [28] III - [7]
2005	Matsusaki et al.[19]	NS	PBF	Vascularised pedicle iliac bone graft combined with transtrochanteric anterior rotational osteotomy	17	2/17 (11.76%)	>1 year	82.35% (14/17)	JIC II – [3] IIIA – [13] IIIB – [1]
2006	Yen et al.[36]	Prospective	PBF	Vessel not stated (Iliac bone flap)	39 (61)	4/39 (10.26%)	>3 years	81.3% (26/33) patients (H)	Steinberg II - [11] III - [12] IV - [16]
2006	Zhao et al.[24]	Retrospective	PBF	Ascending branch of the lateral femoral circumflex artery pedicle bone flap	226	14/226 (6.19%)	3 years	86.3% (195/226)	Ficat and Arlet II - [91] III - [93] IV - [42]
2009	Baksi et al.[22]	Prospective	MPBF	Tensor fascia lata muscle-pedicle bone flap	187 (176)	NS	16.5 years	85.8%* 151/176	Ficat and Arlet I [4] II [75] III [97]
2009	Chen et al.[20]	Retrospective	PBF	Deep circumflex iliac artery pedicle bone flap	33	25/33 (75.58%)	69 months	NS	ARCO IIIA [26] IIIB [7]

(Continues)

Table 1. (Continued)

Year	Author	Study Type	Type of Pedicle Flap	Muscle Flap, Bone Flap or Vessel (Supplying Flap)	Number (Followed Up)	THA	Mean Follow-up	Good to Excellent/ Clinical Success or Mean Post-op Score	Classification
2009	Babhulkar[23]	Retrospective	PBF	Deep circumflex iliac	31	1/31 (3.23%)	8 years	70.9% (22/31)	ARCO IIB [9] IIIC [22]
2010	Wang et al.[45]	NS Prospective^	MPBF	Quadratus Femoris (Deliquesce strut + MPBF vs MPBF)	28 (12 + 16)	0	19.2 months	82.1% (23/28)	ARCO IIB – [8] IIC – [20]
2016	Zeng	Retrospective	PBF	Vascularised greater trochanter flap combined with free iliac flap	64	0	35.8 months	87.5% (56/64)	ARCO IIIA - [16] IIIB - [22] IIIC – [26]
2014	Elmalı et al.[21]	Retrospective	PBF	Deep circumflex iliac	26	5/26 (19.23%)	36 months	69.2% (18/26)	ARCO II - [11] III - [15]
2016	Chen et al.[41]	Retrospective	MPBF	Sartorius	67 (64)	9/64 (14.06%)	34.48 months	79.7% (51/64)	ARCO I - [21] II - [35] III - [8]
2016	Li et al.[43]	Retrospective	PBF	Iliac - Lateral femoral circumflex	48	4/48 (8.33%)	NA Post op + 6 months	91.7% (44/48)	ARCO II – [38] III – [10]
2019	Lei et al.[47]	Retrospective	PBF	Iliac	(19) 11(a)AVN	1/19 (5.26%)	23 months	90.91% (10/11)	ARCO I – [6] II – [4] III – [1]
2020	Popere et al.[44]	Retrospective	MPBF	Quadratus Femoris	(60) 33(a)AVN	4/60 (6.67%)	NS	83.3% (All patients)	NS

**denotes the value calculated.*

AVN: Avascular necrosis; MPBF: muscle pedicle bone flap; NS: not significant; PBF: pedicle bone flap; TFL: tensor fasciae latae; THA: total hip arthroplasty; THR: total hip replacement

Among all studies, 82.4% of the patients achieved a good or excellent outcome (760 out of 922 cases) with a range of 56.5–91.7%. The mean Harris Hip score (HHS) was calculated at 88 and 85.8 by two studies, and another study reported the JOA score as 82.64.

Free vascular grafts

The first reports of a free vascularised bone graft were from McCullough in the early 1970s,[48] where a rib was used for reconstruction of a bony mandibular defect. This was closely followed by the use of a free vascularised fibular graft (FVFG) by Taylor et al.,[49] with Brunelli also describing the use of the FVFG at a similar point in time.[50] Urbaniak et al. published a long-term follow-up series of ONFH treated with FVFG.[51]

Since then, the FVFG has continued to be a popular treatment for ONFH and has been described in a number of studies (Table 2).[36,52–71]

Urbaniak et al. described the use of a bone graft of harvested autologous fibula and its associated vascular supply, which is anastomosed to the recipient vessels, the lateral femoral circumflex vessels.[51] It is used in conjunction with core decompression and removal of necrotic bone, in order to provide structural support to the subchondral bone as well as provide a vascular supply. For this reason, it is used in instances where the patients are young and active, where a THA is not an ideal solution.[72] In Urbaniak's original study, 11% of the patients required conversion within the first 5 years and 30% required conversion to THR in the total follow-up period of 12.2 years.[51] As microvascular techniques have improved, recent studies have reported more favourable outcomes with conversion rates ranging from 0–37%.[36,52–60,63,64,73]

For management of ONFH, the only other described free vascular graft in the literature is the use of a vascularised free "iliac bone flap,"[47] however, this was a small sample of 19 patients, where one converted to THR in the mean follow-up period of 23 months (range 18–33).

For patients who had FVFG, the overall conversion rate to arthroplasty was 10.45%, considering the studies that reported the conversion rates (244 out of 2335 cases). Where mean follow-up was stated in a way that could be analysed, this was at a mean of 60.8 months. The this was at a mean of 54.99 months.

A good or excellent patient-reported outcome was achieved by 69.72% of the patients, where data were available for calculation. The mean HHS was calculated at 83.66, which corresponded to a "good" reported outcome.

Non-vascularised bone grafts

Non-vascularised grafts can theoretically be taken from anywhere, however, like vascularised grafts they are commonly taken from the fibula[52,61,62] or ilium.

Vascularised bone grafts have, however, been associated with better outcomes. When considering radiographic parameters, the use of vascularised versus non-vascularised bone grafts has shown to have significantly more favourable outcomes, particularly when considering collapse and depression of the articular surface.[62] Furthermore, these favourable findings also extend to patient-reported outcome measures.[62] However, non-vascularised grafts have a big advantage over the vascularised grafts, in that, they do not require the same level of microvascular surgical skills as a free vascularised graft and hence offers a technique that is more accessible and can be more widely used. Additionally, in appropriately selected patients, the use of non-vascularised grafts is often considered in the context of the technique used for graft insertion.

Phemister technique

In 1949, Phemister published a manuscript on the use of a non-vascularised graft for femoral head, for the treatment of AVN.[74] This involved a process which utilised reamers to remove cylindrical areas of bone from the head and neck. These were then replaced with cylindrical "bone plugs" to act as a graft. The drilling technique is not too dissimilar to core decompression.

Since then, a number of studies have described the use of the so called "Phemister technique"[75–80] (Table 3).

A number of surgeons have adopted the technique and have made their own modifications[2,75,81,82]

Table 2. Characteristics and Outcomes of Studies on Free Vascularised Fibular Grafts (FVFG)

Year	Author	Study Type	Type of Graft	Number of Cases with Graft (Total Studies Followed Up)	THA	Mean FU	Good to Excellent/ Clinical Success (If not Stated Means Score Where Possible)	Classification
1983	Fujimaki and Yamauchi[73]	NS	FVFG	6	0	29 months	66.67% (4/6)	NS
1991	Richards[64]	Retrospective	FVFG	24	5/24 (20.83%)	32.8 months	20.83% (5/24)	II – [7] III – [4] IV – [20] V – [1]
1995	Urbaniak et al.[51]	Prospective	FVFG	103	46/103 (44.66%)	Median 7	Mean post op HHS 79	M&E II – [19] III – [22] IV – [40] V – [22]
1995	Malizos et al.[63]	Prospective	FVFG	10 (64)	0	25.5 months*	100% 10/10	Marcus–Ennek-ing II - 2 III - 3 IV – 2 V - 2
1996	Kane et al.[54]	Prospective Comparative	CD versus FVFG	20 (39)	4/20 (20%)	2–5 years	NS	Ficat and Arlet IIA - [4] IIB - [4] III – [12]
1997	Sotereanos et al.[65]	Retrospective	FVFG	88	21/88 (23.86%)	5.5 years	68.18% (60/88)	Steinberg IC – [10] IIA – [3] IIB – [16] IIC – [19] IIIB – [6] IIIC – [10] IVA – [6] IVB – [15]

1998	Scully et al.[53]	Prospective comparative	CD versus FVFG	614 (712)	27/614 (43.97%)	21–50 months	NS	Ficat and Arlet I – [3] II – [111] III – [500] IV
1999	Louie et al.[66]	Retrospective	FVFG	63	16/63 (25.40%)	50 months	Mean HHS post op 83.6	Steinberg II – [5] III – [7] IV – [38] V – [7] VI – [1]
2001	Soucacos et al.[67]	Retrospective	FVFG	228	14/228 (6.14%)	4.7 years	Mean HHS Post op 87	Steinberg II – [39] III – [45] IV – [77] V – [23]
2003	Plakseychuk et al.[62]	Retrospective	NVFG versus FVFG	220 (343)	31/220 (14.09%)	5 years	70% (154/220)	Pittsburgh I - [14] II – [21] III – [15]
2005	Zhang et al.[60]	Retrospective	FVFG	56	0	16 months	Mean HHS post op 86.7*	Steinberg II – [9] III – [16] IV – [31]
2005	Kim et al.[61]	Retrospective	NVFG versus FVFG	23 (46)	3/23 (13.04%)	4 years	Mean HHS post op 74	IIC – [10] IIIC – [2] IVC – [11]
2006	Yen et al.[36]	Retrospective	PBG versus FVFG	22 (61)	2/22 (9.09%)	>3 years	Mean Merle d'Aubigne and Postel's score 15/18	Steinberg II – [4] III – [11] IV – [7]

(Continues)

Table 2. (Continued)

Year	Author	Study Type	Type of Graft	Number of Cases with Graft (Total Studies Followed Up)	THA	Mean FU	Good to Excellent/ Clinical Success (If not Stated Means Score Where Possible)	Classification
2007	Kawate et al.[58]	Retrospective	FVFG	73	13/73 (17.81%)	7 years	64.38% (47/73)	Steinberg I – [3] II – [28] III – [3] IV – [34] V – [3]
2008	Yoo et al.[59]	Retrospective	FVFG	124	13/124 (5.42%)	13.9 years	79.03% (98/124)	Ficat and Arlet II – [59] III – [65]
2011	Tetik et al.[52]	Prospective	NVFG versus FVFG	8 (21)	0	22 months	Mean HHS post op 83.09	Ficat and Arlet IIA – [4] IIB –[4] III – [3] IV
2012	Eward et al.[69]	Retrospective	FVFG	65	26/65 (40%)	14.4 years	Mean HHS post op 89	Ficat and Arlet I – [5] II – [60]
2013	Gao et al.[70]	Retrospective	FVFG	578	23/578 (3.98%)	5.0 years	Mean HHS post op 86.9	Steinberg II – [156] III – [95] IV – [294] V – [33]
2014	Gokhan et al.[71]	NS	FVFG	10	0	3.0 years	90% (9/10)	Steinberg II – [2] III – [5] IV – [3]

**denotes the value calculated.*

FVFG: free vascularised fibular graft; HHS: Harris Hip Score; NS: not significant; NVFG: non-vascularised fibular graft; PBG: preformed bone graft; THA: total hip arthroplasty

Table 3. Non-vascularised Techniques

Technique	Procedure	Author	Year	Cases	Classification	Mean FU	Conversion to THA
Phemister	Reamers to remove cylindrical areas of bone from the head and neck. These are then replaced with cylindrical "bone plugs" to act as a graft.	Bonfiglio and Bardenstein[75]	1958	55	NS	3 years 11 months	NS
		Wang and Thompson[76]	1976	11	NS	Minimum 2 years	27.27% (3/11)
		Smith et al.[80]	1980	56	NS	9 years	NS
		Nelson and Clark[77]	1993	52	Marcus and Enerking II – [17] III – [11] IV – [22] V – [2]	Minimum 2 years	7.69% (4/52)
		Keizer et al.[79]	2006	80	Ficat and Arlet 0– [6] I – [3] IIA – [31] IIB – [16] III – [13] IV – [9]	7 years	32.5% (26/80)
		Wu et al.[78]	2019	29	ARCO IIA – [9] IIB – [13] IIC – [4] IIIA – [3]	14 years	34.48% (10/29)
Lightbulb	Creation of a cortical window in the femoral neck, debridement of necrotic bone and packing of the void left by this with corticocancellous graft.	Rosenwasser et al.[87]	1994	13	Ficat and Arlet I – [1] II – [9] III – [5]	12 years	15.4% (2/13)
		Mont et al.[90]	2003	21	Ficat and Arlet II Or III– [21]	48 months	14.3% (3/21)
		Cheng[93]	2009	11	ARCO IIC – [5] IIIA – [6]	61 months	27.27% (3/11)
		Wang et al.[45]	2010	138	ARCO IIA – [4] IIB – [30] IIC – [33] IIIA – [71]	25.37 months	18.84% (26/138)
		Zhang[106]	2016	85	ARCO IC – [5] IIA – [19] IIB – [25] IIC – [22] IIIA – [9] IIIB – [3] IIIC – [2]	2.3 years	7.06% (6/85)

(Continues)

Table 3. (Continued)

Technique	Procedure	Author	Year	Cases	Classification	Mean FU	Conversion to THA
		Yildiz et al.[92]	2018	28	Steinberg I – [4] II – [12] III – [10] IV – [2]	5 years	14.29% 4/28
		Cheng et al.[93]	2020	67	ARCO II – [45] III – [22]	91.2 months (matched comparison group)	13.43% 9/67
		Brojeni et al.[94]	2020	58	Ficat and Arlet IIB – [30] III – [28] III – [5]	60 months	1.72% (1/58) (secondary trauma following fall)
Trapdoor	Creation of a trapdoor within the articular cartilage to remove necrotic bone and graft with non-vascularised bone.	Ko et al.[95]	1995	10		4.5 years	0
		Mont et al.[97]	1998	30		4.8 years	4/30
		Seyler et al.[86]	2008	39	Ficat and Arlet II – [22] III – [17]	36 months	33.33% (13/39)
		Cheng et al.[93]	2020	67	ARCO II – [45] III – [22]	91.2 months	4.48% 3/67

NS: not significant; THA: total hip arthroplasty

or use a similar technique of non-vascularised grafting through core decompression tunnels.[80,82–85]

The use of this form of drilling and non-vascularised grafting technique has been associated with survivorship rates (when considering conversion to THR), within study follow-up periods ranging from 7 months to 12.9 years, of around 60–95%.[2,75–79,81–86] Despite such preservation rates, when authors have considered "satisfactory" clinical outcomes, which are often poorly defined in the earlier literature, results have been less encouraging.[80] However, more recent studies have shown significant improvements in patient-reported outcome measures.[78,82]

It is evident, however, that the more progressive the disease and greater the collapse, prior to treatment, the poorer the outcomes.[78,80,82–85]

Lightbulb technique

The lightbulb technique is the name attributed to the procedure performed at the Columbia-Presbyterian Medical Centre in the late 70s to the early 80s. It was proposed by Rosenwasser et al.[87] as a means of managing ONFH. The procedure involved the creation of a cortical window in the femoral neck, debridement of the necrotic bone and packing of the void with corticocancellous graft in a series of 13 patients. Out of this small series, only two converted to THR (13%), and as a cohort, there were improvements seen in the HHS. Despite this technique having been popularised in this manuscript, Ganz and Büchler had also provided a description of the use of a femoral neck cortical window to deal with the necrotic bone within a femoral head with

ONFH;[88] however, this was an arteriovenous vascularised procedure, similar to that described by Hori for management of AVN of the scaphoid.[89] Mont described the use of a cortical window, in addition to the use of a trapdoor, and found similar THA conversion rates for both Lightbulb and Trapdoor at 13.3 and 14.3%, respectively.[90] Less favourable results were seen in the studies by Cheng et al.[20] and Wang et al.,[91] at 27.27 and 18.84%, respectively. However, in the last decade, studies with medium- and long-term data have showed more promising outcomes, when considering the need for arthroplasty, with Zhang, Yildiz et al.[92] and Cheng et al.[93] showing conversion rates of 7.06, 14.29 and 13.43%, respectively. Cheng had a follow-up period of just over 7-and-a-half years, and Brojeni et al. demonstrated a conversion secondary to trauma, and not collapse (Table 3).[94]

Trapdoor

The concept of utilising a trapdoor in the articular cartilage of the femoral head has been described by a number of authors. Meyers[33] and Ko et al.[95] have described on the procedures at the level of the junction of femoral neck and articular cartilage, as well as the use of a trapdoor within the articular cartilage, to remove necrotic bone and graft, in adolescent patients. It can also be used for tumour resection in the proximal femur.[96]

In a cohort overseen by Meyers, Ko et al.[95] described a THR conversion rate of 2 (14.3%) in 13 patients (14 hips). Ten cases had containment procedures as well as the trapdoor procedure, and of these 10 cases, 8 had a good result and 2 had fair results, with 100% survivorship, suggesting that additional containment may improve outcomes in this group of patients.[95]

Further in 1998, Mont et al.[97] published a series of 23 patients (30 procedures) in Stage III or IV ONFH, who underwent the so called “trapdoor procedure.” This involved an anterolateral approach to the hip and capsulotomy done in such a way that the blood supply was preserved. A trapdoor was then made in the articular cartilage. Here, between 10 and 30% of the surface of the femoral head formed the trapdoor, and through this the necrotic bone removed. Corticocancellous struts from the iliac crest were used for grafting, and this technique provided structural support for the articular cartilage. The trapdoor was then replaced and closed using an absorbable fixation method. Out of this, 73% had a good or excellent result, and 23% required an arthroplasty, either hemi- or total.

More recently, Seyler et al.[86] reported the outcomes of 39 patients who utilised this technique. The conversion to arthroplasty was observed in a third of the patients, a finding mirrored by Gagala et al.[98] However, the most recent trapdoor study by Cheng et al.[93] showed more favourable outcomes with a conversion rate of under 5% (Table 3).

Patients undergoing non-vascularised grafting were grouped for comparative purposes. The overall conversion rate to arthroplasty was 16.45%, considering the studies that reported the conversion rates (125/760 cases).

Structural Support Techniques and Synthetic Grafting

The role of core decompression is out with the publication of this article, as are some of the biological strategies (e.g. platelet-rich plasma, bone morphogenic proteins and mesenchymal stem cells). Though this article focuses, largely, on grafting techniques, the authors feel it poignant to explore the use of synthetic bone grafts and structural support using rods.

Structural support: Porous rods

The use of porous rods (such as those made from tantalum) has been well described in the orthopaedic literature, particularly in the context of arthroplasty.[99] However, a number of studies were found detailing the use of rods in ONFH, such as those made from tantalum,[100–110] bio-ceramic[111] and nano-hydroxyapatite or polyamide 66.[103]

The rod provides structural support and helps prevent collapse of the articular surface. Furthermore, the porous nature of the rods allows for bony ingrowth and is reported to have angioconductive properties in some instances.

Tantalum rod use was described by Veillette[100] in 2006 in a cohort of 58 patients with fair results, which showed a mean HHS of 77.5 when all patients were considered. Studies by Liu G et al.,[101] Liu Z et al.,[102]

Table 4. Characteristics and Outcomes of Studies on Structural Support with Rod Insertion

Year	Author	Study Type	Type of Rod	Number of Cases with Rod (Total Study Followed up)	THA	Mean FU	Good – Excellent/ Clinical Success (If not Stated Mean Score Where Possible)	Classification
2006	Veillette et al.[100]	Retrospective	Tantalum	58	9/58 (15.5%)	24 months	Mean HHS post op 77.5*	Steinberg I – [1] II – [49] III – [8]
2010	Liu et al.[101]	Prospective	Tantalum	49	1/49 (2.04%)	15.2 months	Mean HHS post op 83.7	Steinberg I – [21] II – [26] III – [2]
2014	Liu et al.[102]	Prospective	Tantalum	138	43/138 (31.16%)	38.46 months	Mean HHS post op 79.50	ARCO II – [79] III – [89]
2014	Yang et al.[103]	Retrospective	Hydroxyapatite/ polyamide 66	84 (34 in Rod group)	8/34 (23.53%)	21.78 months	NS (Mean HHS > 80)	Steinberg IB – [3] IC – [4] IIA – [8] IIB – [10] IIC – [8] IIIA – [5]
2015	Pakos[104]	Retrospective	Tantalum	58	4/58 (6.90%)	5 year minimum	Mean Merle d'Aubigne post op 17.0	Steinberg IIa – [6] IIb – [22] IIc – [10] IIIa – [20]

2015	Zhao et al.[105]	Retrospective	Tantalum	31	5/31 (16.12%)	64.35 months	Mean HHS post op 77.23	ARCO IIC – [19] IV – [12]
2016	Zhang et al.[106]	Prospective	Tantalum	14	4/14 (25.57%)	19 months	Mean HHS post op 81.11	ARCO II- [10] III – [4]
2018	Lu et al.[111]	Retrospective	Bio-ceramic	72	7/72 (9.72%)	26.74 months	Mean HHS post op 82.27	ARCO II- [43] III – [29]
2018	Li et al.[107]	Prospective	Bio-ceramic	20:20	NS	18 months	Mean HHS post op 91.8 89.65	ARCO I – [13] II – [14] IIIA – [13]
2020	Fang et al.[108]	Prospective	Tantalum	41	5/41 (12.2%)	33.5 months	Mean HHS post op 68.63	Ficat I – [10] II – [20]
2020	Peng et al.[109]	Prospective	Tantalum	74 (30 in rod group)	NS	12 months	Mean HHS post op 95.8	ARCO I – [13] II – [17]
2020	He et al.[110]	Retrospective	Tantalum	40	12/40 (30%)	120 months	Mean HHS post op 94	ARCO II – [27] III – [13]

**denotes the value calculated.*

Harris Hip Score; NS: not significant; THA: total hip arthroplasty

Zhang et al.,[106] Peng et al.[109] and He et al.[110] have shown more favourable results with good outcomes, which demonstrated by mean HHS of over 90. Yang demonstrated similar outcome scores with the use of a nano-hydroxyapatite or polyamide 66 rod, with a mean HHS > 80.[103] Similar scores were mirrored by bioceramic rods in studies by Lu et al.[111] and Li et al.[107] The conversion rates to THR ranged from 2.04 to 31.6%.

Patients who underwent arthroplasty with all types of porous rods were grouped for comparative purposes. The overall conversion rate to arthroplasty was 18.32%, considering the studies that reported the conversion rates (98/583 cases).

The mean HHS was calculated at 82.939.

Synthetic grafting: Calcium-based composites

Since Ficat et al.[112] first described the use of core decompression for management of AVN of the femoral head, others went on to publicise this technique.[113]

Synthetic grafting is done by utilising an injectable calcium sulphate ($CaSO_4$) or calcium phosphate ($CaPO_4$) composite graft,[114] in addition to core decompression, to fill the void left by the removed necrotic bone.

A preliminary clinical study conducted in 2003 by Wood et al. is the first documented use of cementation for ONFH.[115]

Hungerford et al. showed, in 38 Ficat Stages I–III hips, with 6–16 months follow-up, that 32 of their 38 hips saw benefit in terms of pain relief, with those experiencing more pain preoperatively, getting better resolution of their pain. A study by Jiang et al.[116] also observed similar good to excellent results in 92.6% of their 48 patients with Stages I, II or III ARCO ONFH.

In a series by Civinini et al.[117] of 37 hips with Steinberg Stages IC–IIIA ONFH, HHS increased from 68 points preoperatively to 86 points post-operatively. Out of the series, three hips required conversion to THR (8.1%). Landgraeber et al.[118] demonstrated successful treatment in 75.9% of a 29-patients cohort, after a mean follow-up of 30.06 months, with success being defined as no further collapse or conversion to total hip replacement (THR). Steinberg Stage 2A fared better than 2B and 2C, with this treatment.[118] Similar to the other techniques, outcomes appeared to be related to the stage of the disease, that is, the more advanced the ONFH, the poorer the outcome.

Given the heterogeneous nature of intervention, comparative review appeared impossible.

Comparison of Techniques

When comparing conversion to arthroplasty, chi-squared test revealed a statistically significant difference between all groups ($P < 0.001$), however, sub-analysis revealed no statistical differences between the pedicle flap graft versus FVFG ($P = 0.945$) and non-vascularised graft and porous rod ($P = 0.860$). However, there was a statistically significant difference between the pedicle flap and non-vascularised graft ($P < 0.001$) and FVFG versus non-vascularised graft ($P < 0.001$), FVFG and porous rod ($P < 0.001$), pedicle flap graft and porous rod ($P = 0.001$).

When considering conversion to arthroplasty, this would suggest that there is a statistically significant difference when considering the lower conversion rates between vascularised techniques (muscle pedicle grafting and FVFG) and non-vascularised techniques (non-vascularised graft and porous rod), but no statistical difference in conversion rates between the two vascular techniques and the two non-vascular techniques.

CONCLUSIONS

There are a number of different techniques that have been described for ONFH.

Where there is such a plethora of management options for a particular condition, some of which are described in other articles, this highlights that there is no one "excellent" option for management of this condition. From a surgical decision making "perspective", the options for the surgical management described in this article should be tailored to patient factors (aetiology, age, collapse, etc.) and surgical skills set (microvascular surgery, pedicle grafting versus non-vascularised versus synthetic grafting). However, vascularised techniques seem to result in more favourable outcomes,[53,54,61,62] and this is true for both pedicle flap–based grafting or free pedicle grafting, when considering arthroplasty conversion rates, with rates of 10.04% for pedicle flap grafting and 10.01% for free pedicle grafting when compared to 16.44% for non-vascularised grafting and 18.32% for porous rod insertion.

Despite the, apparent, more favourable outcomes associated with vascularised grafting, the authors recognise that these techniques are more challenging and technically demanding than non-vascularised grafting.[119]

For more advanced disease, arthroplasty may be a more feasible option; however, as discussed, arthroplasty post AVN is associated with poorer outcomes.[8]

When considering the studies included in this scoping review, the authors note the variability in the use of classification system, reporting of results and the relatively small sample sizes encountered. These highlight the limitations of this review, where there is a relative lack of homogenicity amongst the studies, and hence the authors feel that there is a need for more standardisation when considering the reporting of outcomes in joint-preserving grafting or structural support surgery for ONFH. This requires larger, prospective, randomised studies to consider the best standard of care. From the current data available, however, it can be observed that vascularised techniques appear to result in a lesser rate of conversion to arthroplasty. Therefore, it could be used preferentially over non-vascularised grafting as use of these, where a surgeons technical ability allows for this.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

REFERENCES

1. Arlet J. Forage-biopsie de la terefemorale dans losteonecrose primitive. Observations histopathologique portant surhuit forages. Rev Rhum. 1964;31:257–64.
2. Marcus ND, Enneking WF, Massam RA. The silent hip in idiopathic aseptic necrosis. Treatment by bone-grafting. J Bone Joint Surg Am. 1973;55(7):1351–66.
3. Steinberg M, Hayken G, Steinberg D, et al. Bone circulation. Baltimore, MD: Williams and Wilkins; 1984.
4. Gardeniers J. Report of the Committee of Staging and Nomenclature. ARCO News Lett. 1993;5(2):79–82.
5. Kerboul M, Thomine J, Postel M, et al. The conservative surgical treatment of idiopathic aseptic necrosis of the femoral head. J Bone Joint Surg Br. 1974;56(2):291–6.
6. Sugano N, Atsumi T, Ohzono K, et al. The 2001 revised criteria for diagnosis, classification, and staging of idiopathic osteonecrosis of the femoral head. J Orthop Sci. 2002;7(5):601–5. https://doi.org/10.1007/s007760200108
7. Allami M, Fender D, Khaw F, et al. Outcome of Charnley total hip replacement across a single health region in England: The results at ten years from a regional arthroplasty register. J Bone Joint Surg Br. 2006;88(10):1293–8. https://doi.org/10.1302/0301-620X.88B10.17933
8. Ancelin D, Reina N, Cavaignac E, et al. Total hip arthroplasty survival in femoral head avascular necrosis versus primary hip osteoarthritis: Case-control study with a mean 10-year follow-up after anatomical cementless metal-on-metal 28-mm replacement. Orthop Traumatol Surg Res. 2016;102(8):1029–34. https://doi.org/10.1016/j.otsr.2016.08.021
9. Van Meekeren J. Heel en geneeskonstige aanmerkingen. Amsterdam, The Netherlands: Commelijn; 1668.
10. De Boer HH. The history of bone grafts. Clin Orthop Relat Res. 1988(226):292–8.
11. Davis JB. The muscle-pedicle bone graft in hip fusion. J Bone Joint Surg Am. 1954;36-A(4):790–9.
12. Hartley J, Silver N. Muscle-pedicle bone grafts. J Bone Joint Surg Am. 1954;36-A(4):800–9.
13. Crenshaw AH. Muscle pedicle bone graft in arthrodesis of the hip. South Med J. 1957;50(2):169–77. https://doi.org/10.1097/00007611-195702000-00004
14. Davis JB, Fagan TE, Beals RK. Follow-up notes on articles previously published in the journal. Muscle-pedicle bone graft in hip fusion. J Bone Joint Surg Am. 1971;53(8):1645–7.
15. Asmus A, Vogel K, Vogel A, et al. Gefäßgestieltes Beckenkammtransplantat zur Behandlung der Femur kopfnekrose. Oper Orthop Traumatol. 2020:1–12.
16. Xie H, Wang B, Tian S, et al. Retrospective long-term follow-up survival analysis of the management of osteonecrosis of the femoral head with pedicled vascularized iliac bone graft transfer. J Arthroplasty. 2019;34(8):1585–92. https://doi.org/10.1016/j.arth.2019.03.069

17. Iwata H, Torii S, Hasegawa Y, et al. Indications and results of vascularized pedicle iliac bone graft in avascular necrosis of the femoral head. Clin Orthop Relat Res. 1993(295):281–8.
18. Pavlovcic V, Dolinar D, Arnež Z. Femoral head necrosis treated with vascularized iliac crest graft. Int Orthop. 1999;23(3):150–3. https://doi.org/10.1007/s002640050334
19. Matsusaki H, Noguchi M, Kawakami T, et al. Use of vascularized pedicle iliac bone graft combined with transtrochanteric rotational osteotomy in the treatment of avascular necrosis of the femoral head. Arch Orthop Trauma Surg. 2005;125(2):95–101. https://doi.org/10.1007/s00402-004-0777-z
20. Chen C-C, Lin C-L, Chen W-C, et al. Vascularized iliac bone-grafting for osteonecrosis with segmental collapse of the femoral head. J Bone Joint Surg. 2009;91(10):2390–4. https://doi.org/10.2106/JBJS.H.01814
21. Elmalı N, Ertem K, Karakaplan M, et al. Vascular pedicled iliac bone grafting is effective in patients with an early stage of femoral head avascular necrosis. Eklem Hastalik Cerrahisi. 2014;25(1):2–7. https://doi.org/10.5606/ehc.2014.02
22. Baksi DP, Pal AK, Baksi DD. Long-term results of decompression and muscle-pedicle bone grafting for osteonecrosis of the femoral head. Int Orthop. 2009;33(1):41–7. https://doi.org/10.1007/s00264-007-0455-1
23. Babhulkar S. Osteonecrosis of femoral head: Treatment by core decompression and vascular pedicle grafting. Indian J Orthop. 2009;43(1):27. https://doi.org/10.4103/0019-5413.45320
24. Zhao D, Xu D, Wang W, et al. Iliac graft vascularization for femoral head osteonecrosis. Clin Orthop Relat Res. 2006;442:171–9. https://doi.org/10.1097/01.blo.0000181490.31424.96
25. Nagoya S, Nagao M, Takada J, et al. Predictive factors for vascularized iliac bone graft for nontraumatic osteonecrosis of the femoral head. J Orthop Sci. 2004;9(6):566–70. https://doi.org/10.1007/s00776-004-0841-0
26. Eisenschenk A, Lautenbach M, Schwetlick G, et al. Treatment of femoral head necrosis with vascularized iliac crest transplants. Clin Orthop Relat Res. 2001;(386):100–5. https://doi.org/10.1097/00003086-200105000-00013
27. Ishizaka M, Sofue M, Dohmae Y, et al. Vascularized iliac bone graft for avascular necrosis of the femoral head. Clin Orthop Relat Res. 1997;(337):140–8. https://doi.org/10.1097/00003086-199704000-00016
28. Hasegawa Y, Iwata H, Torii S, et al. Vascularized pedicle bone-grafting for nontraumatic avascular necrosis of the femoral head A 5-to 11-year follow-up. Arch Orthop Trauma Surg. 1997;116(5):251–8. https://doi.org/10.1007/BF00390047
29. Wassenaar RP, Verburg H, Taconis WK, et al. Avascular osteonecrosis of the femoral head treated with a vascularized iliac bone graft: Preliminary results and follow-up with radiography and MR imaging. Radiographics. 1996;16(3):585–94. https://doi.org/10.1148/radiographics.16.3.8897626
30. Leung P. Femoral head reconstruction and revascularization: Treatment for ischemic necrosis. Clin Orthop Relat Res. 1996;(323):139–45. https://doi.org/10.1097/00003086-199602000-00019
31. Palazzi C, Xicoy J. The pediculate bone graft as treatment for the aseptic necrosis of the femoral head. Arch Orthop Unfallchir. 1975;83(1):115–22. https://doi.org/10.1007/BF00415988
32. Salacz T, Manninger J, Szita J, et al. [Aseptic femur head necrosis and therapeutic possibilities by using a bone graft with a vascular pedicle]. Magy Traumatol Ortop Kezseb Plasztikai Seb. 1993;36(2):129–39.
33. Meyers MH. The treatment of osteonecrosis of the hip with fresh osteochondral allografts and with the muscle pedicle graft technique. Clin Orthop Relat Res. 1978;(130):202–9.
34. Lee CK, Rehmatullah, NR. Muscle-pedicle bone graft and cancellous bone graft for the "silent hip" of idiopathic ischemic necrosis of the femoral head in adults. Clin Orthop Relat Res. 1981;(158): 185–94.
35. Stein H, Volpin G, Hörer D. Vascularized muscle pedicle flap for osteonecrosis of the femoral head. Orthopedics. 2002;25(5):485–8. https://doi.org/10.3928/0147-7447-20020501-14
36. Yen C-Y, Tu Y-k, Ma C-H, et al. Osteonecrosis of the femoral head: Comparison of clinical results for vascularized iliac and fibula bone grafting. J Reconstr Microsurg. 2006;22(01):21–4. https://doi.org/10.1055/s-2006-931902
37. Millikan PD, Karas V, Wellman SS. Treatment of osteonecrosis of the femoral head with vascularized bone grafting. Curr Rev Musculoskelet Med. 2015;8(3):252–9. https://doi.org/10.1007/s12178-015-9285-8
38. Kay A, Davison B, Badley E, et al. Hip arthroplasty: Patient satisfaction. Br J Rheumatol. 1983;22(4):243–9. https://doi.org/10.1093/rheumatology/22.4.243
39. Hasegawa Y, Sakano S, Iwase T, et al. Pedicle bone grafting versus transtrochanteric rotational osteotomy for avascular necrosis of the femoral head. J Bone

Joint Surg Br. 2003;85(2):191–8. https://doi.org/10.1302/0301-620x.85b2.13190

40. Zhao D, Huang S, Lu F, et al. Vascularized bone grafting fixed by biodegradable magnesium screw for treating osteonecrosis of the femoral head. Biomaterials. 2016;81:84–92. https://doi.org/10.1016/j.biomaterials.2015.11.038
41. Chen X, Tan X, Gao S, et al. Sartorius muscle-pedicle bone graft for osteonecrosis of the femoral head. Int Orthop. 2016;40(7):1417–25. https://doi.org/10.1007/s00264-015-2921-5
42. Zhang L, Fan Y, Zhang Y, et al. Comparison of sartorius muscle-pedicle and circumflex iliac deep bone flap grafts in the treatment of early non-traumatic osteonecrosis of femoral head in young adults. Acta Orthop Traumatol Turc. 2019;53(4):255–9. https://doi.org/10.1016/j.aott.2019.04.005
43. Li D, Li M, Liu P, et al. Core decompression or quadratus femoris muscle pedicle bone grafting for nontraumatic osteonecrosis of the femoral head: A randomized control study. Indian J Orthop. 2016;50(6):629–35. https://doi.org/10.4103/0019-5413.193478
44. Popere S, Shinde SS, Patel R, et al. A cross sectional study of outcomes of muscle pedicle grafting in neck of femur fractures and avascular necrosis of femoral head. Injury. 2020;51(7):1622–5. https://doi.org/10.1016/j.injury.2020.04.026
45. Wang YS, Zhang Y, Li JW, et al. A modified technique of bone grafting pedicled with femoral quadratus for alcohol-induced osteonecrosis of the femoral head. Chin Med J (Engl). 2010;123(20):2847–52.
46. Cho KJ, Park KS, Yoon TR. Muscle pedicle bone grafting using the anterior one-third of the gluteus medius attached to the greater trochanter for treatment of Association Research Circulation Osseous stage II osteonecrosis of the femoral head. Int Orthop. 2018;42(10):2335–41. https://doi.org/10.1007/s00264-018-3839-5
47. Lei P, Du W, Liu H, et al. Free vascularized iliac bone flap based on deep circumflex iliac vessels graft for the treatment of osteonecrosis of femoral head. J Orthop Surg Res. 2019;14(1):397. https://doi.org/10.1186/s13018-019-1440-2
48. McCullough DW, Fredrickson JM. Composite neovascularized rib grafts for mandibular reconstruction. Surg Forum. 1972;23(0):492–4.
49. Taylor GI, Miller GD, Ham FJ. The free vascularized bone graft. A clinical extension of microvascular techniques. Plast Reconstr Surg. 1975;55(5):533–44. https://doi.org/10.1097/00006534-197505000-00002
50. Brunelli G. Free vascularized fibular graft in treatment of osteonecrosis affecting the hip. Presented at the Symposium of the Groupe pour l'Avancement de la Microchirurgie (GAM), La Grande Motte; 1980.
51. Urbaniak JR, Coogan PG, Gunneson EB, et al. Treatment of osteonecrosis of the femoral head with free vascularized fibular grafting. A long-term follow-up study of one hundred and three hips. J Bone Joint Surg Am. 1995;77(5):681–94. https://doi.org/10.2106/00004623-199505000-00004
52. Tetik C, Başar H, Bezer M, et al. Comparison of early results of vascularized and non-vascularized fibular grafting in the treatment of osteonecrosis of the femoral head. Acta Orthop Traumatol Turc. 2011;45(5):326–34. https://doi.org/10.3944/AOTT.2011.2259
53. Scully SP, Aaron RK, Urbaniak JR. Survival analysis of hips treated with core decompression or vascularized fibular grafting because of avascular necrosis. J Bone Joint Surg. 1998;80(9):1270–5. https://doi.org/10.2106/00004623-199809000-00004
54. Kane SM, Ward WA, Jordan LC, et al. Vascularized fibular grafting compared with core decompression in the treatment of femoral head osteonecrosis. Orthopedics. 1996;19(10):869–72. https://doi.org/10.3928/0147-7447-19961001-10
55. Beris AE, Lykissas MG, Payatakes A, et al. Free vascularized fibular graft for treatment of pathological femoral neck fracture and osteonecrosis of the femoral head: A case report with a long-term follow-up. Microsurgery. 2009;29(3):240–3. https://doi.org/10.1002/micr.20598
56. Zhang C, Sun Y, Chen S, et al. Free vascularised fibular graft for post-traumatic osteonecrosis of the femoral head in teenage patients. J Bone Joint Surg Br. 2011;93(10):1314–9. https://doi.org/10.1302/0301-620X.93B10.26555
57. Garrigues GE, Aldridge III JM, Friend JK, et al. Free vascularized fibular grafting for treatment of osteonecrosis of the femoral head secondary to hip dislocation. Microsurgery. 2009;29(5):342–5. https://doi.org/10.1002/micr.20648
58. Kawate K, Yajima H, Sugimoto K, et al. Indications for free vascularized fibular grafting for the treatment of osteonecrosis of the femoral head. BMC Musculoskelet Disord. 2007;8(1):1–8. https://doi.org/10.1186/1471-2474-8-78
59. Yoo M-C, Kim K-I, Hahn C-S, et al. Long-term follow up of vascularized fibular grafting for femoral head necrosis. Clin Orthop Relat Res. 2008;466(5):1133–40. https://doi.org/10.1007/s11999-008-0204-9

60. Zhang C, Zeng B, Xu Z, et al. Treatment of femoral head necrosis with free vascularized fibula grafting: A preliminary report. Microsurgery. 2005;25(4):305–9. https://doi.org/10.1002/micr.20118
61. Kim S-Y, Kim Y-G, Kim P-T, et al. Vascularized compared with nonvascularized fibular grafts for large osteonecrotic lesions of the femoral head. J Bone Joint Surg. 2005;87(9):2012–8. https://doi.org/10.2106/JBJS.D.02593
62. Plakseychuk AY, Kim S-Y, Park B-C, et al. Vascularized compared with nonvascularized fibular grafting for the treatment of osteonecrosis of the femoral head. J Bone Joint Surg. 2003;85(4):589–96. https://doi.org/10.2106/00004623-200304000-00001
63. Malizos KN, Soucacos PN, Beris AE. Osteonecrosis of the femoral head. Hip salvaging with implantation of a vascularized fibular graft. Clin Orthop Relat Res. 1995(314):67–75.
64. Richards RR. Bone grafting with microvascular anastomosis in osteonecrosis of the femoral head. Semin Arthroplasty. 1991;2(3):198–207.
65. Sotereanos DG, Plakseychuk AY, Rubash HE. Free vascularized fibula grafting for the treatment of osteonecrosis of the femoral head. Clin Orthop Relat Res. 1997(344):243–56.
66. Louie BE, McKee MD, Richards RR, et al. Treatment of osteonecrosis of the femoral head by free vascularized fibular grafting: An analysis of surgical outcome and patient health status. Can J Surg. 1999;42(4):274–83.
67. Soucacos PN, Beris AE, Malizos K, et al. Treatment of avascular necrosis of the femoral head with vascularized fibular transplant. Clin Orthop Relat Res. 2001(386):120–30. https://doi.org/10.1097/00003086-200105000-00016
68. Tetik C, Başar H, Bezer M, et al. Comparison of early results of vascularized and non-vascularized fibular grafting in the treatment of osteonecrosis of the femoral head. Acta Orthop Traumatol Turc. 2011;45(5):326–34. https://doi.org/10.3944/AOTT.2011.2259
69. Eward WC, Rineer CA, Urbaniak JR, et al. The vascularized fibular graft in precollapse osteonecrosis: Is long-term hip preservation possible? Clin Orthop Relat Res. 2012;470(10):2819–26. https://doi.org/10.1007/s11999-012-2429-x
70. Gao YS, Chen SB, Jin DX, et al. Modified surgical techniques of free vascularized fibular grafting for treatment of the osteonecrosis of femoral head: Results from a series of 407 cases. Microsurgery. 2013;33(8):646–51. https://doi.org/10.1002/micr.22149
71. Gokhan M, Ulusal AE, Atik A, et al. Descending branch of the lateral circumflex femoral artery as a recipient vessel for vascularized fibular grafts: Clinical case series. Microsurgery. 2014;34(8):633–7. https://doi.org/10.1002/micr.22299
72. Aldridge JM 3rd, Urbaniak JR. Avascular necrosis of the femoral head: Role of vascularized bone grafts. Orthop Clin North Am. 2007;38(1):13–22, v. https://doi.org/10.1016/j.ocl.2006.10.012
73. Fujimaki A, Yamauchi Y. Vascularized fibular grafting for treatment of aseptic necrosis of the femoral head–Preliminary results in four cases. Microsurgery. 1983;4(1):17–22. https://doi.org/10.1002/micr.1920040108
74. Phemister DB. Treatment of the necrotic head of the femur in adults. J Bone Joint Surg Am. 1949;31A(1):55–66.
75. Bonfiglio M, Bardenstein MB. Treatment by bone-grafting of aseptic necrosis of the femoral head and non-union of the femoral neck (Phemister technique). J Bone Joint Surg Am. 1958;40–A(6):1329–46.
76. Wang GJ, Thompson RC. Treatment of aseptic necrosis of the femoral head with Phemister-type bone grafts. South Med J. 1976;69(3):305–8. https://doi.org/10.1097/00007611-197603000-00017
77. Nelson LM, Clark CR. Efficacy of Phemister bone grafting in nontraumatic aseptic necrosis of the femoral head. J Arthroplasty. 1993;8(3):253–8. https://doi.org/10.1016/s0883-5403(06)80086-0
78. Wu CT, Yen SH, Lin PC, et al. Long-term outcomes of Phemister bone grafting for patients with non-traumatic osteonecrosis of the femoral head. Int Orthop. 2019;43(3):579–87. https://doi.org/10.1007/s00264-018-4013-9
79. Keizer SB, Kock NB, Dijkstra PD, et al. Treatment of avascular necrosis of the hip by a non-vascularised cortical graft. J Bone Joint Surg Br. 2006;88(4):460–6. https://doi.org/10.1302/0301-620X.88B4.16950
80. Smith K, Bonfiglio M, Montgomery W. Non-traumatic necrosis of the femoral head treated with tibial bone-grafting. A follow-up note. J Bone Joint Surg. 1980;62(5):845–7.
81. Buckley PD, Gearen PF, Petty RW. Structural bone-grafting for early atraumatic avascular necrosis of the femoral head. J Bone Joint Surg Am. 1991;73(9):1357–64.
82. Yue J, Guo X, Wang R, et al. Single approach to double-channel core decompression and bone grafting with structural bone support for treating osteonecrosis of the femoral head in different stages. J Orthop Surg Res. 2020;15(1):198. https://doi.org/10.1186/s13018-020-01717-3

83. Hsu JE, Wihbey T, Shah RP, et al. Prophylactic decompression and bone grafting for small asymptomatic osteonecrotic lesions of the femoral head. Hip Int. 2011;21(6):672–7. https://doi.org/10.5301/HIP.2011.8760
84. Israelite C, Nelson CL, Ziarani CF, et al. Bilateral core decompression for osteonecrosis of the femoral head. Clin Orthop Relat Res. 2005;441:285–90. https://doi.org/10.1097/01.blo.0000192365.58958.84
85. Steinberg ME, Larcom PG, Strafford B, et al. Core decompression with bone grafting for osteonecrosis of the femoral head. Clin Orthop Relat Res. 2001;(386):71–8. https://doi.org/10.1097/00003086-200105000-00009
86. Seyler TM, Marker DR, Ulrich SD, et al. Nonvascularized bone grafting defers joint arthroplasty in hip osteonecrosis. Clin Orthop Relat Res. 2008;466(5):1125–32. https://doi.org/10.1007/s11999-008-0211-x
87. Rosenwasser MP, Garino JP, Kiernan HA, et al. Long term followup of thorough debridement and cancellous bone grafting of the femoral head for avascular necrosis. Clin Orthop Relat Res. 1994;(306):17–27.
88. Ganz R, Büchler U. Overview of attempts to revitalize the dead head in aseptic necrosis of the femoral head—Osteotomy and revascularization. Hip. 1983;296–305.
89. Hori Y, Tamai S, Okuda H, et al. Blood vessel transplantation to bone. J Hand Surg Am. 1979;4(1):23–33. https://doi.org/10.1016/s0363-5023(79)80101-x
90. Mont MA, Etienne G, Ragland PS. Outcome of nonvascularized bone grafting for osteonecrosis of the femoral head. Clin Orthop Relat Res. 2003;(417):84–92. https://doi.org/10.1097/01.blo.0000096826.67494.38
91. Wang B-L, Sun W, Shi Z-C, et al. Treatment of nontraumatic osteonecrosis of the femoral head using bone impaction grafting through a femoral neck window. Int Orthop. 2010;34(5):635–9. https://doi.org/10.1007/s00264-009-0822-1
92. Yildiz C, Erdem Y, Koca K. Lightbulb technique for the treatment of osteonecrosis of the femoral head. Hip Int. 2018;28(3):272–7. https://doi.org/10.5301/hipint.5000576
93. Cheng Q, Zhao F-C, Xu S-Z, et al. Modified trapdoor procedures using autogenous tricortical iliac graft without preserving the broken cartilage for treatment of osteonecrosis of the femoral head: A prospective cohort study with historical controls. J Orthop Surg Res. 2020;15(1):183. https://doi.org/10.1186/s13018-020-01691-w
94. Brojeni SS, Hesarikia H, Rahimnia A, et al. Treatment of femoral head osteonecrosis (Stages 2B, 3 Ficat) through open direct core decompression by allograft impaction and light bulb technique. Arch Bone Jt Surg. 2020;8(5):613–9. https://doi.org/10.22038/abjs.2020.49380.2452
95. Ko JY, Meyers MH, Wenger DR. "Trapdoor" procedure for osteonecrosis with segmental collapse of the femoral head in teenagers. J Pediatr Orthop. 1995;15(1):7–15. https://doi.org/10.1097/01241398-199501000-00003
96. Liu Q, He H-B, Zeng H, et al. Modified trapdoor procedures by surgical dislocation approach to treat chondroblastoma of the femoral head. Bone Joint J. 2019;101–B(6):732–8. https://doi.org/10.1302/0301-620X.101B6.BJJ-2018-1599.R1
97. Mont MA, Einhorn TA, Sponseller PD, et al. The trapdoor procedure using autogenous cortical and cancellous bone grafts for osteonecrosis of the femoral head. J Bone Joint Surg Br. 1998;80(1):56–62. https://doi.org/10.1302/0301-620x.80b1.7989
98. Gagala J, Tarczyńska M, Gawęda K. Clinical and radiological outcomes of treatment of avascular necrosis of the femoral head using autologous osteochondral transfer (mosaicplasty): Preliminary report. Int Orthop. 2013;37(7):1239–44. https://doi.org/10.1007/s00264-013-1893-6
99. Hailer N. 20 years of porous tantalum in primary and revision hip arthroplasty—Time for a critical appraisal. Acta Orthop. 2018;89(3):254–5. https://doi.org/10.1080/17453674.2018.1463007
100. Veillette CJ, Mehdian H, Schemitsch EH, et al. Survivorship analysis and radiographic outcome following tantalum rod insertion for osteonecrosis of the femoral head. J Bone Joint Surg. 2006;88 Suppl 3):48–55. https://doi.org/10.2106/JBJS.F.00538
101. Liu G, Wang J, Yang S, et al. Effect of a porous tantalum rod on early and intermediate stages of necrosis of the femoral head. Biomed Mater. 2010;5(6):065003. https://doi.org/10.1088/1748-6041/5/6/065003
102. Liu Z, Guo W, Li Z, et al. Porous tantalum rods for treating osteonecrosis ofthe femoral head. Genet Mol Res. 2014;13(4):8342–52. https://doi.org/10.4238/2014.October.20.10
103. Yang P, Bian C, Huang X, et al. Core decompression in combination with nano-hydroxyapatite/polyamide 66 rod for the treatment of osteonecrosis of the femoral head. Arch Orthop Trauma Surg. 2014;134(1):103–12. https://doi.org/10.1007/s00402-013-1885-4

104. Pakos EE, Megas P, Paschos NK, et al. Modified porous tantalum rod technique for the treatment of femoral head osteonecrosis. World J Orthop. 2015;6(10):829–37. https://doi.org/10.5312/wjo.v6.i10.829
105. Zhao D, Liu B, Wang B, et al. Autologous bone marrow mesenchymal stem cells associated with tantalum rod implantation and vascularized iliac grafting for the treatment of end-stage osteonecrosis of the femoral head. BioMed Res Int. 2015;2015:240506. https://doi.org/10.1155/2015/240506
106. Zhang X, Wang J, Xiao J, et al. Early failures of porous tantalum osteonecrosis implants: A case series with retrieval analysis. Int Orthop. 2016;40(9):1827–34. https://doi.org/10.1007/s00264-015-3087-x
107. Li B, Lei P, Liu H, et al. Clinical value of 3D printing guide plate in core decompression plus porous bioceramics rod placement for the treatment of early osteonecrosis of the femoral head. J Orthop Surg Res. 2018;13(1):1–7. https://doi.org/10.1186/s13018-018-0812-3
108. Fang Y, Ding C, Wang Y, et al. Comparison of core decompression and porous tantalum rod implantation with conservative treatment for avascular necrosis of the femoral head: A minimum 18 month follow-up study. Exp Ther Med. 2020;20(1):472–8. https://doi.org/10.3892/etm.2020.8669
109. Peng K, Wang Y, Zhu J, et al. Repair of non-traumatic femoral head necrosis by marrow core decompression with bone grafting and porous tantalum rod implantation. Pak J Med Sci. 2020;36(6):1392–6. https://doi.org/10.12669/pjms.36.6.2176
110. He M, Wei Q, Chen Z, et al. Porous tantalum rod implantation is associated with low survival rates in patients with type C2 osteonecrosis of the femoral head but has no effect on the clinical outcome of conversion total hip arthroplasty: A retrospective study with an average 8-year follow-up. BMC Musculoskelet Disord. 2020;21(1):1–9. https://doi.org/10.1186/s12891-020-03860-8
111. Lu Y, Lu X, Li M, et al. Minimally invasive treatment for osteonecrosis of the femoral head with angioconductive bioceramic rod. Int Orthop. 2018;42(7):1567–73. https://doi.org/10.1007/s00264-018-3919-6
112. Ficat P, Arlet J, Vidal R, et al. [Therapeutic results of drill biopsy in primary osteonecrosis of the femoral head (100 cases)]. Rev Rhum Mal Osteoartic. 1971;38(4):269–76.
113. Hungerford DS. Response: The role of core decompression in the treatment of ischemic necrosis of the femoral head. Arthritis Rheum. 1989;32(6):801–6. https://doi.org/10.1002/anr.1780320623
114. Hungerford DS. The use of an injectable calcium sulfate/calcium phosphate composite in the treatment of osteonecrosis of the femoral head. J bone Joint Surg Br. 2007;91-B(SUPP_II):331.
115. Wood ML, McDowell CM, Kelley SS. Cementation for femoral head osteonecrosis: A preliminary clinic study. Clin Orthop Relat Res. 2003;(412):94–102. https://doi.org/10.1097/01.blo.0000072465.53786.58
116. Jiang HJ, Huang XJ, Tan YC, et al. Core decompression and implantation of calcium phosphate cement/Danshen drug delivery system for treating ischemic necrosis of femoral head at Stages I, II and III of antigen reactive cell opsonization. Chin J Traumatol. 2009;12(5):285–90.
117. Civinini R, De Biase P, Carulli C, et al. The use of an injectable calcium sulphate/calcium phosphate bioceramic in the treatment of osteonecrosis of the femoral head. Int Orthop. 2012;36(8):1583–8. https://doi.org/10.1007/s00264-012-1525-6
118. Landgraeber S, Warwas S, Claßen T, et al. Modifications to advanced core decompression for treatment of avascular necrosis of the femoral head. BMC Musculoskeletl Disord. 2017;18(1):479. https://doi.org/10.1186/s12891-017-1811-y
119. Sen RK. Management of avascular necrosis of femoral head at pre-collapse stage. Indian J Orthop. 2009;43(1):6–16. https://doi.org/10.4103/0019-5413.45318