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Wear Performance of Materials Used in Artificial Hip Joints

—1. THR Diameter/Wear Ratios in Artificial Hip Joints: A 63-Year Charnley Legacy

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Abstract

Following the 1956 introduction of polytetrafluoroethylene (PTFE) total hip replacements (THR), a concerning question was how much wear debris could periarticular tissues tolerate before onset of adverse reactions. John Charnley's historical studies demonstrated that wear in PTFE ("Teflon") bearings led to destructive hip lesions within 3 years. While smaller femoral heads somewhat reduced wear, Teflon debris remained intolerable. In 1962 Charnley's laboratory identified polyethylene (UHMWPE) as a substantially more wear-resistant polymer, launching the Charnley low-friction arthroplasty (LFA) in 1962. Three important results were clear: 1) femoral head diameter is the major wear determinant, *i.e.* the Charnley Diameter-Wear effect ("CDW"), 2) laboratory studies demonstrated UHMWPE had superior wear resistance to PTFE, and 3) major differences existed between laboratory predictions and clinical wear data, a phenomenon we shall term Laboratory Wear Divergence ("LWD"). This review examines wear data published by four laboratories to evaluate reproducibility, accuracy, and relevance of historical wear studies (1956-1976). Charnley's wear laboratory described Teflon:UHMWPE wear ratios ranging 200:1 to 500:1 (1969). The introduction of UCLA's wear machine in 1978 provided a dramatic improvement in experimental procedures. Using gravimetric weight-loss measurements in bovine-serum lubricated studies, the UCLA method for 316SS:UHMWPE samples achieved a wear precision of 0.2 mm^3/Mc (±15%). Despite this precision, the LWD wear ratio (1600:1) for PTFE:UHMWPE wear greatly exceeded Charnley's clinical (16:1) and laboratory (200:1) ratios. Orthopedic Hospital of Los Angeles (OHLA) reported (1981) a simulator design that incorporated multi-directional motion using crossing-path wear (CPW) motion. The pilot PTFE study (28 mm THR) yielded exceptionally high wear (2100 mm^3/Mc), representing a debris release of 180 mm^3 per 24-hours and prompted termination of study. This PTFE simulator wear overshot the clinical 28 mm Teflon wear (1171 mm^3/year), a ratio of 1.8:1. This PTFE:Teflon wear (laboratory vs clinical) will be designated "WRP". Kinamed (1996) investigated the Charnley-diameter-wear effect (CDW) using Al_2O_3: UHMWPE THR (22.25, 26, 28 mm dia.). Assuming Charnley's clinical report is typical of LFA (60 mm^3/year), the UHMWPE simulator ratio PCR = 0.6:1, *i.e.* it undershot the clinical UHMWPE datum. The 32.8 mm^3/Mc wear rate (28 mm THR) corresponded to a CDW ratio of 6.9%, closely matching the Teflon clinical CDW value (6.8%), demonstrating the head-diameter-wear phenomenon was also present in UHMWPE THR. LLUMC conducted 8 PTFE THR experiments using four THR diameters to evaluate precision and reproducibility in laboratory studies. All wear trends were linear, and the Charnley-Diameter-Wear algorithm was present with both CoCr and ceramic femoral heads and precision comparable to UCLA's report. With simulator PTFE wear-rate (28 mm THR) averaging 4227 mm^3/Mc and Kinamed's UHMWPE study averaging 32.8 mm^3/Mc, the THR laboratory ratio (LWD) was 160:1. The grand-average wear-rates (7-replicated PTFE studies) were in perfect linear accordance with the CDW algorithm but again overshot Charnley's Teflon data (WRP ratio = 3.6:1). Thus, simulator THR wear was underestimated in UHMWPE bearings and overestimated in PTFE bearings. With the precision evident in computer-controlled simulators, and using Charnley's wear algorithms as internal controls, the most likely laboratory-relevant parameter for improved clinical simulation would appear to be choice of bovine-serum lubricant.

Keywords

Total Hip Replacement (THR), Wear, Teflon, Ultra-High Molecular Weight Polyethylene (UHMWPE), Simulator Wear Dichotomy (SWD), Femoral Head Diameter, *In Vitro* Wear Simulation, Charnley Hip Arthroplasty

1. Introduction

The history of total hip replacement surgery (THR) can be traced back to England in the 1940s. Artificial reconstructive implants were in great need following World War II. Several hip design and material developments emerged, first with metal-on-metal (MOM) hip bearings, then progressing to plastic materials. In those days, very little was known regarding wear test parameters. A well-known series of metal-on-metal THR (MOM) began with English surgeon G. McKee in the 1950s using a CoCr femoral head and socket design. Unfortunately, the 54% failure rate was unacceptable [1]. In the 1950s, plastic-on-plastic and metal-on-plastic designs were introduced by another English surgeon, John Charnley, who was searching for a "slippery" plastic that would offer low-friction properties. Charnley developed several hip designs from 1958 to 1963. Beginning his pioneering studies at the "Wrightington Centre for Hip Surgery" (WCH), he used "Fluon" (PTFE, ICI Chemicals, UK) and several other brands [1] [2]. Nevertheless, TeflonTM (Dupont, USA) is the polytetrafluorethylene brand most referenced in publications describing Charnley's results, so we shall adhere to that convention.

Charnley's large-diameter, hip-resurfacing designs (RSA) were initially custom-made at WCH. Details of the "Teflon" shells are few. The RSA design offered several advantages: 1) low-friction bearings, 2) the ability to be custom machined at WCH, 3) the reshaping of arthritic femoral heads was possible during surgery, and 4) hip-joint stability was improved with such large-diameter hips. Charnley's pioneering THR began with a combination of a Teflon socket and a one-piece, stainless-steel stem and head [1] [2]. The femoral prosthesis was a molybdenum-enhanced stainless steel (EN58J: marine/chemical environments), forged in Sheffield (UK) and machined by Chas. F. Thackray Ltd. We shall refer to Charnley's femoral head as 316SS material. Charnley's patient criteria included those most infirm and deconditioned cases suffering the most from hip arthritis. The first 316SS/Teflon THR was implanted in 1959. Some patients regained full mobility after surgery, while others did not. Although such hip replacements greatly relieved pain, all "Teflon" components wore rapidly (**Figure 1**) with wear debris producing extensive foreign-body reactions. By the end of 1961, the clinical study included 300 patients, and in early 1962 adverse tissue reactions were noted around the hip implants. The decision was made that Teflon sockets were unsuitable as hip bearings and the majority of cases would need to be revised.

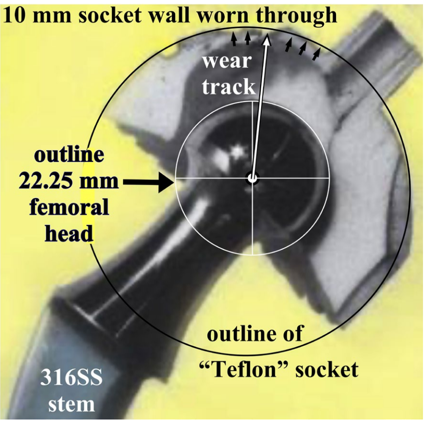


Figure 1. Retrieved Teflon socket sectioned to measure wear track [3] [4] (ref: https://www.digitalcollections.manchester.ac.uk/view/MH-02015-00027/1).

Laboratory attempts to "simulate" wear over the ensuing 15 years faced a myriad of "unknowns". The first MOM simulator study was published in England in 1966 [5]. Since that time, wear studies in artificial hip joints have consumed substantial laboratory time and resources [6]-[9]. The majority of laboratory research naturally focused on Charnley's discovery of UHMWPE with its exceptional wear resistance [3]. However, such studies required months of diligent work for wear machines having only 2 - 4 test channels [5] [6]. Consequently, a decade later, Professor Swanson was moved to comment, "No significant feature of current practice has been based on results obtained in simulators" [10]. Professor Dumbleton appeared slightly more optimistic, remarking that "Simulators are useful, but they have been improperly used" [11]. In this report, we shall revisit the challenges that faced laboratory wear studies from 1969 to 2000. Our review will explore key wear developments in 5 sections as follows:

1969 Wrightington Center for Hip Replacement (WCH): wear machine (N = 4 test samples);

1978 Orthopaedic Biomechanics Laboratory (UCLA): wear machine (N = 12 samples);

1981 Orthopaedic Hospital of Los Angeles (OHLA): Hip Simulator (N = 10 THR);

1987 Kinamed Inc. (KMD), Newbury Park: Hip simulator studies (N = 9 THR);

1997 Loma Linda University Medical Center (LLUMC): Hip simulator studies (N = 9, 12 THR).

2. Methods

It goes without saying that laboratory measurements of wear need to be relatable to wear measurements made in patients with total hip replacements (THR). Measurements of patients' THR wear were commonly given in linear units. Charnley reported patient wear rates as "total linear wear per year" (S mm/year) [2]-[4]. In contrast, test durations in laboratory wear machines may be measured by hours of study, numbers of test cycles (N), and sliding distance per experiment (S mm). Charnley used "inches per mile of sliding" distance in the WHC wear machine. A hip simulator has the advantage of accumulating millions of gait cycles and measuring THR wear similarly to clinical studies. The main challenge is how to relate laboratory wear data to the number of steps walked by an "average" patient in one year. There are many variations; some hip patients may log hours of television viewing daily, while others may walk 10,000 steps daily. It has been reported that elderly people on vacation walk 1.5 to 6.5 thousand cycles per day. This is believed to approximate one million walking steps per year [12]. Charnley estimated his THR patients could walk 2.5 miles per day [13]. Combining the Seedhom and Charnley estimates, a 22.25 mm diameter hip joint would arguably have a sliding distance (S mm) amounting to approximately 10.7 km per year (corresponding to a 55˚ hip flexion arc) [14]-[16].

Simulator studies of polyethylene wear commonly use the "weight-loss" method with correction for fluid absorption [6] [8]. These data may be converted to linear wear rates (S mm/Mc) and volumetric wear rates (WR mm^3/Mc). The latter is helpful in defining the volume of wear debris released into the hip joint [8] [14] [17] [18]. Estimates of clinical wear rates per year (WR_c mm^3/year) are typically presented as comparable to laboratory wear simulations per million cycles of test duration (WR_s mm^3/Mc).

With simulators now able to evaluate multiple diameters of THR simultaneously, a new wear term was created to define the relationship of THR wear rates to diametral differences in selected THRs [19]. The volumetric wear index (VWI) represents the percent change in volumetric wear rates per millimeter increase in THR diameter. The wear gradient normalizes simulator wear rates (WR) produced due to THR diametral differences, *i.e.*, Kp = WR/mm (represented by mm^3/Mc/mm). This term permits comparisons between different diameters of THR as reported in clinical and simulator studies. The Charnley-Diameter-Wear index (CDW) is also used in this review because it relies on the 22.25 mm THR as the primary datum (see **Figure A1**).

3. Results

3.1. Clinical/Laboratory Wear Ratios (4 THR Dia. 316SS/Teflon)

Review of laboratory wear methodologies must begin with the clinical and laboratory studies of John Charnley [3] [4] [13]. The earliest wear results (41.5 mm diameter) are represented by only two cases (**Table 1**) before the Charnley team realized there was a need to save all Teflon components retrieved during revision surgeries. Teflon THR wear, begun in 1959 with the 25.25 mm design, was analyzed in 58 patients that represented 19% of his cohort of 300 cases. These would help document patient selection and modifications to THR designs that influenced in-vivo wear. Charnley had developed a strong interest in the tribology of biomaterials, *i.e.*, the science of friction and wear in implantable bearings. He attributed excessive wear in the earliest Teflon cases to the large "hip sliding distance" in 41.5 mm sockets. Charnley accordingly downsized THR diameters in 3 stages—41.5 mm, 28.5 mm, 25.25 mm, ending with 22.25 mm.

Table 1. Wear data from Teflon retrievals [3].

THR#	Dia. (mm)	THR arc (S mm)	WR (mm^3/year)
2	41.5	16.7	1905
6	28.5	11.4	1134
11	25.25	10.1	1006
39	22.25	8.9	835

Reducing head diameters from 41.5 mm to 22.25 mm decreased the arcs of sliding from 16.7 mm to 8.9 mm.

The THR diameters developed by Charnley (41.5, 28.5, 25.25, 22.25) appear unique today. It is to be remembered that the 1" and 1/8" scales were in common use in the UK in the 1950s-60s. The corresponding hip diameters machined at WHC would have been 1 5/8", 1 1/8", 1" and 7/8". Thus, Charnley's introduction in 1962 of the 316SS:UHMWPE THR (25.25 mm dia.) represented a 0.5" reduction from his largest THR [2]. The other remarkable finding in Charnley's selection of diameters was that they lined up perfectly as a linear-regression trend [19].

Reducing head diameters decreased the arc of hip sliding from 16.7 mm to 8.9 mm (**Figure 2(a)**), and the Teflon wear rates dropped from 1905 to 835 mm^3/year in patients (**Figure 2(b)**). This supported Charnley's hypothesis that small heads generated less wear. However, despite a favorable 56% wear reduction overall, the foreign-body response to wear debris remained intolerable. Such clinical results were devastating to Charnley, and he considered abandoning his concept of a "Low Friction Arthroplasty" [2]. Fortunately for Charnley, the wear laboratory at Wrightington Hip Center (WHC) made a very timely and significant discovery. A salesman visiting WHC had a polymer sample labelled "Ultra High Molecular Weight Polyethylene" (UHMWPE), marketed under the tradename "RCH1000" (RhurChemie AG Works, Germany). Harry Craven, Charnley's engineering assistant, was given a disc "several inches in diameter" to machine into wear samples (May-Jun period, 1962) [2]. He had assembled a wear machine, likely the first used to study polymer bearings in a laboratory setting (WHC, 1962). The machine oscillated test samples under four stainless-steel (316SS) femoral heads with water as the lubricant (**Figure 3**). The movement of the femoral heads during the test (representing wear) was measured continually by sensitive air gauges. The Teflon and UHMWPE test samples revealed wear rates of 79 and 0.39 microns per kilometer of sliding distance in the wear machine (um/km), respectively (**Table 2**). UHMWPE wear was reduced ×200-fold compared to Teflon in the laboratory [2]. Nevertheless, a ×200-fold laboratory prediction could have been unsettling because such a pilot wear study could have been quite arbitrary. However, on a yearly basis, retrieval and later radiographic studies showed that Teflon and UHMWPE sockets averaged 2.29 mm/year and 0.16 mm/year, respectively (**Table 3**). Compared to Teflon cases, patient wear with UHMWPE sockets was reduced ×14.4-fold.

Table 2. WHC wear rates for Teflon and UHMWPE samples [2].

Laboratory	Inch/mile	mm/km	um/km
TEFLON	0.005000	0.07888	79
UHMWPE	0.000025	0.00039	0.39
ratio	×**200**		

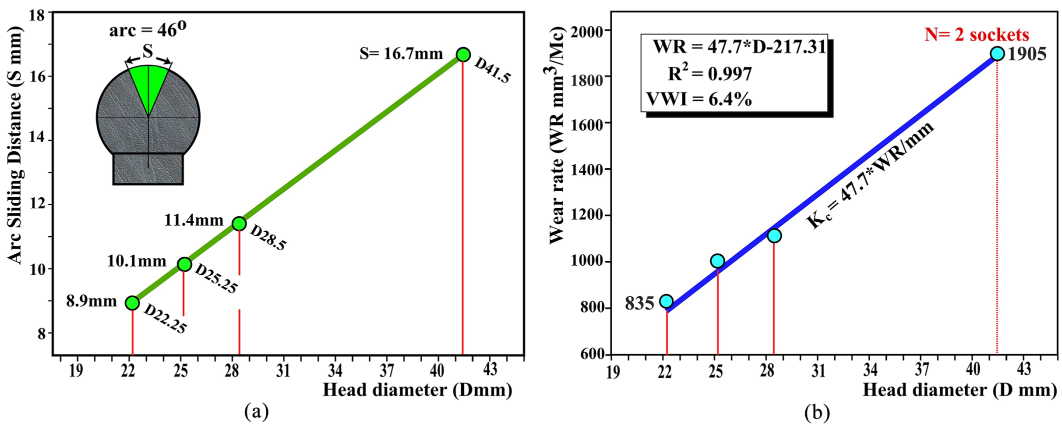


Figure 2. Teflon wear parameters; (a) Hip sliding distance (S) varies with THR diameter [3] [4], and (b) Teflon wear rates vary linearly with THR diameter [19].

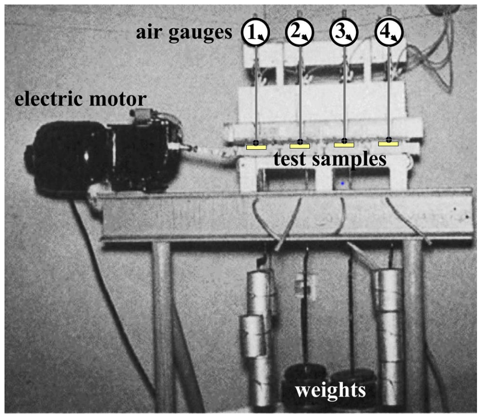


Figure 3. 4-station wear machine in the WHC laboratory, 1961-1963 era (see **Table 4**) [2].

Table 3. Clinical wear rates of Teflon UHMWPE samples [2] [3] [13].

Patients	Inch/year	mm/yr	um/week
TEFLON	0.0900	2.286	44
UHMWPE	0.0063	0.159	3
ratio	×**14.4**		

Charnley later reported Teflon: UHMWPE laboratory wear ratios as ×500-fold and clinical wear ratios as ×16.5-fold (**Figure 4**). In doing so, Charnley revealed a major disconnect between laboratory predictions and clinical reality. The actual clinical ratios reported may have varied somewhat (×14.4, ×16.5, ×18), but the differences in laboratory wear rates LWD = ×200 (**Table 2**) and ×500 (**Figure 4**) were too large to ignore. There was no possible way to disagree with Charnley's clinical assessment of THR wear. From today's perspective, the design of the WHC test machine was very basic, and we could probably deem at least five of WHC's wear parameters(*) invalid (**Table 4**) [6]. In particular, dimensional assessment of Teflon wear offered no compensation for polymer creep, and wear trends represented incredibly small dimensional changes (**Table 2**). As a case in point, Charnley's clinical experiences revealed very different results. As indicated (**Table 3**), the Teflon wear rates averaged 44 microns per week *in vivo*. One micrometer (µm) represents a very small dimension. In addition, water lubrication would certainly be considered irrelevant today [6] [20].

> ***"Comparing the wear resistance of Teflon and H.D.P. in the laboratory, both lubricated with distilled water, it would appear that H.D.P. is at least 500 times more wear resistant than Teflon; but taking 1mm in 5 years as the worst wear performance of H.D.P. in the human subject, and the worst wear of Teflon in the human as 10mm in 3 years, the H.D.P. in these circumstances would seem to be only 16.5 times more durable than Teflon."***
>
> **John Charnley, Internal Report #23, January 1970**

Figure 4. In WHC tests, the 316SS:Teflon to 316SS:UHMWPE ("HDP") wear ratio (LWD) was 500:1 whereas clinical wear ratio was only 16.5:1.

Table 4. WHC wear rates Teflon [2] compared to OHLA simulator [8].

Parameters	H. Craven test	Simulators
metal head	316 SS	316SS, CoCr
polymer sample	Fluon	PTFE
geometry	sphere-on-flat	THR
applied load	constant	Paul gait (2 kN)
contact pressure	2.1 MPa	3.5 - 7 MPa
samples	4	9 - 12
sliding path	LPW	CPM
lubricants	water	bovine serum
measurement	dimensional	weight-loss
duration	3 weeks	2 weeks
wear units	inch/mile	mm^3/Mc

The very good news for Charnley's team was the WHC prediction that UHMWPE had much higher wear resistance than Teflon. Charnley made a pivotal shift to UHMWPE sockets beginning in November 1962. By the end of 1969, Charnley had performed 3800 THR surgeries using UHMWPE sockets. Subsequent radiographic studies revealed very low wear rates (60 to 90 mm^3/year), *i.e.*, a most welcome improvement compared to Teflon (**Tables 1-3**). This truly remarkable result set the stage for the worldwide use of hip-joint replacements featuring 22.25 mm femoral heads (stainless steel) and UHMWPE sockets (**Figure 5**). We now recognize at least six wear axioms that may relate to Charnley's studies (**Table 5**).

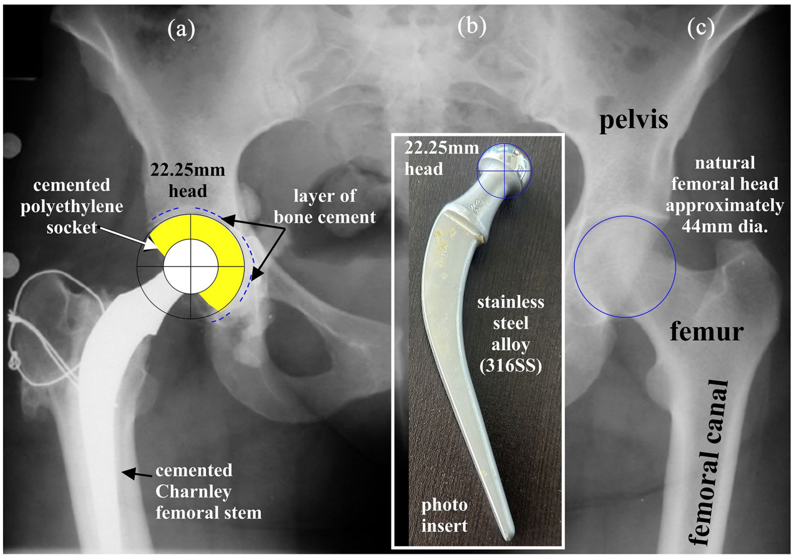


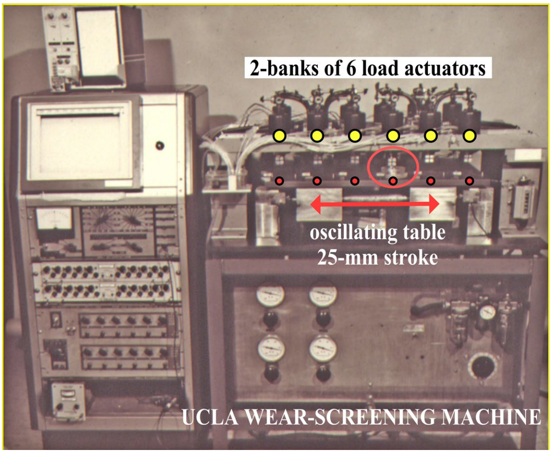
Figure 5. Bilateral radiograph depicting Charnley hip replacements, courtesy of the authors (EJS); (a) Cemented THR, (b) femoral stem photo inset, (c) natural hip joint (circled).

Table 5. Contrasting patient wear and laboratory wear parameters.

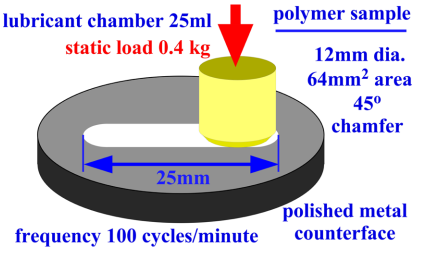
ID	Wear Recommendations	Wear parameters
1	Different units of wear	clinical wear = mm^3/year, simulator = mm^3/Mc
2	Patients are infirm and deconditioned.	Simulator runs a 2 kN load cycle at 60 cpm frequency.
3	High wear is unmeasurable in patients.	Sockets excluded (heads worn through 10 mm wall)
4	Wear-screening machines	Unable to simulate the "crossing-path" motion of the human hip.
5a	Wear tests do not provide adequate simulation.	(a) Choice of simulator "lubricant" may be key.
5b		(b) Lubricant degradation during the test may be a key.

3.2. UCLA: Laboratory Procedures (Multi-Station Test Machine)

The Biomechanics Research Section of UCLA-Orthopaedics presented results from a multi-specimen wear machine (Figure 6(a)) that greatly improved scientific perceptions of laboratory wear tests (Table 6). This tabletop machine used an oscillating platform to slide 12 polymer pins across either metal or ceramic plates (Figure 6(b)), with the tracks producing linear-path wear (LPW) [6] [7].



(a)



(b)

Figure 6. UCLA wear-screening machine; (a) 12 sample stations loaded on the oscillating table and (b) pin-on-flat wear sample (LPW motion) [6].

Table 6. UCLA-recommended wear test procedures [6] [7].

Wear Recommendations	Wear parameters
It is recommended to use a biological lubricant.	bovine serum
Recommended wear measurement method (polymers)	by weight loss with corrections for fluid absorption
Use of soak-control samples is recommended.	pre-testing and also during wear tests
A minimum of 3 replicate samples per selected material pair.	Weight-loss average defined by the linear wear phase
Machine design for three material pairs (three replicates each)	Simultaneous evaluation using multiple samples
Duration of wear experiments	Judged by evidence of linear regression trends

Being able to accurately measure polymer wear using rigorous "weight-loss" techniques represented a breakthrough for UCLA. This required compensation for weight gains due to fluid absorption. Wear and soak-control specimens were pre-soaked in bovine serum for several weeks prior to testing (Table A2). Meticulous cleaning and dehydration schedules were specified prior to each weighing session. Test durations of 2.5 - 3.5 Mc established linear wear trends for UHMWPE specimens. The repeatability of results using serum lubricant was judged excellent, given 316SS/UHMWPE = 0.2 mm^3/Mc (+15%) and CoCr/UHMWPE = 0.17 mm^3/Mc (+24%).

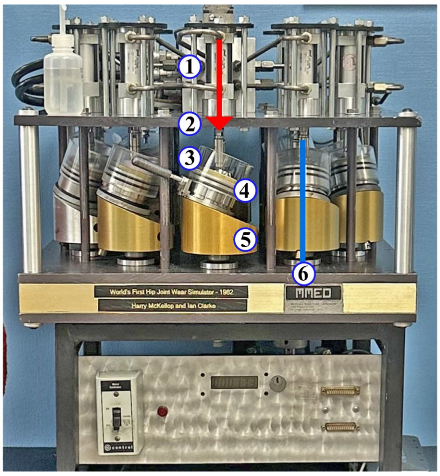
There was also a dramatic ranking given for polymers with known clinical experience (Table 6). UCLA's Teflon ratio (SWD = 1610:1) was of particular interest. In the earlier WHC wear study, Charnley reported a Teflon: UHMWPE ratio LWD = 500:1 (Figure 4). The UCLA study, with the benefit of improved wear-measurement techniques, demonstrated a PTFE:PE ratio more than 3-fold higher than the WCH prediction. What made these laboratory wear ratios so extreme compared to the clinical ratio Charnley reported LWD = 14.4 (Table 3) and ×16.5 (Figure 4)? This question may have been asked but, as far as we know, has not been addressed in the literature. However, it is to be noted that the UCLA test recommendations have stood the test of time (Table 6 & Table 7) [21] [22].

Table 7. Laboratory wear ranking for polymers used in THR designs [6].

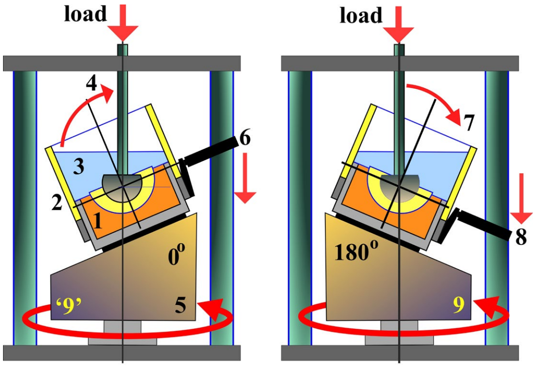
Polymer	WR mm^3/Mc	Scatter	LWD ratio
UHMWPE	0.2	15%	1
Delrin	9.4	13%	47
Polyester	160	23%	800
Teflon	322	3%	1610

3.3. OHLA: CoCr/PTFE Wear (Multi-Station THR Simulator)

Orthopaedic Hospital of Los Angeles (OHLA) acquired the first commercial, multi-station simulator in 1982 (MMED, Matco Corporation, La Canada, CA). This had an innovative cam mechanism that generated orbital motion in each of the 10 hip chambers (**Figure 7(a)**). This was a new introduction to laboratory wear studies, creating unique crossing-path motions (CPM) that closely mimicked human hip-joint articulation. The test chambers were constrained to move in the vertical XY-plane while experiencing alternating motion (YZ-plane) as the cam rotated (**Figure 7(b)**). A microprocessor synchronized both hip loading and motion profiles.



(a)



(b)

Figure 7. MMED multi-station hip simulator with crossing-path wear (CPW) motion (Matco Inc, La Canada, CA. [8]): (a) Ten axial-loading actuators (1) are mounted on the top plate (2), with Plexiglass lubricant chambers below (3) containing hip sockets (4) that orbit on a 23˚ inclined surface (5) as the cam rotates 360˚ on the vertical axis (6). (b) The sealed specimen chamber (2, 4) holding 40 ml of lubricant (3) oscillates through 46˚ arcs (5, 7) as the cam rotates (1, 9). Constrained in the vertical plane (6, 8), the socket follows continuous crossing-path wear profiles.

Surgeons at OHLA typically used Charnley-style THR (**Figure 5**) with 28 mm heads and UHMPWE. For the pilot study, 28 mm PTFE sockets were custom machined from bar stock. There was no need to sterilize PTFE sockets. Charnley's Teflon sockets had been sterilized overnight in a formaldehyde solution [2]. The 28 mm UHMPWE sockets (N = 14) were supplied sterile by the manufacturer. These were pre-soaked for 100 - 250 days, gaining 2.8 mg within 11 days, then stabilized at 56 µm/day gain. The sockets were mounted using acrylic molds in the base of each chamber (**Figure 7(b)**). Charnley's retrieval data for 28.25 mm Teflon sockets (**Table 1**) served as the clinical wear standard. OHLA's simulator with crossing-path wear (CPW) motion demonstrated extremely high PTFE wear and the study was terminated at 60,000 cycles. In contrast, the sterilized 28 mm UHMWPE sockets showed no visible wear in this short test. PTFE wear rates averaged 2100 mm^3/Mc, which almost doubled Charnley's Teflon rate (28.5 mm THR, 1134 mm^3/year) (**Table 4**). The equivalent linear wear rate in the PTFE sockets would be 3.4 mm/Mc, whereas Charnley's average was 1.78 mm/year. Clearly, simulator wear data were approximately 90% higher than the clinical target. Several factors may have contributed to this (**Table 8**).

Table 8. Contrasting clinical and simulator PTFE wear studies [2] [8].

ID	Challenging wear parameters	Contrasting patient and simulator wear variables
1	Different units of wear	clinical wear = mm^3/year, simulator = mm^3/Mc
2	Patients are infirm and deconditioned.	Simulator runs a 2 kN load cycle at a 60 cpm frequency.
3	High-wear Teflon sockets were excluded.	heads worn through 10 mm wall (unmeasurable)
4	Crossing-path wear motion	The simulator CPW model is too aggressive.
5a	Wear tests do not provide adequate simulation.	(a) Simulator "lubricant" may be a key factor.
5b		(b) Lubricant degradation may be a key factor.
6	PTFE bar stock versus Teflon brand	Differences in wear resistance are unknown.

This PTFE wear rate (28 mm THR: 2100 mm^3/Mc) represents the first simulator comparison to Charnley's clinical Teflon measurements (**Table 1**), but represents a ×1.9 times overshoot. A simulator running at 60 cycles per minute generates 86,400 cycles every 24 hours. It follows that the wear magnitude in this experiment represented 11.6 days of simulator run time (24-hour days). Thus, the volume of debris generated would be approximately 180 mm^3 every 24 hours. This would represent 0.2 ml debris volume. Possibly in the 40 ml lubricant chamber, PTFE wear was exacerbated compared to lower accumulation with UHMWPE. This was also the first demonstration of success with the UCLA test procedures used successfully in THR simulator studies and still applicable today [21]-[23].

3.4. Kinamed: Al_2O_3/UHMWPE Wear (Multi-Station THR Simulator)

By the mid-1980s, Kyocera's Bioceram division (Kyoto, Japan) found itself on the edge of a major transition. The company had years of ceramic expertise, but bringing ceramic THR innovations into the U.S. market required a "Master Device File" (MDF) to submit to the US Food and Drug Administration (FDA). An important part of the FDA submission was the inclusion of simulator wear data representing Bioceram's ceramic THR designs. Kyocera realized they needed a U.S. presence—an orthopaedic company that could bridge Bioceram's engineering with American regulatory demands. The result was Kinamed Inc., a start-up orthopaedic company, created as a subsidiary of Kyocera America. The available commercial simulator—the MMED system—was not suitable for studying wear in ceramic THR. Its hydraulic actuators sat directly above the test chambers, risking oil leaks into the lubricant. The chambers themselves were too small, the lubricant volume too limited, and converting the system into the FDA-required "Anatomical" test mode would be nearly impossible. Kinamed commissioned Shore Western Manufacturing (Monrovia, CA) to design 9- and 12-station simulators capable of running Kyocera THR in both Inverted (Figure 7(b) and Figure 8) and Anatomical (Figure 1 and Figure 5) test modes. Lubricant chamber volumes could vary 100 - 700 ml depending on nature of the experiment. The large range of ceramic THR demanded higher driving torques and a hydraulic system powerful enough to load 24 stations at once—12 wear stations and 12 soak controls. The SWM-9 system was packed into an 800-pound wheeled cabinet carrying a hydraulic motor, oil reservoir, and valve systems. The first SWM 9 simulators were shipped to Kinamed in Los Angeles and to Bioceram in Kyoto.

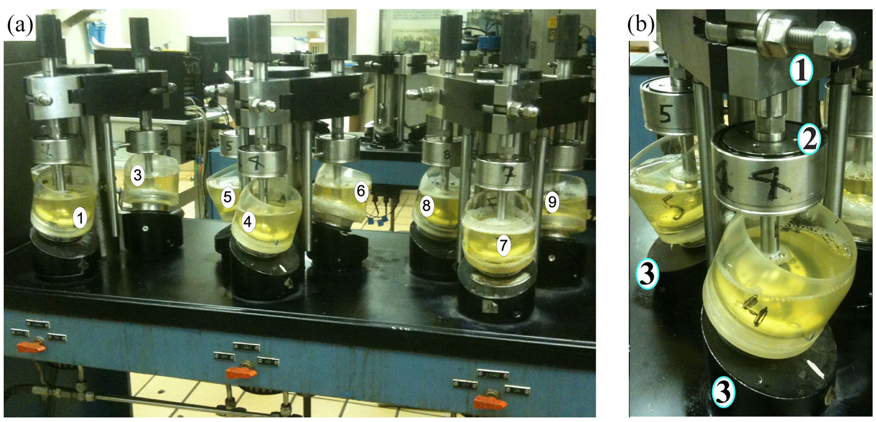


Figure 8. SWM multi-station hip simulator with crossing-path wear (CPW) motion (Shore Western Manufacturing, Monrovia, CA) [19] [23]: (a) Inverted test mode in the SWM-12 simulator, with 3 test stations in each load tower; (b) One switch disables each load tower, one lock dismounts individual test stations (1) with a self-aligning fixture in the load axis (2) above the THR lubricant chamber that orbits on a rotating cam.

With the SWM-9 simulator system in place, Kinamed launched its first multi-diameter wear study. Three ceramic/UHMWPE hip diameters—22.25, 26, and 28 mm—were evaluated. The UHMWPE wear rates ranged from 23.2 to 32.8 mm^3/Mc, and although the CDW effect appeared in some comparisons, the trends did not align cleanly with predictions (Figure 9). The Al_2O_3/UHMWPE trends overshot predictions (D26 = +21%, D28 = +16%). The CDW effect was apparent in two diametral comparisons (WR28 > WR22 and WR26 > WR22). However, there was also a CDW contradiction evident (WR26 > WR28). Clearly, there were limitations in this first ceramic/UHMWPE simulator study: 1) the UHMWPE test of 1.6 Mc was not adequate for definitive wear trends, and 2) the diametral difference was too narrow (D28 – D26 = 2 mm) to differentiate UHMWPE wear. The average wear rate with 28 mm ceramic heads was 32.8 mm^3/Mc. The OHLA study with 28 mm 316SS/PTFE averaged 2100 mm^3/Mc. Comparison of UHMWPE to PTFE provided a wear ratio LWD = 64:1—further confirmation of how poorly PTFE performed. Even more striking, the CDW index for ceramic/UHMWPE (6.9%) fell almost in line with Charnley's 316SS/Teflon clinical data (6.7%: Appendix). This appeared to be a powerful validation of Charnley's original hypothesis: PTFE and UHMWPE wear is governed primarily by THR diameter—by sliding distance (Figure 2(a))—not by specific material pairings or test parameters. The 7% CDW index signifies that a 28 mm THR would create 42% more wear debris (i.e. 7% × 6 mm) than 22 mm control THR.

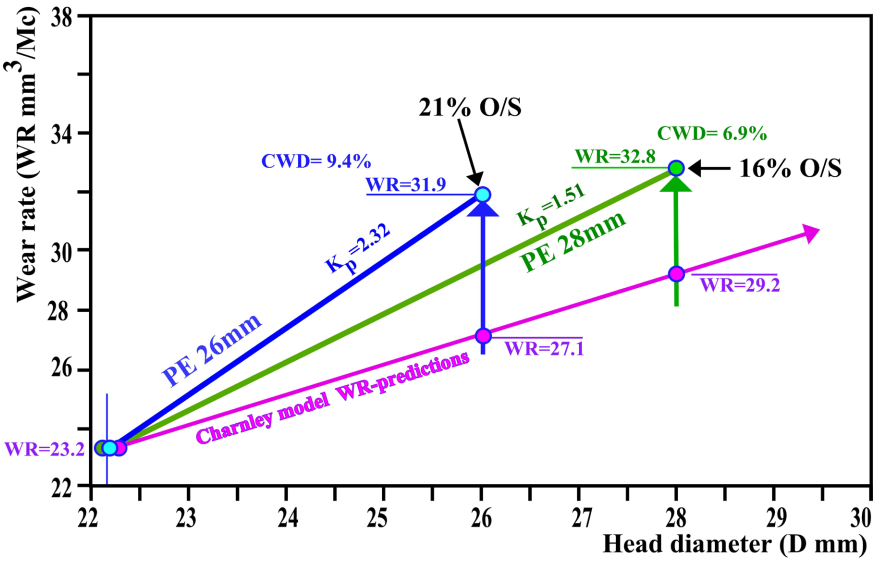


Figure 9. Ceramic: UHMWPE THR (22.25, 26, 28 mm) wear run in SWM-9 simulator [23] contrasting predicted Charnley-diameter-wear predictions (CDW) with overshoot (O/S) in simulator wear rates (WR: 26 mm, 28 mm).

3.5. 316SS, CoCr, Al_2O_3, PTFE Wear in a 12-Station Simulator (LLUMC)

A tribology research initiative was conceived at Loma Linda University Medical Center (LLUMC) to address persistent uncertainties in polyethylene wear mechanisms in total hip replacement systems. Dr. Alan Gustafson, Center for Joint Replacement (CJR), envisaged a tribology research group to improve understanding of THR wear failures due to UHMWPE debris and inflammation in hip joints ("osteolysis"). He was supported in this by Howard and Irene Peterson, whose involvement facilitated the creation of the Howard and Irene Peterson Tribology Laboratory (HIPTL). The collaboration expanded when Dr. Clarke joined the program as a consultant.

The orthopaedic industry required THR wear data for their UHMWPE developments in order to satisfy the FDA's "pre-marketing" requirements. However, conventional UHMWPE wear studies were expensive and labor-intensive, requiring months of gravimetric measurements to detect extremely small weight changes due to socket wear. Charnley's Teflon (PTFE) studies suggested there could be an alternative economical wear model with very short test durations. Fitting multiple PTFE experiments into HIPTL schedules was thought possible within an 18-month period. Also, custom machining of PTFE sockets from certified bar stock would avoid the proprietary issues of commercial THR designs. The HIPTL team therefore initiated a systematic PTFE wear program using SWM 9 and SWM 12 simulators, leveraging the CoCr and Al_2O_3 femoral heads held in LLUMC inventory.

Using SWM-9 simulators, CoCr/PTFE pairings were run in the first 3 experiments and Al_2O_3-PTFE pairs in the second set (THR 22, 28, 42 mm dia.). The set of 4 THR diameters reported by Charnley (22.25, 25.25 mm, 28.5 mm, 41.5 mm) was also studied (SWM-12 simulators). Parameters held constant included: 1) 23˚ orbital cam (**Figure 7(b)** and **Figure 8(b)**), 2) "Inverted" test mode, 3) dynamic loading (peak 2 kN), and 4) 100% bovine serum lubricant. Experimental variables included head diameters, ceramic versus metal heads, sinusoidal loading versus Paul gait-curve [24], and comparing 3 and 4 diameters of femoral heads (SWM-9 vs SWM-12). A custom database was built to work with the data that included test protocols and experimental variables (**Table A3**). The THR weight-loss measurements in approximately 80 THR pairs would likely accumulate over 3000 weight measurements. Note the same set of CoCr and Al_2O_3 heads was used in each of the 8 experiments and tracked by serial numbers, comparing performance across multiple experiments. This ensured traceability and cross-experimental analysis.

The first PTFE experiment (HE 002) produced anomalously low wear (e.g., THR_{22}: "1515 mm^3/Mc"), prompting a repeat study (HE 004) that yielded approximately double the wear rate. Across the remaining experiments, PTFE wear consistently ranked with head diameter (22 < 28 < 38 < 42 mm), with replicate scatter within ±5% and inter-experiment scatter of ±16% (**Table 9**).

Table 9. LLUMC wear ranking for precision, repeatability, and clinical accuracy in PTFE simulator studies.

ID	Parameters	PTFE wear definitions	Units	Scatter	Charnley
1	Replicated wear trends	Three linear regression trends per head diameter	mm^3/Mc	(+/) 5%	
2	Avg. WR (each head diameter)	3 head diameters, 7 experiments, 16 months	mm^3/Mc	(+/) 16%	
3	WR vs Diameter chart	Average gradient (Kp) of 7 experiments	WR/mm	273 (+30%)	56

Continued

4	Charnley-Diameter-Wear index	CDW, 7 experiments	CDW%	8.5 (+30%)	6.7
5	Simulator vs Charnley trend	22.25 mm head diameter	ratio	×3.4	
6	Simulator vs. Charnley trend	41.5 mm head diameter	ratio	×4.3	

There were no wear differences apparent when comparing Al_2O_3 and CoCr heads, sinusoidal loading versus human-gait profiles, or SWM-9 versus SWM-12 simulators. Average wear gradients (Kp) were tightly clustered (mean 241 WR/mm). Corresponding grand averages for THR diameters 22.25 mm, 28 mm, and 42 mm THR were 2843 mm^3/Mc (scatter +16%), 4227, and 8192, respectively (**Figure 10**). The wear averages demonstrated a perfect linear wear trend increasing with respect to head diameter. This aggregated data demonstrated a Kp gradient of 273 WR/mm and a CDW index of 8.5%. These findings represent one of the clearest demonstrations to date of the precision and repeatability achievable in hip simulator tests.

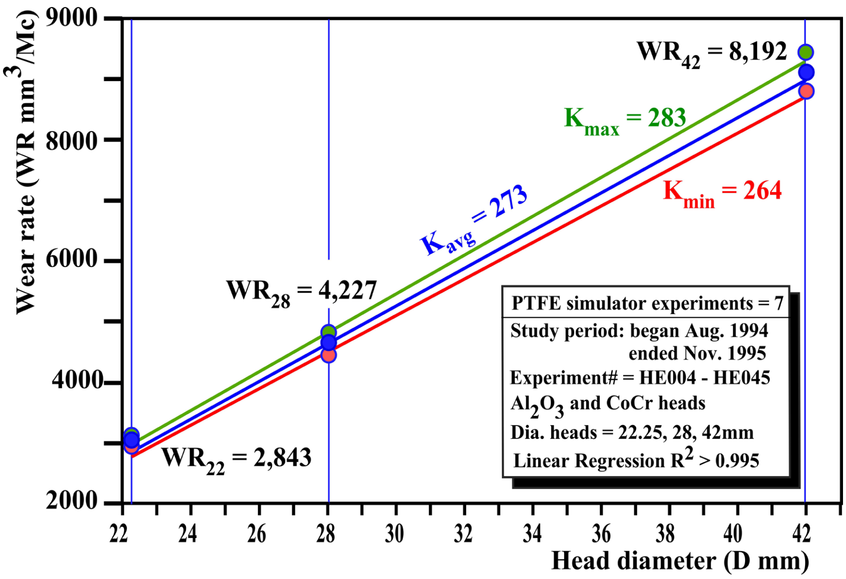


Figure 10. Summary of 7 PTFE simulator experiments depicting linear CDW trends using both ceramic and CoCr femoral heads (22.25 to 42 mm THR) [19].

Despite the internal consistency of the HIPTL data, the absolute wear magnitudes diverged sharply from Charnley's clinical Teflon results. The PTFE simulator wear-trends (SWD ×3.3 to ×4.2) were significantly higher than those observed in Teflon patients (**Figure 11**). This discrepancy mirrors a long-standing pattern in which laboratory PTFE: UHMWPE ratios greatly exceed clinical observations—e.g., WHC (×500), UCLA (×1600), Kinamed (×64), and LLUMC (×128). The convergence of two independent low wear studies (LLUMC HE 002 and OHLA/MMED) further complicated interpretation, as both produced wear rates 50% lower than the other PTFE experiments.

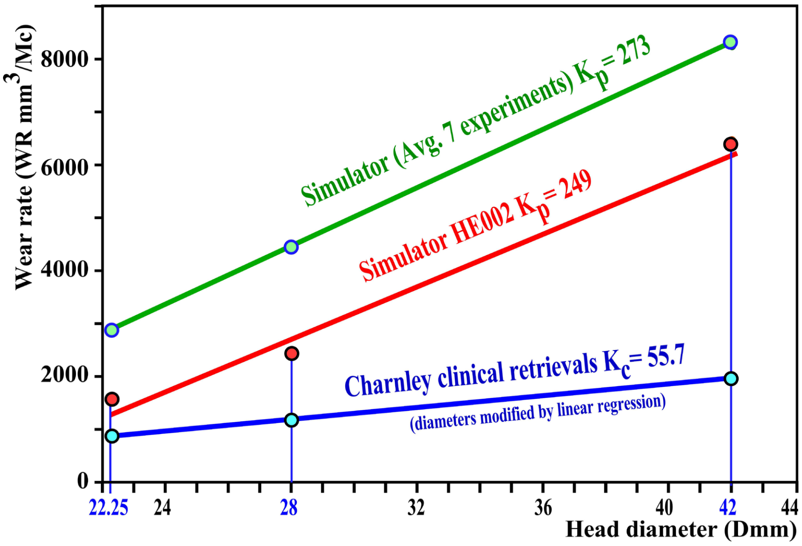


Figure 11. Comparing linear CDW wear trends in PTFE THR (8 simulator experiments) [19] significantly overshooting Charnley's clinical Teflon trends [3].

The simulator program at LLUMC yielded several robust findings:

- Wear-screening recommendations proposed by UCLA (**Table 5**) were validated for use in THR simulator studies.
- Increasing femoral head diameters consistently increased PTFE wear, confirming Charnley's original observations (**Table 1**). There have been alternative suggestions, one noting that 47 mm CoCr heads produced less UHMWPE wear than a 32 mm head [3]. This was likely an artifact of reliance on water lubrication [25].
- No measurable PTFE wear differences were observed between CoCr and ceramic heads. A previous simulator wear study described near zero UHMWPE wear using zirconia femoral heads [26]. This was likely another lubricant artifact, using water as the lubricant. The Kinamed study [23] with alumina femoral heads in serum lubrication reported 28 mm UHMWPE wear rates as 32.8 mm^3/Mc. There would be little likelihood of zirconia bearings behaving any differently.
- Linear regression trends from earlier PTFE analyses [19] were reproduced exactly across seven experiments.
- The inability to replicate Charnley's lower wear rates in Teflon patients, and the persistent exaggeration of PTFE:UHMWPE wear ratios in laboratory (LWD) and simulator settings (SWD) remain unexplained after more than five decades of wear studies.

4. Discussion

In our opinion, Charnley's publication of Teflon wear rates in revised patients represents an important clinical foundation for laboratory wear studies of THR bearings. His linear measurements of wear tracks in revised hip sockets were only possible because Teflon wear was so rapid *in vivo*. Clearly, Harry Craven, Charnley's assistant, provided a most fortunate and timely laboratory demonstration that Teflon/UHMWPE wear was 200:1 in favor of the polyethylene sample (**Table 2**). This was a pivotal moment in the history of Charnley's "Low Friction Arthroplasty" (LFA). As it turned out, the fact that UHMWPE showed such superior wear resistance, albeit in a quite "primitive" wear model, launched the LFA success story for all to benefit worldwide. Further evidence of serendipity was provided with Charnley documenting socket wear rates relative to four femoral-head diameters. His ranking clearly identified Teflon wear increasing in an orderly fashion with THR diameters; *i.e.*, 22.25 mm < 25.25 mm < 28.5 mm < 41.5 mm. Those data also verified Charnley's theory that THR wear would be related to the "arc of sliding" in the human hip joint (**Figure 2**). The Teflon THR disaster, in fact, represents a most valuable THR "wear model," *i.e.*, the "Charnley-Diameter-Wear" effect (CDW). Adding to this model, Charnley later reported the Teflon:UHMWPE wear ratio in his patients was approximately LWD = 16.5. However, the challenge Harry Craven had presented in WHC was the much higher wear laboratory ratio (**Table 2**: LWD = ×200). This amazing dichotomy, laboratory versus clinical wear, does not seem to have been debated anywhere. We could perhaps speculate that the WHC wear procedure represented an outdated methodology (**Figure 3**). How then do we explain the LWD ratio = 1600:1 in the much more sophisticated UCLA study [20]?

UCLA's multi-specimen techniques for weight-loss measurement using a biological lubricant such as bovine serum represented a breakthrough in THR laboratory studies. Prior wear studies using dimensional measurements of polymer wear could vary by several hundred percent between repeated tests. The UCLA weight-loss method necessitated compensation for weight gains due to fluid absorption. Wear and soak-control specimens needed pre-soaking in bovine serum for several weeks prior to testing. In addition, meticulous cleaning and dehydration schedules were specified prior to each weighing session. Thus, wear in 316SS/UHMWPE specimens could be recorded as low as 0.2 mm^3/Mc (±15%). The astonishing result in the UCLA study was the Teflon: UHMWPE ratio reported LWD = ×1600. What made UCLA's laboratory ratio so extreme? This question may have been asked but, as far as we can tell, has never been addressed. Such conflicts suggest there is still much to learn about simulating THR wear mechanisms in laboratory machines.

OHLA's multi-station hip simulator demonstrated that UCLA's measurement techniques also worked in THR simulator studies, provided the hip sockets were pre-soaked for 100 - 250 days. As expected, the 28 mm PTFE sockets created extremely high wear, and the study was terminated by 60,000 cycles. The dramatic contrast was that UHMWPE sockets showed no visible wear. The PTFE wear rates (28 mm THR = 2100 mm^3/Mc) averaged approximately 90% higher than Charnley's clinical average for 28.5 mm Teflon sockets (**Table 1**). Nevertheless, this was considered a satisfactory introduction to the first multi-station THR study incorporating UCLA's weight-loss techniques and using bovine serum as a biologically relevant lubricant. The UCLA test procedures for wear-screening tests and hip simulator studies are still very much in evidence today [21] [22].

Kinamed's simulator study of UHMWPE utilized Charnley's CDW algorithm. Wear with Al_2O_3 femoral heads (22.25 mm, 26 mm, 28 mm) predicted UHMWPE wear rates would be 27.1 and 29.2 mm^3/Mc for 26 mm and 28 mm diameters, respectively. However, the actual wear rates exceeded those predictions by 21% and 16% respectively. It was encouraging that the CDW_{28} index (6.9%) in this UHMWPE study corresponded fairly well with Charnley's Teflon data (**Figure 2(b)**: CDW28 = 6.8%). Thus, despite the short test duration, UHMWPE cups appeared to be following Charnley's hypothesis, *i.e.*, ceramic femoral-head diameter was the dominant factor in THR wear with 7% penalty for each millimeter increase in diameter.

Some may wonder why LLUMC launched such an ambitious simulator program with PTFE sockets that have not seen clinical use in over 60 years. The obvious answer is that there does not appear to be any published study of precision, reproducibility, and clinical accuracy in UHMWPE simulator predictions. Such a definitive study may be considered impossible due to corporate priorities and the financial and time commitments needed for UHMWPE tribology studies. The clinical relevance of PTFE studies is that they offer direct comparison to Charnley's published Teflon wear data at multiple levels of internal validation. The LLUMC PTFE simulator program produced precise and internally consistent wear data, confirming the Charnley Diameter-Wear (CDW) relationship with no exceptions (78 THR test runs). However, given the high precision of the LLUMC PTFE data, the experimental system itself cannot explain the discrepancy between laboratory and clinical PTFE wear. Wear in total hip replacement is governed by at least five interacting parameters: socket material, femoral head diameter (sliding distance), crossing path wear (CPW) motion, dynamic load-profile/magnitude, and lubricant composition and behavior. LLUMC experiments controlled four of these parameters. CPW motion is a fixture in orbital simulators (**Figure 7(b)**: 23˚ cam), and the dynamic load-profiles showed no significant variation. The only variable across PTFE and UHMWPE studies appeared to be the definition of lubricant. Lubricant-related factors differ sharply between PTFE and UHMWPE protocols and between laboratory and *in vivo* environments. Serum protein levels in simulator studies vary widely and may not reflect synovial fluid composition in human joints. The protein concentrations strongly influence boundary lubrication and transport of wear particles. Additionally, the ratio of lubricant volume to the mass of released wear debris may affect protein adsorption, boundary film formation, and third body interactions. This project contrasted the simulator wear rates for 28 mm THR; *i.e.*, Kinamed UHMWPE study (32.8 mm^3/Mc) and LLUMC PTFE (4227 mm^3/Mc). The PTFE wear rate of 4227 mm^3/Mc (**Figure 10**: 28 mm LLUMC) represents the average per million simulator cycles. Thus, it follows that the experiment represented 11.57 days of simulator run-time (24-hour days). Thus, the volume of PTFE debris accumulating daily would be 365 mm^3. The corresponding UHMWPE debris rate (**Figure 9**: 32.8 mm^3/Mc, 28 mm OHLA) would be 2.8 mm^3/day, and combining the two simulator studies would represent a SWD ratio of 130:1. This difference in debris accumulation may alter the wear behavior of the serum lubricant, influencing bearing friction (temperature effects), protein degradation, and other wear mechanisms. Also contrasted is the difference in wear events to determine component weight loss; 20,000 cycles may be adequate for a PTFE wear event, whereas 300,000 cycles would be more appropriate to determine a weight loss change in UHMWPE sockets. As a result, additives such as sodium azide (antibacterial) and EDTA, unnecessary for short PTFE studies, become essential for longer UHMWPE protocols. By the end of each wear event, the initially gold color of bovine serum lubricant (**Figure 8(b)**) may resemble a white cloud of circulating debris and degraded proteins. Collectively, these variables create a lubrication environment fundamentally different from the *in vivo* synovial system, which continuously replenishes proteins, lipids, hyaluronic acid, and cellular components.

The strength in the LLUMC PTFE studies lay in the adherence to the Charnley wear model developed from Charnley's Teflon retrievals. Eight experiments with CoCr/PTFE and Al_2O_3/PTFE convincingly demonstrated:

1) Precision in replicated THR-diameter sets < +5%, similar to the UCLA experience [6] [7];

2) Linear regression coefficients in THR wear trends (R^2) > 0.995 (no exceptions);

3) THR diameter wear ranking: 22.25 < 28 < 38 < 42 mm (no exceptions);

4) Virtually linear wear rates relative to THR diameters (no exceptions);

5) No wear difference using CoCr and Al_2O_3 femoral heads.

Despite this precision, the overall PTFE simulator trend was consistently 4 to 5 times higher in magnitude than the Teflon retrieval data (**Figure 11**). Also, the PTFE: UHMWPE ratio, comparing two simulator studies, revealed SWD 130:1. Laboratory wear predictions greatly over-shooting the clinical criteria have been evident since the Teflon studies of Charnley (**Figure 4**). It is well known that the serum proteins (biological lubricants) play an essential role in UHMWPE wear mechanisms [2]. We propose here the hypothesis that bovine serum lubricants have greatly exaggerated PTFE wear rates. It is therefore particularly intriguing that simulator studies of ceramic: UHMWPE THR with water lubrication, *i.e.*, no proteins, described near zero wear rates [19] [26]. However, a simulator study using serum lubricant rated Al_2O_3/PTFE wear rate as 32.8 mm^3/Mc (**Figure 9**). This suggests that while serum proteins are essential for wear in polymers, there may be a serum dilution that would provide a lower rate of PTFE wear, thereby accurately simulating the Charnley-Diameter-Wear model.

The next significant simulator validation study, if it were possible, would be a duplication of LLUMC studies using UHMWPE sockets with THR diameters ranging from 22.25 to 42 mm. This would be an admirable study if corporate support were available. The hip sockets could also be custom machined economically from UHMWPE bar stock, thereby avoiding proprietary design issues and high

THR pricing. THR designs are all modular, so there are many sources available for new femoral heads (316SS, CoCr, alumina, zirconia), and they could also be provided in major institutions with orthopaedic inventories. The choice of serum lubricant would be an important parameter in that UHMWPE wear model.

5. Conclusion

The accumulated evidence from clinical retrievals, laboratory wear tests, and increasingly sophisticated hip joint simulators leads to a consistent and unavoidable conclusion: UHMWPE has proven vastly superior to PTFE/Teflon as a bearing material in total hip replacement. The Teflon: UHMWPE wear ratio (LWD = 16:1) in Charnley's clinical experience clearly favored UHMWPE as the socket bearing of choice. The puzzle lay with laboratory studies predicting dramatically higher wear ratios. WHC's Teflon: UHMWPE ratio of 200:1 (water lubrication) (**Figure 4**) and UCLA's ratio of 1600:1 (serum lubrication) deserve further discussion. With hip simulators able to study wear in THR devices and incorporating human joint kinematics, "biological lubrication", and precision in wear measurements, that huge gap in laboratory: clinical should have been reduced to a minimum. Kinamed and LLUMC simulator studies confirmed Charnley's clinical observations, *i.e.*, there was a fundamental relationship between sliding distance, femoral-head diameter, and THR wear that could be easily confirmed by linear regression techniques. Nevertheless, PTFE: UHMWPE wear ratios still amounted to ~64:1 and ~130:1, far exceeding Charnley's original clinical finding (LWD~16:1). Despite the reproducibility of the LLUMC results, a persistent and unexplained divergence remains between THR-derived PTFE wear and the much lower wear observed in Charnley's patients. This indicates a fundamental mechanistic difference between *in vivo* wear processes and the operational assumptions built into laboratory wear simulations. Clearly, there is still much to question regarding simulating THR wear in a laboratory setting.

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Finally, the authors recognize the late Professor Harlan Amstutz of UCLA, whose foundational work on implant wear has had a lasting influence, and the late Professor J. Paul for research insightfulness, Bioengineering Dept., Strathclyde University, Scotland.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix

Key: WR = wear-rate (mm^3/Mc)

Reference head diameter $= D_c$ — 1

Large head diameter $= D_d$ — 2

Reference wear-rate $= WR_c$ — 3

Large-diameter WR $= WR_d$ — 4

Wear-rate difference DWR $= WR_d - WR_c$ — 5

Normalized DWR = NDR $= (WR_d - WR_c)/WR_c$ — 6

Diametral difference DD $= (D_d - D_c)$ — 7

$$\text{CDW} = \frac{\text{NDR}}{\text{DD}} \quad \text{— 8}$$

CDW% = 100* CDW — 9

Figure A1. Charnley-volume-diameter equations.

Table A1. CDW calculations from Teflon data [19].

Equation	Diameter (D mm)	WR (LinReg)		
1	WR(c) for 22.25 mm	835		
	25.25 mm	1006		
	28.5 mm	1171		
2	41.5 mm	1895		
	Diameter choices	25.25 - 22.25	41.5 - 22.25	41.5 - 28.5
5	WR-difference (DWR)	167	1072	724
6	NDR = DWR/WR(c)	0.203	1.303	0.880
7	DD = D(d) – D(c)	3	19.25	13
8	CDW = NDR/DD	0.068	0.068	0.068
9	CDW%	6.8%	6.8%	6.8%

Table A2. UCLA "pin-on-flat" test parameters [1] versus simulators.

Wear Parameters	Details
number of test stations	12
sliding motion (oscillating)	25 mm
metal, ceramic counterfaces	41 mm dia.
wear-pin specimens	12.7 mm dia.
replicated pin sets/variable	N = 3
contact stress	3.45, 6.9 MPa
pre-test "soak" conditioning	"several weeks"
control "soak" specimens	Weighed during the wear test

Continued

friction sensors	monitor "high friction"
lubricant temperature	monitored, not controlled
Sterile bovine serum (frozen)	25 ml lubricant
antibacterial additive	3 ml sodium azide
evaporation control	distilled water
replicated UHMWPE wear-sets	316lSS, CoCr
wear test intervals	250,000 - 300,000 cycles
wear-interval number per test	6 - 12
1st (0.5 Mc) interval deleted	yes
Wear durations	2.5 - 3.5 Mc
Linear analysis wear trends	yes
lab-patient unit conversion	0.21 Mc = "1-year"
UHMWPE wear rates	0.2 mm^3/Mc (+24%)
wear compared to clinical data	yes

Table A3. Test parameters in the custom simulator database [5].

ID	HIPTL Test Protocols in the custom database LLUMC	Details
1	Hip experiment ID (PTFE sockets)	HE series
2	Experiment dates	logged
3	Operator IDs	logged
4	Simulator types	SW9, SW12
5	Certifications for lubricants and hip components	logged
6	Component cleaning and dehydration procedures	logged
7	Pre-test "soak" procedures	logged
8	Wear-soak procedure	logged
9	Sequential weight-measurement procedures	logged
10	Sartorius Microbalance reports to the database	Weight
11	Serial IDs: CoCr, Al_2O_3, PTFE IDs, fixtures	FH, HC, dia.
12	Test replicates per experimental pairing	3
13	Soak test serial IDs (socket set)	1 to 12
14	Wear test serial IDs (socket set)	1 to 12
15	Head and socket pairings	logged
16	Sequencing replicate socket weights	2 - 4 replicates
17	Load profiles and peak loads (sinusoidal/human gait)	2 kN
18	Loading procedures (2 kN) sinusoidal/human gait profiles	logged

Continued

19	Selection test station IDs	1 to 12
20	Selection test fixture IDs	serialized
21	Selection test mode configuration (8 experiments)	Inverted
22	Selection of wear events per experiment	3 to 9
23	Event durations (cycles)	catalogued
24	Wear-sockets corrected for soak weight changes	catalogued
25	Weights converted to volumetric wear (mm^3)	trend analysis
26	Experimental notes	logged
27	Wear data analysis was ported to a spreadsheet.	Excel

Table A4. Key acronyms and symbols.

Acronymn	Details
316SS	EN58J (UK) 316 low-carbon stainless steel
Al_2O_3	alumina ceramic
CDW	Charnley-Diameter-Wear index (see Appendix)
CoCr	cobalt chrome alloy
CPW	crossing-path wear motion
FDA	Food and Drug Administration
Fluon	PTFE trademark, ICI Chemicals, UK
Km	gradient for wear magnitudes (mm^3) vs simulator cycles
Kp	gradient for wear-rates (WR) vs head diameters
LPW	linear path wear motion
LWD	laboratory wear divergence ratio (laboratory vs clinical)
Mc	1-million test cycles in laboratory setting
PTFE	polytetrafluorethylene
RSA	resurfacing design of total hip arthroplasty
S	cyclical sliding distance (mm) in human hip joint
scatter	estimate of wear variance (max-min/avg)
SWD	simulator wear divergence (laboratory vs clinical)
Teflon	PTFE trademark, DUPONT USA
test-Anatomical	socket mounted above head in simulator
test-Inverted	socket mounted below head in simulator
THR	total hip replacement
UHMWPE	ultra high molecular weight polyethylene
VWI	Volumetric Wear Index (refer to CDW)

Continued

WR	wear-rate per million load cycles
WRc	clinical wear-rate for 22.25 mm THR
Acronymns	**Universities and Vendors**
HIPTL	Howard and Irene Peterson Tribology Laboratory (LLUMC)
KAI	Kyocera America Inc, San Diego, CA
LLUMC	Loma Linda University Medical Center, Loma Linda, CA
MATCO	Materials and Technology Corporation, La Canada, CA
MMED	10-station hip simulator (MATCO, La Canada, CA)
OHLA	Orthopaedic Hospital of Los Angeles
SWM	Shore Western Manufacturing Inc, Monrovia, CA
SWM-9, 12	9 and 12 station hip simulators (SWM)
UCLA	University of California in Los Angeles
USC	University of Southern California
WCH	Wrightington Center for Hip Replacement