FERROGRAPHIC ANALYSIS OF WEAR IN HUMAN JOINTS

EVALUATION BY COMPARISON WITH ARTHROSCOPIC EXAMINATION OF SYMPTOMATIC KNEES

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Ferrography is a technique for analysing wear by means of the magnetic separation of wear particles. To evaluate its application in human joints, the results of the ferrographic analysis of saline washings of symptomatic human knees were compared with the results of the arthroscopic examination of the same knees. Ferrography was found to be an extremely sensitive monitor of articular erosion, with a resolution far greater than that of arthroscopy. This was particularly apparent with knees suffering from a torn anterior cruciate ligament: arthroscopy detected no damage to the cartilaginous surfaces whereas ferrography detected a substantial level of "microdamage". The spectrum of wear particles showed qualitative and quantitative alterations depending upon the condition of the knee. Ferrography thus holds much promise as a potential differential diagnostic technique of great sensitivity, with particular relevance to the very early changes which precede clinical symptoms. Study of wear particles is also justified by evidence indicating an active role in the pathophysiological progression of arthritis.

Clinical orthopaedics suffers from the absence of a routine diagnostic technique which is accurate, objective, sensitive, and non-invasive. It is also frustrating that, although approximately 41 per cent of the population will develop arthritic disorders by the age of 65 years (Wood 1977), there is no way to predict which individuals will be the ones affected; such foresight might permit preventive intervention in those at risk. Ferrographic analysis of synovial fluid aspirates, or saline washings of joints, may have the potential to make good these deficits.

Ferrography is a technique which was originally developed to analyse wear in machines (Scott, Seifert and Westcott 1974). As the bearing surfaces of a machine wear, they shed particles into the lubricating oil. These particles provide much information concerning the conditions of wear which produced them. For their ferrographic analysis, a sample of the lubricating oil is removed from the machine and pumped slowly along a thin glass microscope slide (the substrate) under the influence of a strong external magnetic field. Most of the wear particles are ferromagnetic. The magnet and substrate are so arranged that particles separate out under the influence of the magnetic field and deposit at various positions along the substrate; the position that a given particle will occupy depends largely upon its

volume and magnetic susceptibility. When fixed and dried, the substrate, with its magnetically graded wear particles (now termed a ferrogram), is examined by light and electron microscopy. Ferrographic analysis of engine oil has become a highly sophisticated and accurate way of establishing the wear of a machine. Not only does it diagnose particular tribological problems in machines, but it has a valuable predictive function.

Arthritis involves destruction of the tissues of the joint, especially articular and meniscal cartilage. In osteoarthritis there is an important mechanical component to this process. It has been known for decades that cartilaginous fragments occur in the synovial fluid of osteoarthritic joints (Horowitz 1948). The possibility thus arises that synovial fluid may be amenable to a ferrographic type of analysis and that such analysis might constitute an accurate diagnostic and prognostic technique for orthopaedic surgeons. Such an analysis could also further our knowledge of the basic pathophysiology of arthritic disorders in the same way that ferrographic analysis of engine oil has contributed important new information on basic tribology and rheology.

New techniques permitting the ferrographic analysis of synovial fluid aspirates or saline washings of joints have recently been developed (Evans *et al.* 1980; Evans

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and Tew 1981). In a preliminary study to evaluate this method, a series of synovial fluid aspirates and saline washings of joints was examined (Evans, Mears and McKnight 1981). Ferrograms were made using samples drawn from patients who presented with a range of different arthritides, representing several different affected joints. The results were extremely promising. Wear particles, ranging in size from a few micrometres to several hundred micrometres, were clearly identifiable: they were not random detritus, but fell into a limited number of discrete morphological categories. At least two different regimes of wear could be identified. As with machines, the size of the wear particles increased with the severity of mechanical erosion of the articular surface. Most of the particles were cartilaginous, but the few cases with osseous particles had radiological evidence of exposure of the subchondral bone. The ferrograms made from rheumatoid synovial fluid were quite different from those made from mechanically injured joints, indicating the diagnostic potential of ferrographic analysis of synovial fluid. It is interesting to note that the examination of cartilaginous wear particles in equine synovial fluid lends similar diagnostic advantages to the veterinary surgeons (Tew and Hackett 1981).

A further study was then initiated and is reported here. To eliminate as many variables as possible it was decided to concentrate on a single joint, the knee. Ferrograms were made from saline washings retrieved from knees after arthroscopy. Restricting the study to samples of this kind limited the range of arthritic conditions encountered, thus again reducing the number of variables. Other advantages were the wealth of arthroscopic literature on the knee and the detailed information yielded by arthroscopy. Such precision is essential for an accurate and valid interpretation of the ferrographic analyses.

MATERIALS AND METHODS

Arthroscopy. The limb was exsanguinated with a rubber bandage and the arthroscopic procedure carried out under a pneumatic tourniquet pressure of 350 millimetres of mercury.

An 18-gauge needle was inserted into the suprapatellar pouch at the superolateral corner and 100 millilitres of saline injected into the joint cavity. A five-millimetre incision was then made in the anterolateral geniculate triangle and a sharp trocar used to puncture the anterolateral capsule of the knee. A blunt trocar was used to puncture the synovium, and the arthroscope sheath was introduced into the joint. Then 30 to 50 millilitres of the saline were extracted and placed in a sterile vial for ferrographic analysis.

A further 50 millilitres of saline were then injected into the knee cavity, and a five-millimetre arthroscope was introduced. Examination of the suprapatellar pouch, patellar surface, lateral and medial gutters and lateral and medial compartments of the knee was carried out with specific attention being paid to the integrity of the articular cartilage of the patella, femur and tibia.

The menisci were then viewed under direct vision and, by means of a curved probe (introduced through a medial stab incision), examined for mobility and abnormalities on their edges and superior and inferior surfaces. The cruciate ligaments were inspected and a curved probe used to demonstrate any evidence of laceration or laxity. If adequate

visualisation of all compartments could not be achieved via the lateral port, other approaches were used for the scope and the probe.

On completion of the arthroscopic inspection, the joint cavity was irrigated with 500 millilitres of saline, the arthroscopic instruments removed, the stab wound covered with adhesive strips and a compression dressing applied.

Preparation of ferrograms. A full account of the method of preparation of ferrograms is given in Evans *et al.* (1980). Essentially, wear particles were retrieved from saline washings aspirated from joints by centrifuging for 15 minutes at 3000 *g*. After two washes by resuspension in saline and recentrifuging, the particles were magnetised with a solution (P-2) containing the trivalent cations of erbium (Evans and Tew 1981). The suspension of wear particles in one millilitre of the P-2 solution was pumped slowly along a thin glass microscope slide (the substrate) lying in a strong magnetic field. Particles of sufficiently positive magnetic susceptibility deposited on the substrate. The ferrogram was quickly washed and allowed to dry in a particle-free environment.

Identification and classification of wear particles. Ferrograms were first examined by light microscopy using both polarised and unpolarised light. A magnification of 100 was used for initial evaluation, with higher magnifications (200, 400, or 1000) serving for closer examination of individual particles.

Certain ferrograms were further examined by scanning electron microscopy, using an ETEC Autoscan microscope. Ferrograms were coated with gold or carbon, the latter being preferred when x-ray elemental analysis was conducted in conjunction with scanning microscopy. The elemental analysis was performed with a Kevex energy spectrometer. For most wear particles, it was necessary to subtract the background spectrum of the glass substrate to permit clear identification of peaks resulting from elements in the particles.

RESULTS

The patients in this study were divided into two groups on the basis of the arthroscopic examination: those knees in which intra-articular damage was judged to be extremely small or absent (Group I) and those in which intra-articular damage had been clearly seen (Group II). Different categories within these two groups were distinguished as shown in Table I.

Ferrographic analysis

Group I. The 10 patients in this group formed an interesting progression. Ferrographic analyses of the first three patients, with normal or nearly normal knees, are

Table I. Arthroscopic features of the knees

	Condition of knee	Number of patients	Age (years)	
			Mean	Range
Group I	Normal, or near normal	3	12.3	11-14
	Torn anterior cruciate ligament	7	21.1	16-29
Group II	Chondromalacia patellae	7	27.5	14-51
	Degenerative joint disease	3	57.0	51-62
	Torn meniscus	21	33.5	20-58
	Others	2	41.5	34-49
Total		43	31.0	11-62

summarised in Table II. These showed two or three different types of particles (Figs 1 to 5) and some amorphous material.

In five of the seven cases with torn anterior cruciate ligaments, the arthroscopic examination found all the articulating surfaces intact (Table III). However, ferrograms made from washings of each of these joints contained raised numbers of wear particles of a variety of types, including those which appear grey or silver under polarised light. One interesting kind of wear particle found on three of these five ferrograms, which did not appear on those from the near-normal knees, consisted of very small "spherules" of articular cartilage, with a diameter of about five micrometres (Figs 6 and 7). In some areas on the ferrogram, these appeared to form aggregates of extremely large size (Fig. 8). On one ferrogram the entry deposit was largely amorphous material of weak optical activity (Fig. 9) while another patient with a similar arthroscopic diagnosis showed small round particles at the entry point (Fig. 10).

Two patients in whom the torn anterior cruciate ligament was superimposed on a previous articular

Table II. Comparison of the arthroscopic and ferrographic examination of normal, or nearly normal, knees

Patient number	Age (years)	Damage revealed by arthroscopy	Description of ferrogram	Maximum particle size (μm)
1909	12	None (healed peripheral meniscal tear)	Three small lamellae of superficial cartilage (Fig. 1) Light patches of amorphous debris	40
1921	14	Softening of femoral condyle?	Numerous lamellae of superficial cartilage Cartilaginous particles appearing silver under polarised light (Fig. 2) Small amount of amorphous material	80
1918	11	Softening of patella? Moderate synovitis	Larger lamellae of superficial cartilage Particles of coarse fibrous nature (Figs 3 to 5)	80

Fig. 1

Patient 1909. Entry deposit of three lamellae of superficial cartilage from a normal knee. Partially crossed polars. ($\times 150$.)

Fig. 2

Patient 1921. Cartilaginous wear particles from a knee with very slight softening of the femoral condyle. Polarised light. ($\times 75$.)

Fig. 3

Fig. 4

Fig. 5

Patient 1918. Figure 3—Cartilaginous wear particles from the knee with very slight patellar softening. Unpolarised light. ($\times 120$.) Figure 4—The same section of the ferrogram under polarised light. Figure 5—Scanning electron micrograph of one of these cartilaginous lamellae. ($\times 780$.)

Fig. 6

Fig. 7

Fig. 8

Table III. Results of the arthroscopic and ferrographic examination of knees with torn anterior cruciate ligaments (ACL)

Patient number	Age (years)	Damage (other than ACL) revealed by arthroscopy	Description of ferrogram	Maximum particle size (μm)
1924	18	None	Lamellae of superficial cartilage Small spherules (Figs 6 and 7) Particles appearing silver under polarised light	60 5
1883	16	None	Lamellae of superficial cartilage Amorphous debris Cartilaginous particles appearing silver under polarised light Aggregates of spherules (Fig. 8)	80
1943	20	None	Lamellae of superficial cartilage Silver particles Amorphous debris with weak optical activity (Fig. 9)	70
1873	21	None	Lamellae of superficial cartilage Fibrous, grey and silver particles under polarised light (Fig. 10)	50
1975	24	None	Lamellae of superficial cartilage Grey particles Spherules	60
1925	29	Slight softening of femoral condyle Marked synovitis	Heavy, varied deposits Lamellae Fibrous particles Spherical particles Fragments of cartilage (Figs 11 to 14)	200
1882	20	Ragged meniscus Marked synovitis	Lamellae Very small spherules Fibrous particles	1

Figure 6—Patient 1924. Spherules of cartilage from a knee with torn anterior cruciate ligament. ($\times 300$.) Figure 7—The same spherules under polarised light. Figure 8—Patient 1883. Deposits from a knee with torn anterior cruciate ligament, showing aggregates of these spherules. ($\times 75$.)

Fig. 9

Patient 1943. Entry deposit from a knee with a torn anterior cruciate ligament. Most of the deposit is amorphous and has only weak optical activity. ($\times 150$.)

Fig. 10

Patient 1873. Entry deposit from a knee with torn anterior cruciate ligament. ($\times 150$.)

Fig. 11

Fig. 12

Fig. 13

Patient 1925. Figure 11—Entry deposit from a knee with torn anterior cruciate ligament superimposed on mild softening of the femoral condyle. Polarised light. ($\times 60$.) Figure 12—Triangular and spherical cartilaginous wear particles from the top left of Figure 11. Polarised light. ($\times 240$.) Figure 13—Scanning electron micrograph of the same particles. ($\times 300$.)

Fig. 14

Patient 1925. Cartilaginous wear particles from a different part of the ferrogram.

disorder were of special interest. Patient 1925 had already developed mild softening of the femoral condyle before suffering a torn anterior cruciate ligament and had marked synovitis. Here the concentration of wear particles was far higher than with either a torn cruciate or slight condylar softening alone. In addition to the cartilaginous particles a larger, triangular particle (200 micrometres) and one spherical particle (25 micrometres in diameter) were found on the ferrogram (Figs 11 to 13). The sphere seen at high magnification had the faint yellow tinge described in an earlier paper (Evans, Mears and McKnight 1981). A large number of smaller particles was found further down the ferrogram, some of which were embedded in amorphous material. Closer scrutiny of this part of the ferrogram (Fig. 14) revealed some flattened, lamellar particles of cartilage along with a sliver of cartilage of moderate optical activity. In another patient (1882), the torn cruciate was superimposed on a ragged-edged meniscus. This also generated a raised number and variety of wear particles, some being very small "spherules" down to one micrometre in diameter. Fibrous particles were present, along with a marked synovitis.

Group II. The wear particles in the saline washings of these knees (Table IV) were markedly larger than those in Group I, with one notable exception: a rheumatoid

knee with softening of the femoral condyle in which were found small lamellae of superficial cartilage and cartilaginous spherules down to five micrometres in diameter (Fig. 15). This contrasted with a heavy deposit in a knee with non-rheumatoid softening (Fig. 16). Many of the samples drawn from knees with torn menisci or degenerative joint disease contained particles visible to the naked eye. For technical reasons, these were too large to appear on ferrograms.

As well as these quantitative differences in the pattern of wear particles, there were qualitative differences. In addition to the thin, "glass-like" lamellae of the Group I knees, there were particles which appeared grey, silver, or white under polarised light. Certain ferrograms contained an amorphous material of weak-to-moderate optical activity. Sometimes, discrete particles of the types

Table IV. Results of the ferrographic analysis of saline washings from knees of patients from Group II

Number of patients	Diagnosis by arthroscopy	Description of ferrogram	Maximum particle size* (μm)
7	Chondromalacia patellae	Lamellae Particles appearing silver grey or white under polarised light Optically active amorphous material	400
3	Degenerative joint disease	All types, including large particles which do not fall into recognisable categories	1000
21	Torn meniscus		
1	Rheumatoid, softening of femoral condyle	Lamellae (Fig. 15) Spherules	20
1	Softening of meniscus and femoral condyle	Lamellae Particles appearing silver under polarised light (Fig. 16) Fibrous deposits lacking optical activity	500

*1000 μm (1mm) is about the maximum size of particle which, for technical reasons, can deposit on ferrograms.

Fig. 15

Fig. 16

Figure 15 Light deposit of cartilaginous lamellae and amorphous material from mild, rheumatoid softening of the femoral condyle. ($\times 150$.)
 Figure 16 Heavy deposit of cartilaginous wear particles of various types from mild, non-rheumatoid softening of the femoral condyle. ($\times 150$.)

already indicated were seen embedded in this amorphous material. Torn menisci produced more of the fibrous particles than the other types of injury.

DISCUSSION

The data presented here demonstrate the extreme sensitivity of ferrography to articular erosion. Ferrography reveals "microdamage" to the articulating surfaces of the knee which eludes detection by arthroscopy (Casscells 1980). Furthermore, the spectrum of wear particles changes both qualitatively and quantitatively as the intra-articular wear conditions alter. These conclusions are well illustrated by the results of the ferrographic analysis of the group of patients, all of similar age, whose knees were found to be normal or nearly normal by arthroscopy. Ferrograms from the knee which appeared completely normal arthroscopically contained little wear debris. Those particles which were recovered consisted of small (40 micrometre and under) lamellae of superficial cartilage resembling frosted glass under polarised light. Such particles, commonly found on ferrograms made from synovial fluid aspirates, have been reported previously (Evans, Mears and McKnight 1981). In addition, "normal" knee joints of young patients sometimes contained amorphous debris with no optical activity which may originate from synovium. In the two nearly normal knees, with minimal softening of the patella or of the femoral condyle ferrography clearly demonstrated the greater extent of cartilaginous damage: thin lamellae of superficial cartilage were found in greater numbers, and their maximum size was moderately increased to around 80 micrometres. In addition, cartilaginous particles of higher optical activity, in some cases with a silver appearance under polarised light, were found. It has been noticed previously (Evans, Mears and McKnight 1981) that such particles seem to indicate greater levels of cartilaginous erosion.

Comparison of the ferrographic analysis and arthroscopic examination of knees with torn anterior cruciate

ligaments strengthens the foregoing conclusions. In five of these seven patients the torn ligament appeared to be the only injury, and arthroscopy detected no cartilaginous damage at all; ferrography revealed otherwise. In each case the affected knee contained greater concentrations and different types of wear particles than age-matched controls. Particle size was not greatly enhanced. In addition to the "glass-like" lamellae and silver slivers of cartilage there were small cartilaginous spherules one to five micrometres in diameter, which in certain regions of the ferrogram were found in association with large aggregates of similar overall appearance under polarised light. The spherules may form these aggregates in the joint, or artefactually under the conditions of ferrography. Conversely, the aggregates may be precursors of the spherules. It is also possible that appearances may be misleading, and there may be no precursor or product connection between the two types of deposit.

This "microdamage" to the joint may result from the altered biomechanical forces produced by rupture of the anterior cruciate ligament. In particular, the change from a sliding to a rolling movement in the knee might produce more wear particles. This interpretation is reinforced by the two examples where this injury occurred to a joint in which the cartilage was already damaged, one by softening of the femoral condyle, and the other by a slightly ragged meniscus. In both cases, superimposition of the torn anterior cruciate ligament provoked the generation of wear particles to an extent exceeding that of either the torn ligament or the cartilaginous disturbance alone. Not only was the size of the particles increased, but also their types were altered. The ragged meniscus, in particular, produced particles with a coarse fibrous appearance of high optical activity. It has been noted previously (Bullough *et al.* 1970; Evans, Mears and McKnight 1981) that the meniscus might be a rich source of this type of particle.

Two factors help to explain why ferrography is more sensitive than arthroscopy to intra-articular cartilaginous

injury. First, examination of isolated wear particles is an intrinsically more sensitive monitor of erosion than is examination of the bulk material. Secondly, microscopic examination of the wear particles on ferrograms permits very high magnifications to be used, whereas the arthroscope is limited to a magnification of 10.

In knees with clear arthroscopic evidence of articular damage, ferrographic analysis of saline washings gave a rich harvest of wear particles, which were larger and more abundant than from normal knees. Particularly intriguing was an amorphous deposit which was nevertheless visible under polarised light, with discrete wear particles embedded within it. The significance of this is, as yet, unclear. It is probably not an artefact of the ferrographic procedure, as similar accumulations can be filtered from freshly aspirated synovial fluid (Tew, personal communication). Possible explanations include its production from cartilage by grinding action within affected joints or by partial enzymic digestion of cartilage. Similar deposits have been found on ferrograms made from rheumatoid synovial fluid (Evans, Mears and McKnight 1981), where cartilage is likely to be enzymically degraded. It is interesting that samples from patients of a similar age, with an identical diagnosis, yielded quite dissimilar populations of wear particles. Two explanations of this come to mind. One is that many of the standard diagnostic "labels" cover heterogeneous collections of abnormalities. The second is that the sensitivity of ferrography enables arthritis to be examined at a more subtle level than with other diagnostic tools and, in consequence, previously unrealised variations in the arthritides may be uncovered.

Rupture of the anterior cruciate ligament of canine knees produces a condition which closely resembles human osteoarthritis (Muir 1977); unrepaired damage of this kind in human knees may also lead to osteoarthritis. Elevated concentrations of wear particles occur in human

knees with torn anterior cruciate ligaments. As ferrography detects them before there is obvious damage to the cartilage, they may be involved with early events leading to osteoarthritic degeneration. One mechanism by which they could do so is by the cellular release of enzymes, and perhaps other factors which mediate directly, or indirectly, in the degradation of cartilage (Evans, Mears and Cosgrove 1981). This hypothesis is supported by evidence from animal studies: injections of cartilaginous particles into the knee joints of dogs (Chrisman, Fessel and Southwick 1965) or rabbits (Evans, Mazzocchi, Nelson and Rubash, unpublished observations) provoke a mono-articular arthritis.

The biochemical disturbances of joint tissues as a direct or indirect consequence of cellular reactions to wear particles should foster the generation of yet more particles. Owing to the altered ambient conditions under which these "secondary" wear particles are produced, their morphologies and chemistries might well be changed. Ferrography detects changes in morphology. Chemical characterisation of the wear particles should prove a fruitful study, but one requiring extremely sensitive techniques. Although a single synovial fluid aspirate often contains sufficient wear debris for its aggregate chemical properties to be established (Cheung *et al.* 1980), characterisation of individual particles on a ferrogram will probably require monospecific antibodies to the different types of collagen and to other antigenic components of cartilage such as the "link" and "core" proteins of proteoglycans. Antibodies specific for Types I and II collagen would be invaluable in determining the specific origin of individual cartilaginous wear particles. In this way, damage to the articular or meniscal cartilage, for instance, could be readily distinguished. This is important in view of our observation that ferrography can detect articular damage in advance of other indications of where such damage might have occurred.

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REFERENCES

- Bullough PG, Munuera L, Murphy J, Weinstein AM. The strength of the menisci of the knee as it relates to their fine structure. *J Bone Joint Surg [Br]* 1970;**52-B**:564-70.
- Casscells SW. The place of arthroscopy in the diagnosis and treatment of internal derangement of the knee. *Clin Orthop* 1980;**151**:135-42.
- Cheung HS, Ryan LM, Kozin F, McCarty DJ. Identification of collagen subtypes in synovial fluid sediments from arthritic patients. *Am J Med* 1980;**68**:73-9.
- Chrisman OD, Fessel JM, Southwick WO. Experimental production of synovitis and marginal articular exostoses in the knee joints of dogs. *Yale J Biol Med* 1965;**37**:409-12.
- Evans CH, Bowen ER, Bowen J, Tew WP, Westcott VC. Synovial fluid analysis by ferrography. *J Biochem Biophys Methods* 1980;**2**:11-8.
- Evans CH, Mears DC, McKnight JL. A preliminary ferrographic survey of the wear particles in human synovial fluid. *Arthritis Rheum* 1981;**24**:912-18.
- Evans CH, Mears DC, Cosgrove JL. Release of neutral proteinases from mononuclear phagocytes and synovial cells in response to cartilaginous wear particles in vitro. *Biochim Biophys Acta* 1981;**677**:287-94.
- Evans CH, Tew WP. Isolation of biological materials by use of erbium (III)-induced magnetic susceptibilities. *Science* 1981;**213**:653-4.
- Horowitz T. Bone and cartilage debris in the synovial membrane. *J Bone Joint Surg [Am]* 1948;**30-A**:579-88.
- Muir H. Molecular approach to the understanding of osteoarthritis. *Ann Rheum Dis* 1977;**36**:199-208.
- Scott D, Seifert WW, Westcott VC. The particles of wear. *Sci Amer* 1974;**230**(5):88-97.
- Tew WP, Hackett RP. Identification of cartilage wear fragments in synovial fluid from equine joints. *Arthritis Rheum* 1981;**24**:1419-24.
- Wood PHN, ed. *The challenge of arthritis and rheumatism*. London: British League Against Rheumatism, 1977.