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How different is human hair? A critical appraisal of the reported differences in global hair fibre characteristics and properties towards defining a more relevant framework for hair type classification.

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Introduction

For humans, scalp hair is more than just an evolutionary trait. It is an indication of culture, fashion, religion, socio-economic status, and sexuality. Beneath the hairstyle, the visual appearance of the hair varies from individual to individual. Hence, hair phenotypes have long been one of the factors that divide humans into racial groups, due to the broad similarities that are seen within races.

All scalp hair fibres have the same basic morphology, comprising the cuticle, cortex and medulla, and broad chemical composition, including approximately 90% (dry weight) of proteins, 4% lipids, 1% sugars. Thus, the observable and measurable differences at macro level such as hair shape, geometry, colour, surface friction, lustre, mechanical properties, and sensory characteristics are believed to be influenced by microscopic, nanoscopic, chemical and biophysical variations in the hair fibres, presumably with origins in genetics. Studies comparing hair types from different perspectives (chemical, geometric, mechanical) and loosely based on race or a combination of race and geographical origin, have been published since the 1950s. Recently, a case for developing a taxonomy for human hair classification based on a systems approach for reporting all fibre constituents was proposed (1). The aim was to address the complexities of researching human hair fibre by addressing systematically the following “associated networks” of fibre characteristics and properties: biological structure, geometric, biochemical, and physico-mechanical properties. Based on extensive literature review, the authors also proposed a systematic representation of how the different hair properties interact, suggesting that future data generation should contribute towards shared databases. Aside from this work, an extensive and current critical appraisal of the available literature on human hair fibre variability is substantially lacking.

The aim of this review is to critically appraise the current knowledge of different characteristics of human hair fibres to provide an overview of the known variation, to highlight gaps in the available data and to reconsider the current hair classifications independently of race and geography.

Methods

The following online databases and libraries were accessed: MEDLINE (via PUBMED), Science Direct, Whiley Online Library and KOSMET. Three study domains were set out: hair chemistry; hair morphology, structure, follicle, density; technical hair fibre properties. Separate searches were conducted within each domain (Table 1).

The following inclusion and exclusion criteria were applied to the retrieved articles.

Inclusion criteria: Experimental studies or reviews must be published in peer reviewed papers. At least one objective of the study must be a comparison of hair types or an investigation of the variability within a broadly defined hair type. The papers must be published from 1995 to the current date. Exceptions were made for seminal studies which might have been older.

Exclusion criteria: Papers with poorly defined hair types or hair sources. Papers focused on the hair responses to cosmetic treatments based on one hair type exclusively.

Relevant studies that were referenced in the shortlisted papers were followed up and included if they met the inclusion criteria.

For the purpose of this review, the terms hair, human hair, and hair fibre have been used interchangeably. The findings have been presented in the following order: historical perspectives, hair characteristics and hair properties. The full details of studies reporting hair characteristics and properties can be found in Supplementary Table ST1.

Historical perspectives on hair classifications

The purpose of appropriate hair classification is not only to aid comparative studies, but to increase the generalisability of studies focused on one hair type. The most common historical classification is based on geo-racial origin and refers to African, Asian (understood as East Asia) and Caucasian hair (understood as originating from Europe). Studies originating in North America also commonly use this classification, referring to descendants of one of these three groups. This classification leaves some geographic areas unaccounted for (e.g., South America, the Middle East) and does not reflect the increasing diversity of hair within geographies. Hence some researchers have attempted to quantify the fibre differences beyond their origin by focusing on geometrical characteristics, an approach which provides a more practical framework for an alternative classification (2)(3).

The largest study, based on 2449 participants from 22 world regions, resulted in a world-wide hair classification into 8 distinct curl-type groups, ranging from completely straight to kinky, and in a classifying method which is easy to apply (4). The authors also demonstrated that specific curl types were more prevalent for the populations from defined regions but suggested that the three-type classification is an oversimplification. A global Genome-Wide Association Study (GWAS) supports these findings by reporting the European hair to be mostly wavy (46.6%) or straight (40.7%) with a lower percentage of curly hair (12.7%) (*n*=2138); East and West Asian hair - mostly straight (46.7) or wavy (41.3%) with some curly hair (12%) (*n*=92); African hair - mostly curly (94.9%) or wavy (5.1%) (*n*=39) (5)**.**

The strength of this curl-based classification is in its universality and independence of origin. However, it has since been suggested that it is simplified by reducing the curly hair types from four to two groups in order to increase the speed and accuracy of the classification process (6). However, this might not be a suitable approach when the specific properties of very curly hair are under investigation.

Hair characteristics

Hair geometry

Several studies have reported geometrical hair data with notable inter and intra racial or geographical group type variabilities (4)(7)(8)(9)(10)(11)(12)(13). These studies classify the cross-sectional area of hair in the following order: Asian>Caucasian>African, whilst noting that the degree of ellipticity and curliness increase in this order.

It is important to note that the intra-group variability can be viewed as a characteristic of the hair type too with some studies focusing specifically on such variabilities. For example, in a study of Caucasian hair (n=151, curl types I to IV), the cross-sectional area was reported to range from 1000 to 4000µm^2. Based on the measurements of the major and minor fibre diameters, the authors computed average dimeters for different age groups and found a 6µm difference between the group with perceived fine hair (d~70 µm) and group with perceived non-fine hair (d~76µm) whilst the fine hair was also straighter (14). Japanese hair's ellipticity (n=132) was reported to range from 1.02 to 2.19 for hair types defined as straight through wavy to frizzy (15). A weak relationship between ellipticity and curl radius was reported (more elliptical fibres were curlier) with a note of the high inter-individual variability. Hair from participants from African descent (n=244, curl types from IV to VIII) was reported to display statistically significant relationships between curl and ellipticity (elliptical fibres were curlier) and curl and cross-sectional area (finer hair was curlier) (16). Finally, a study of Mexican women (n=176, curl types I to IV), considered as of mixed Asian and European descent, reported mean diameter range from 77.5 to 81.5µm, considered to be higher than Caucasian and lower that Asian means, and ellipticity lower than Caucasian but higher than Asian hair, with a moderate diversity of curl type (17). This study is aligned with a GWAS of over 6000 Latin Americans which reported mix ancestry (European 48%, Native 46%, African 6%) and predominant straight and wavy, dark or brown/black hair (18).

When viewed in conjunction, these studies corroborate the earlier reports that within and across hair groups classified based on geo-racial origin, the cross-sectional area, ellipticity and degree of curliness present a defining set of fibre characteristics. Another common observation is the variability and overlaps in ranges between the data sets based on curl types and age (hair becomes thinner with age).

Hence, hair typology based on curl and fibre geometry has the potential to reflect more accurately and sensitively hair diversity. However, a recent study based on hair originating from people from mixed European and African origin (n=140) suggested that there was no causal effect between hair curl and ellipticity once the effect of hair origin was removed (19) thus, for the time being, geometrical fibre characteristics should only be viewed as independent.

Hair shape and the hair follicle

The quantification of hair size, shape and curliness poses the question how these characteristics are determined at the stage of fibre formation in the follicle. A study comparing hair follicles from African, Guyanese, and Caucasian hair showed that African hair follicles exhibited retrocurvature between the bulb and the hair shaft compared to the straight follicles found in most Caucasian samples which lay more at a right angle to the scalp. However, some curly follicles dissected from Caucasian subjects, showed the same retrocurvature as the African follicles. This suggests that hair shape is programmed by the morphology of each individual hair bulb, irrespective of race, but more likely based on gene polymorphisms (20). Interestingly, the Guyanese follicles showed within person variability, with straight follicles found nearby curly ones, explaining the high hair variability reported by many. Furthermore, the shaft shape was maintained in the growth media, hence it is independent of the dermal environment (21). Several other works relate the asymmetry of biomarkers in different parts of the hair fibre to hair curliness(15)(23)(24). Hence, it is now accepted that the hair fibre shape is determined by the follicle shape and position and is controlled autonomously by the follicle.

Hair density

Hair density has been measured in numerous studies, often with the aim to compare groups in the context of health, age, gender, hair colour and geo-racial effect. It is not an uncommon practice for studies focused on one type of hair to directly compare their data to studies based on somewhat different methods. Studies including participants from different geo-racial groups (n>20 per group) have been summarised in Table 2. The data on the hair density is for healthy individuals (studies of participants with hair loss conditions were excluded) and based on phototrichograms. Despite some variability in reported endpoints, the data suggests that the individuals from Caucasian descent have the highest hair density. However, hair density is reported to be quite varied within age, sex and scalp locations, hence it is a less suitable characteristic for hair classification.

Hair chemistry

Early studies of the chemical composition of hair from different geo-racial groups focused on the amino acid content and on proportions of high vs low cystine keratins. Based on the analytical techniques used, the reported differences were considered insignificant (7)(29)(30)(31)(32)(33)(34). Some recent spectroscopic studies have explored the variations in relative protein content representing the Intermediate Filament (IF) and Keratin Associated Proteins (KAPs) fractions. In summary, higher content of random coil and disorganised structure (understood as amorphous and random coil mix) in African vs Caucasian hair (35), in hair from African countries vs African American and Jamaican (16), and in Asian vs (blond) Caucasian hair (36). However, these studies did not provide clear descriptions of the tested hair, hence the observed effects could be resulting from other variables such as donor age, hair damage etc. Proteomic studies have attempted to demonstrate differential protein expression; for example one study including hair from different origins reported relatively small variations, with KAP proteins being more effective differentiators (accounting for 21 out of 32 significant differences)(37). In another study of straight vs very curly Caucasian hair, 14 differentiating proteins were reported, thus suggesting that fibre shape is reflected at protein level (38). Thus, based on current knowledge, chemical/protein differences do not yet present a suitable basis for hair classification. However, proteomic studies could be useful for expanding this important area of fibre knowledge.

Micro and macro structural characteristics

Further understanding of the differences at micro and nano structural level has been offered by Transmission Electron Microscopy (TEM) observations of the cortical cells' macro composition and structures, as the cortex size and shape determines the size and shape of the fibre. The common observation in all studies is that a bilateral segregation of the cortical (C) cell types - para (PCs) and ortho (OCs) - is associated with curled fibres, compared to a more homogenous distribution in straight fibres (39)(40)(41). Notably, such association for curly and straight Japanese fibres was also reported thus inferring that this phenomenon is independent of hair origin (42)(43). Calorimetry studies also found similar fractions of IF and KAP proteins in African, Asian and European hair (44)(45) thus corroborating the theory of cortical cell distribution association with hair curl. So far, studies of the orientation and packing of IF proteins have shown that the underyling helical twist in the macrofibrils is left handed (46)(47) and that the intensity of the twist is a defining feature of the cortex cell type. However; these studies are not based on diverce hair types, hene it is difficult to relate them to the protein composition reports described in the previous section. One possible explanation is that while proteins are expressed within the same quantitative range, the molecular control of their assembly and packing is variable across the varied fibre types, most likely under genetic control. As yet, there is no evidence to support a causal relationship linking protein type to curl i.e. no 'curl protein' has been described. However, despite significant intra-sample variation, hair cortex keratins might offer a means to fingerprint individuals.

Studies of cuticle cell structure variations in human hair beyond cuticle edge shape and overlap are rare. The most prominent study so far reported differences in cuticle thickness and cuticle layers between groups: African<Caucasian; African<East Asian hair (11). In other

studies, Asian hair showed significantly more cuticle layers, higher cuticle thickness and narrower cuticle interval than the Caucasian hair (48)(49). Whilst these studies do not fully corroborate each other, there is a shared understanding that cuticle layers and thickness do vary and can be considered one of the morphologically defining feature of straight and curly hair.

Hair melanin

Aside from hair shape, hair colour can be a grouping characteristic of individuals from different geo-racial groups, based on instrumental or visual assessment (50). Hair colour is caused by the type, concentration, and distribution of melanin pigment granules (melanosomes) present in the hair fibre. Eumelanin has been reported to dominate hair of all colours other than red hair with variations of eumelanin accounting for the colour variation from black through brown to blond, based on number and distribution of melanosomes in the cortex. In red hair the quantities of eumelanin and pheomelanin are comparable (51)(52)(53). Decreasing size and total area occupied by melanosomes within the fibre cross sections of African, East Asian and European hairs have been observed (TEM) with peripheral distribution of melanosomes in the cortex in all types except within red European hairs, in which melanosomes tended to reside towards the centre of the cortex (11). Measurements of hair assembly colour has been reported to vary mostly in the *b* values (L *a b* scale), with the exception of European hair which also shows a large variation of L values and the red hair which is considered a different group due to high *a* values (50). Thus, melanosome type and location as well as hair assembly colour could also make useful contributions to hair classification.

Hair lipids

Hair lipids can be classified as external or internal depending on their origin: the sebaceous glands or follicular matrix cells respectively. Within this, lipids can be classed as bound (covalently) or freely extractable without hydrolysis. Sebum levels can be measured both as a component of free/surface lipids on hair or scalp. Thus, extractable lipids could be a way to classify human hairs, providing a relationship with morphology is observed. African hair was found to have a higher total lipid content than Caucasian hair irrespective of gender (54). Another study of men and women from seven groups reported the highest scalp sebum levels (2-3 days post shampooing) in African American and the lowest in Indian subjects compared to the other groups (55). Internal lipids in the fibre originate from the follicle (56) and African hair was reported to have 1.7x more internal lipids than Asian and Caucasian hair, and a higher content of cholesterol ester and cholesterol sulfate along with lower concentration of ceramides (57). Another study of cuticle lipids also places African hair as presenting the highest amount (58). At the same time Caucasian grey hair was reported to have less lipids in the cuticle than brown hair (59).

In summary, the limited scientific data points towards hair from African origin presenting higher external and internal lipid content (60), however, very little is known of the gender and age effects, which might be significant.

Hair fibre properties

Mechanical properties

Direct comparisons of the mechanical properties of different hair types under the same conditions are scarce in the literature, however, it is generally agreed that Asian and Caucasian hair have higher tensile strength than African hair – hence the tensile strength appears to decrease with increasing curliness (7)(16)(61)(62). Recent studies have suggested the existence of a toe region at the start of the stress/strain curve of very curly hair, thus proposing that it exhibits a certain amount of tensile resistance that isn’t reflected in the stress/strain plot of straight hair (63)(64). Some studies have also reported different fibre breakage patterns for different hair types subjected to tensile stress but such data needs further corroboration (65)(49). A different approach to mechanical hair assessment is offered by fatigue testing, where fibres undergo repeated constant tensile stress cycles until failure. In such test conditions African hair has been reported to require fewer cycles and lower stress to fail than Caucasian hair (66).

Studies comparing the torsional and bending behaviour of different hair types were not found, however, it is known that smaller cross-sectional area and higher ellipticity reported in high curl types will cause higher bending elasticity (67)(14) and large fibres with thicker cuticle (associated more commonly with straight hair Asian hair) will have higher torsional stiffness (68). Thus, mechanical testing can be used to differentiate hair types with inherent fragility, however, the links to origin remains in these studies.

Hair fragility

In a study where grooming was limited to shampooing, drying and combing, Scanning Electron Microscopy (SEM) images of naturally fallen (shed) fibres revealed prevalent damage in virgin African fibres in the form of knots and longitudinal splits whilst cuticle loss was most severe in Caucasian fibres. Another feature of African hair was that the root and tip ends of the collected hair appeared fractured (indicating broken hairs), whilst in the other two groups the majority of collected fibres appeared to have club hairs (indicating shed hairs) (69).

A common theory as to why African hair is fragile refers to the higher instance of natural constrictions (kinks and coils) along fibres, which are more likely to interact with each other. These interactions generate mechanical stress (tensile, torsional and bending) which could result in a range of damage manifestations acting as points of weakness when the fibre is exposed to a higher loads (7)(70)(71). The geometry and packing of cortical cells may also affect the breakage of hair fibres; however, currently, there is no sufficient evidence to confirm this.

The relative fragility (core and surface) of very curly hair is corroborated by the results of studies reporting that the majority of African American respondents experienced hair breakage (27)(72) and/or hair loss, some of which can be read as breakage (73). However, although it is now accepted that curly hair from African origin is more fragile than straighter hair types, comparisons of matched curled hair from varying geo-racial backgrounds are still lacking. If such data showed similar mechanical properties, then curl degree per se would be a ‘strength’ classifier of human hair.

In summary, the various mechanical properties of hair represent a suitable range of characteristics to define more precisely hair types, as they result from the combined effects of geometry and morphology. However, further clarity is needed on the range of tests and test settings that are sensitive to the specific mechanical behaviour of hair with different geometries.

Hair roughness and hardness

In a series of studies using Atomic-Force Microscopy (AFM), hair surface scans were used to quantify the surface roughness (excluding cuticle edges) and to calculate friction force. The surfaces of virgin and damaged Caucasian, Asian and African hair were compared. The virgin Caucasian and African hair surface roughness was reported very similar and higher than Asian hair's, but following chemo mechanical damage, the Asian's hair roughness increased more than the other two types (74). Further studies using AFM reported cuticle and cortex hardness increasing from African, through Caucasian to Asian hair (8)(49). Thus, AFM measurements could be an interesting way to classify hair where this method is available.

Hair lustre

Lustre, or shine, is one of the most desirable attributes of hair. Hair shine can be defined as the light reflected from the hair surface, of which there are two types: specular and diffuse. A study assessed the effect of fibre ell
iticity, diameter and colour on luster, using brown European, dark brown European, black Indian, black Japanese, and black African hairs. When all hairs from all groups were pulled straight and aligned, lustre increased with increasing elipticity and pigmentation, however, when in their natural configuration, curled fibres exhibited lower lustre than straight ones (75). Hence, lustre is an attribute linked to fibre array and alignment and is strongly linked to hair colour. Therefore, it is less likely to be useful as a classifier of human hair, despite being hugely important as a consumer attribute.

Water sorption and swelling of hair fibres

Studies have demonstrated that lipids impact on hair fibre hydration and water dynamics, as water permeation is related to both the amount of lipids and the order of lipids in the cuticle (76) (77) (78). Dynamic vapour sorption comparisons report the highest amount of water in the Caucasian, followed by African, and the lowest in the Asian hair, inferring that Asian hair is more resistant to hydration changes. On the other hand, African hair had the highest diffusion coefficient, and Caucasian the lowest , thus implaying that that water content per se is not related to diffusion capacity (58). Wet Caucasian hair was also reported to have higher radial swelling than in comparison to the other hair types (7). However, these reports do not explain fully their findings, which suggests that the phenomena are not fully understood. Furthermore, whilst the lipid's role in sorption is not disputed, the role of the protein structure has not been investigated. Hence, water swelling, or sorption might be an attribute that's useful for hair classification, but more so in relation to how different hair types respond the cosmetic treatments.

Hair resistance to UV radiation and chemical damage

From an individual's point of view, hair resistance to chemical damage due to cosmetic procedures and solar radiation (SR) is of importance. Several comparative studies including oxidative treatments offer inconsistent results, suggesting that the chemical treatment itself, not the hair type is the decisive factor for the degree of damage (79)(80). Solar radiation was reported to cause less damage measured as protein loss in dark and curly hair (versus blond) (81) and less oxidative stress in dark hair (82), whilst African hair incurred the most severe surface damage, based on lipid extraction (78). Thus, such studies do not contribute to, but will benefit from more precisely classified hair groups.

Discussion

The first challenge of this review, and with comparing hair types in principle, is the variability of study design and test conditions in the published literature. Hence, the data reported in different studies could be useful for comparing and establishing the directions of differences between hair types but not so much their relative magnitudes. A related challenge was the lack of precise detail of the hair origin in a significant number of the studies. Some of these studies were still included as they reported results which corroborated to a degree other studies with more robust methodologies. Therefore, a simple common approach to describing the tested hair is desirable for furthering the knowledge of hair differences and simple methods for hair classification would seem to be a pre-requisite for performing more complex comparative studies. In addition, reporting the size of the hair samples used and, when relevant, information of the donors' physiological characteristics such as age/gender/hormonal status is a good practice.

The second challenge which the review highlights is the sparsity of data directly comparing characteristics and properties of hair that would suggest an obvious means to generating a practical classification away from geo-racial grouping. Overall, the reported comparative geometric characteristics and curl data are the most consistent across studies and are assessed reasonably easily and reliably, hence they could be used as primary characteristics for classifying hair, which could also be.

From scientific point of view, comparative data of cortical cell structure and distribution, and cuticle cell thickness and distribution provide a secondary range of characteristics that are associated with hair geometry and curl. These characteristics are commonly referred to when studying how hair would respond to various daily manipulations and the external environment. Linked to that, further knowledge of the protein and lipid composition of different geometrical hair types could explain the micro and macro-level differences. Such knowledge will also generate better-tuned cosmetic treatments for different hair in terms of effect magnitude and longevity, and with reduced risks to scalp, follicle and fibre health. In this context, one area of research interest, the proteins of the cortex substructure, provides some but so far insufficient distinctions between hair types, as based on analytical techniques such as X-ray diffraction, Raman and IR spectroscopy, however, combining these with proteomics can further this understanding. On the other hand, the reports on lipids have provided more clearly defined distinctions between the geo-racial hair types, suggesting increased hydrophobicity of very curly hair.

Hair's mechanical properties are important for its capacity to be styled, for style retention and for strength and fragility. As these technical characterisations are understood to reflect the hair geometry and morphology, they can be considered as tertiary characteristics when defining hair types. The body of data in this field is already providing an overview of the order of tensile strength and fragility in relation to hair curl. However, tensile testing appears to have been mostly applied to straight hair and may not be the most effective method for assessing curly hair. Therefore, exploring the suitability of alternative mechanical testing for studying the variety of curly hair amongst the different geo-racial groups is recommended.

Finally, the combined effect of fibre's melanin content and geometry on the fibre colour and lustre are well understood and can be defined independently of the traditional geo-racial groups. In the context of fibre characterisation priorities, they are secondary, and measurements of the colour and lustre of the hair array have a higher practical value and are easier to acquire. Hence, it is recommended to consider reporting hair array colour values wherever possible in fibre studies, as the increasing hair diversity means that more variable combinations of geometry and colour are constantly emerging and the better defined a sample is the more robust and comparable the data will be.

This study also reviewed investigations of the follicle/curl effect and reports on hair density. These fields of studies compliment the understanding of how fibre characteristics influence the hair assembly but are not critical to developing a unified characterisation approach.

Conclusions

The current data points to three important directions for expanding the understanding of hair differences: i) exploring further the geometry-size-ellipticity relationships; ii) furthering the knowledge of cortical cell composition and distribution and the link to fibre shape and curl as well as of proteins associated with hair shape; and iii) better understanding of the lipid content and its effect on the water sorption and mechanical properties.

To aid this process, a simple framework for initial hair differentiation outside geo-racial origin is proposed. The premise is that if hair types are defined precisely by at least two geometrical characteristics and colour, further comparisons of morphological characteristics and related properties will be more reliable and will also support some cross study comparisons. Figure 1 summarises qualitatively the range of variations in hair characteristics and properties that are now accepted by the scientific community.

Further recommendations are: i) to ensure that hair sampling is transparent and robust so that reported similarities or differences between the selected types of hair could be compared with other studies; ii) to use a standardised method of hair geometry measurements; iii) to report consistently the hair sources (number, age/sex, hair status) and the fibre acquisition detail such as scalp sites (if applicable), number of fibres acquired. This framework requires a consensus approach to hair classification, and we hope that our review will make a significant contribution to developing this.

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Table 1. Search terms applied for each search topic. *The search term "human" was added when the search returned a large number of animal-based studies.*

Search topic 1: hair chemistry	
(human) hair +	amino acids, proteins, keratin, lipids, melanin, composition
Search topic 2: hair morphology, structure, follicle	
(human) hair +	fibre, cortex, cuticle, morphology
(human) hair +	shape, curvature, cross section
(human) hair +	follicle, density, growth, curly, straight
Search topic 3: technical hair fibre properties	
hair +	properties, strength, mechanical, UV, water sorption, thermal, lustre, optical, resistance

Table 2. Hair density. ** hair count as reported in the study, which may be analgen or anagen and telogen hairs, as well as including or discounting vellus hair; **some differences in the instrumentation and software used;***as reported in the study.*

Participants' origin	Hair density (hairs/cm²)*	Assessment method**	Location(s) of measurements***	Source
African (several countries)	161±50	phototrichogram	temporal, vertex, occipital	(25)
African (several countries)	171	phototrichogram	temple, nape, vertex	(4)
African (USA)	148±25 to 160±27	phototrichogram	frontal, vertex and occipital	(26)
African (USA)	167±7.16	phototrichogram	frontoparietal scalp sites	(27)
Asian (China)	175±54	phototrichogram	temporal, vertex, occipital	(25)
Asian (Japan)	181±21	phototrichogram	not specified	(28)
Asian (several countries)	167	phototrichogram	temple, nape, vertex	(4)
Asian (Thailand)	from 154.3±12.8 to 162.9±15.7	phototrichogram	vertex, temporal and occipital	(12)
Hispanics (USA)	from 169±31 to 178±33	phototrichogram	frontal, vertex and occipital	(26)
Caucasian (USA)	204 ± 8.58	phototrichogram	frontoparietal scalp sites	(27)
Caucasian (USA)	from 214±28 to 230±33	phototrichogram	frontal, vertex and occipital	(26)
Caucasian (France)	226±73	phototrichogram	temporal, vertex, occipital	(25)
Caucasian (several countries)	from 212 to 215	phototrichogram	temple, nape, vertex	(4)

Supplementary table 1. Comparative studies of hair fibre chemistry, morphology and properties. All studies include at least two defined hair types.

Parameters measured	Analytical techniques	Types of hair tested	Sample size	Results	Study authors
Fibre chemistry: amino acid and protein composition					
Chemical composition and mechanical properties	Acid hydrolysis of hair samples followed by column chromatography,reactivity tests, shape and mechanical properties	Brown European, Negroid hair, Lincoln wool	Hair from multiple donors (number not specified)	Greater sulfur content and cross linking in all human hair in comparison with wool, geometrical and mechanical differences are highlighted	Menkard et al (1966)
Characterisation of high sulfur keratins (high mw and basic properties) vs low sulfur keratins (low mw and acidic properties)	Amino acid analysis, 2D electrophoresis, X-ray diffraction, Stress-strain analysis	Caucasian (American), Mongolian (Japanese), African (Nigerian), Australian and Malaysian	5,2 and 1 donors respectively, Australian and Malaysian samples from museum exhibits	No differences detected between groups	Hrdy and Baden (1973)
Low-sulfur proteins protein composition in hair from different races	Protein extraction and alkylation followed by 2D electrophoresis	Japanese=straight hair; Afro-American=curly hair; Caucasian=wavy hair	4 donors of each group	7 low sulfur protein were detected for each hair type were detected. No difference was found within and amongst the groups	Dekio and Jidoi (1988)

High and low sulfur protein (HSP and LSP) comparisons of hair from different origin and with different colour	Protein extraction and alkylation followed by 2D electrophoresis	Fibres from Caucasians (several European countries), African (from Africa), Asian (from several Asian countries) and South American	number of hair samples not reported	Constant HSP found in all samples, LSP varied with hair colour	Nappe and Kermici (1989)
Ratio of fibrous (FP) and matrix proteins (MP)across hair from three races	Protein extraction and alkylation followed by centrifugation to separate FP and MP and dry weight measured	Fibres from Caucasian, African and Asian origin	5 donors (men and women) from each group	Asian hair ratio=0.45; Caucasian=0.29; African=0.18;	Dekio and Jidoi (1990)
Structural organisation of hair keratin	X-ray diffraction: Various structures signal a reflection at specific values: alpha helical arrangement; coiled coils; Ifs	Asian, African, Caucasian	5 individuals of each group (country of origin varied)	No observed differences in the alpha-helical arrangement of keratins, the IFs and microfibrils across the 3 groups, African hair has the lowest percentage of swelling in water, African hair exhibits lowest extension and brake stress than Asian and Caucasian hair	Franbourg *et al*,(2003)

Cystine levels across racial groups	TEM and silver staining	African,Asian,Caucasian, Trichothiodystrophy patients	African - n=10 Asian - n=5 Caucasian - n=5 Trichothiodystrophy patients - n=10	Similar distribution of cystine-rich proteins across the three ethnic groups, a lower cystine content in trichothiodystrophy patients	Khumalo, *et al* (2005)
Structural differences in hair of different origins	2D gel electrophoresis	Ghanaian, Jamaican, Kenyan, Liberian, African American	Ghanaian -n=35 Jamaican -n=50 Kenyan - n=50 Liberian -n=34 African American n=75	More KAP spots seen in hair from African countries than African Americans and Jamaicans	Porter *et al* (2009)
Comparison of straight and curved hair	Amino acid analysis, SEM, curle and diameter comparisons plus TEM	Japanese hair - straight and curved	230 donors, virgin hair cut from the root, 10 & 30 fibres used for curvature and diameter measurements	Identification of Para and Ortho like cells with the corresponding higher cystine content for the former	Nagase *et al* (2008)

Hair protein profiling using proteomic analysis	Mass spectroscopy and protein identification of digested hair proteins from whole fibres and cuticles	Scalp and body hair (undamaged), as well hair collected separately for cuticle analysis	Scalp hair samples: Caucasian=6; African-American=5; Korean=5; Kenyan=5. Cuticle samples: Caucasians=5, Asian=2	High variation in protein expression for individuals within each group, consistent variation between groups were lower, KAP were more useful for discriminating between groups	Laatsch *et al* (2014)
Difference in stretched hair as a manifestation of alpha to beta protein restructuring and cuticle changes	FT -IR Spectroscopy and Scan Electron Microscopy	Asian, Caucasian (blond)	Unspecified, several conditions of hair stretched to different %, and unstretched hair	Caucasian hair structure is more easily destroyed than Asian hair structures	Zhou *et al* 2015
Differences in structure of untreated and chemically or heat damaged hair	Raman Spectroscopy	White Caucasian hair and White African hair from individual donors-undamaged	All hair fibres were collected from the area near the nep; 52 fibres from each	No spectral difference of non treated hair, suggesting very similar chemical composition, except a slightly higher random coil content of African hair; similar spectral responses to treatments	dos Santos *et al* 2019

Insights in human hair curvature by proteome analysis of two distinct hair shapes	LC-MS/MS Liquid Chromatography-tandem Mass Spectroscopy	Hair Type 1 vs Hair Types V-VIII	50 subjects of each group, 100 fibres from each participant were used and hair was pooled into 10 pools of straight and 10 pools of very curly hair	Clear difference in protein profiles based on 217 common proteins 17 proteins identified as significantly different expressed in straight and very curly hair	Maer et al, 2021 (JCS)
Comparisons of hair cross sections	Reflectance microscopy and image analysis hair cross sections	African, Asian and Caucasian hair	Toral=93 donors, Europe=39; North Africa=10; Sub-Saharan Africa=7, Asia=20	European and North African Hair closer, the other groups further apart in dimensions	Guilbeau-Frugier (2006)
Hair morphology: cortex and cuticle structures					
Cortical cell distribution	Fluorescent Light Microscopy	Japanese, African	80 hair fibres form 156 Japanese subjects; unspecified number of fibres from 1 African subject	Hair fibres of different bending stiffness showed different staining patterns, suggesting different distribution on Ortho cortex and Para cortex cells	Ezawa, *et al* (2019)

Cortical cell fractions	Differential Scanning Calorimetry	Merino wool, African, Asian, European	Not specified	No differences in the fractions of PC's and OC's observed between ethnic groups	Wortmann & Wortmann (2018)
Cortical cell grouping and cross-sectional shape as contributors to hair shape	Differential Scanning Calorimetry and light microscopy	Three types of wool fibre and three types of hair	Not specified	Propose a theory of curle formation at the in the zone of cell keratinisation of the hair shaft in the follicle	Wortmann *et all* (2019)
Macro fibril bundles within cortex cell observations	TEM followed by electron tomography	Naturally straight Caucasian hair and high-curl African hair, cell examination was conducted on a pool of cells from 3 Caucasian and 2 African hair fibres	Macro fibrils of both types of hair have identical range appearances, the overall level of variability in human cells was high with circular and irregularly shapes	Identified 4 types of structurally defined cells, need further clarification which ones are to be classified as Ortho and para.	Harland *et all (*2014)
Helical twist direction in macro fibrils	Data mining of ETs for double twist macro fibrils	A pool of wool and human hair tomograms	644 tomograms	Left handed macro fibril twist - universal for all human hair	Harland *et all* (2019)
Structural analysis of cortical cells	Scanning electron microbeam SAXS	African, Caucasian and Asian hair	Individual donors with different curl type	Bilateral distribution of cortical cells found in curlier hair	Kajiura *et al* (2006)

Comparisons of orto cortex structures in straight and curly hair	TEM and silver staining, fluorescent microscopy	High and low curvature Japanese hair	not reported	Cell type bilateral distribution observed in curly hair, helical arrangements in IF also generated via software	Bryson *et al* (2009)
Comparisons of hair with different shape	X-ray diffraction of hair	Donors' racial/ethnic origin not reported clearly	12 individuals representing variations of colour (light blond to black) and shape (from straight to curly) a father and daughter, identical and fraternal twins.	Crystalline structures of proteins not significantly different, differences in lipid structures was noted	Fei-Chi *et al* (2014)
Structural characteristics: melanosomes size and distribution, cuticle layers and overall thickness	Transmission Electron Microscopy	Individuals leaving in the USA with 85% or greater genetic ancestry classified as European, East Asian, African	60 hair samples from 20 participants of each ethnic group, 20 hairs in each sample + 5 extra red European hair samples	Cross-section of melanosomes: A=0.1µm, EA=0.07µm, E=0.05µm; %cross sectional area occupied by melanosomes (A=3.43-3.02% EA=2.4-2.7 %, E1.30-1.45%). Melanosomes located towards the periphery for all populations except red European hairs are equally distributed; hair shape	Koch *et al* (2019)

				(ellipticity - reported in Table 2); cuticle thickness A=2.5µm EA=3.06µm E=2.83µm; and mean number of layers A=5.25, EA=7; E=6.5.	
Hair melanin					
Proportion of melanin types	Hydriodic acid hydrolysis	Black hair, Brown/blonde hair, Red hair	Not reported	Black hair - 99% eumelanin, 1% pheomelanin; Brown/blonde hair - 95% eumelanin, 5% pheomelanin; Red hair - 67% eumelanin, 33% pheomelanin	Borges, *et al* (2001)
Physical and chemical properties of melanin from black and red hair	Extraction of melanin with NaOH followed repeated precipitation with HCl	Black and red hair (natural) pulled samples	donor number not specified	Black hair melanoproteins contained 14% more melanin than red hair melanoproteins, Red hair melanins contained 4.2 times more S than black melanins.	Menon *et all* (1983)
Comparisons of black and red hair melanosomes	Enzymatic isolation of melanosomes an characterisation, AFM imaging	Black Asian hair and red Caucasian hair	Virgin hair, donors not specified	Eumelanosomes=elliptical, pheomelanosones=spherical; different amounts of amino acids	Lui *et al* (2005)

Proportion of melanin types in different hair as and corelation of visual and chemical phenotypes	Analysis of eu and pheo melanin markers in hair after alkali H_2O_2 oxidation	Hair samples classified based on visual colour phenotype: black; dark, medium and light brown; blond; red	228 hair samples	Eumelanin from black, dark brown, medium brown, light brown to blond, with levels of 22.2, 14.6, 10.4, 8.7 and 4.7 lg ⁄mg, respectively. Pheomelanin=nearly constant levels (0.85–0.99 lg ⁄mg)	Ito and Wakamatsu (2003)
Human hair colour measurements	Colorimetric measurements and visual assessment by trained assessors using discriminatory visual scales	Hair clippings from participants with natural (uncoloured) hair	2057 participants (50/50 men and women) from over many nationalities, 2870 hair samples	European hair has the highest colour variability, Oceanic hair higher b-value variability, Asian and African not different, red hair is a separate group	Lozano *et al* (2016)
Hair lipids					
Hair lipid analysis in groups representing difference race, gender and age	Lipids collected from daily wipes and from extraction from pooled hair samples	Adult male and female Caucasian and Afro American (age >20), plus Caucasian male age 6-20	Various amounts of pooled hair (g) per group	African hair has higher total lipid content than Caucasian hair; female hair has the highest total fatty acid content	Nicolaides and Rothman (1953)

Quantification of internal hair lipids	Thin layer chromatography + flame ioniser detector;	European, Asian, African	Not specified	More internal lipids in African hair=3.5% than Asian and European=2%; Similar lipid distribution across the 3 groups Caucasian hair had slightly more FFAs	(Cruz, et al., 2013)
Influence of lipids on structure of hair keratin	X-ray diffraction before and after removal of internal lipids and molecular dynamics simulation	European, Asian, African	Not specified	Sample of African hair with lipids didn't show reflections corresponding to the structural arrangement of keratin (unit length and packaging of helices), however the reflections did show in the African hair with lipids removed. MDS showed how lipid can interfere with the keratin structure	(Cruz, et al., 2013)
Lipid Content	Small and wide angle x-ray scattering patterns of hair	African, Chinese, European, Mixed race	3 doners per ethnicity, 5 fibre used from each doner	Crystalline proteins (IF) do not defer between hair types. Differences seen in the signal from the lipid component of the hair and particular in the lipids of African hair.	(Wade, et al., 2013)

Comparison of lipids in brown and white hair	Synchrotron-based FTIR, DSC and DVS	Caucasian hair	not reported	Cuticle lipid reduction in grey hair, also in the cortex with lower packing order. Grey hair has a reduced capacity to absorb water and increased velocity of exchange with the environment	Oliver et al (2019)
Cuticular lipid content	Infrared micro spectroscopy	African Asian Caucasian	Not specified	African hair had the highest lipid content, while Asian hair had the lowest	Oliver, et al., (2020)
Comparison of sebum secretion post shampooing	Sebum measurement at intervals post shampooing	Men and women in two age groups from US Caucasians, China, France, India, Japan and Thailand	130	3 days after shampooing African scalp had the highest level of sebum, lower sebum in all older age groups and women	Pouradier (2017)
Water sorption of hair					
Radial swelling of hair in water	Specialised measuring device to measure diameter of fibre before, during and after application of water droplet via pipette	Asian African Caucasian	20 hairs from 1 individual from each group	African hair had the lowest radial swelling rate & percentage than Asian and Caucasian (which were similar)	(Franbourg,et al., 2003)

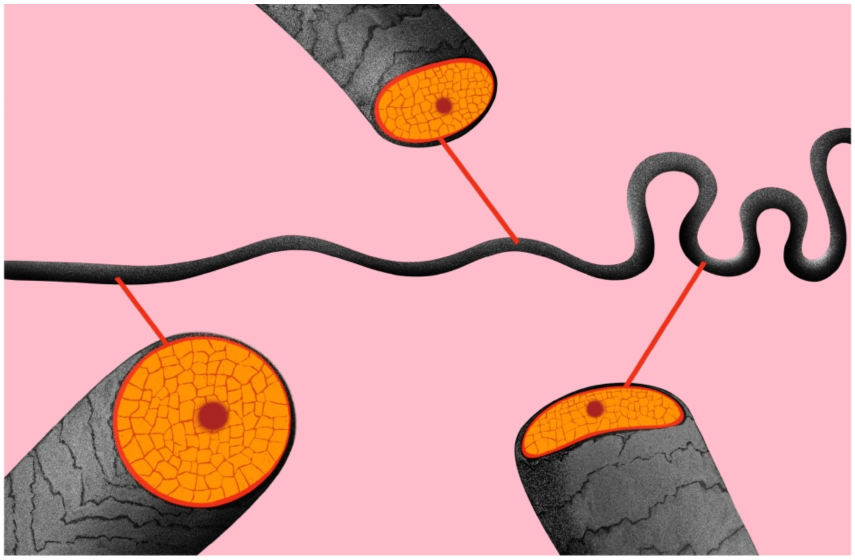
Response of hair to humidity changes	DVS analysis	Asian African Caucasian	Not specified	Caucasian hair had the highest affinity to water and the highest water content, and African the lowest	(Oliver, et al., 2020)
Hair lipids and dynamic sorption properties, mechanical properties.	Extraction of internal and external lipids, followed by TLC/FID), sorption analysis	African, Asian (Chinese) and Caucasian (brown)	Not specified	Total lipids extracted as % of dry fibre weight: Af=6.75+/-0.29; As=2.09+/-0.72; C=2.73+/-0.11; Hydration at 22C and 50%RH Af and As=10.7%, C=11.2%, Apolar lipids: Af>2.%; As and C=0.5%	Marti et all (2016)
			Hair and solar radiation		
Protein damage due to simulated and natural solar radiation	Irradiation of tresses with a simulator: UV, VIS and solar simulator, plus natural solar exposure t=30 and 26C and RH=66 and 50 respectively, spectrophotometry, protein loss (Lowry method)	Virgin Caucasian hair: dark brown, blond and red hair tresses from a pool; also dark brown straight and curly hair from individual donors	Pooled tresses, curly and straight comparison from single donors	Colour change (lightening) increases with the decrease of melanin in the hair; protein loss after radiation observed in all hairs, black and curly hair dark brown hair showed less and constants (not increasing) protein loss after increasing radiation doses	Nogueira and Joekes, 2004

Comparisons of hair shafts under visible light rations	Singlet Oxide detection during vis light irradiation of the hair shaft	Black, brown, white, red and blond hair	not reported	Blond hair generates higher amount of oxygen species	Chiarelli-Neto (2011)
Comparison of the cuticle damage following UV radiation	SEM and TEM images and HP-TLC of extracted lipids of UV-irradiated hair	Asian, African and Caucasian hair	not reported	African hair incurred most severe surface damage, Total extracted lipids was the highest in Asian hair, UV radiation decreased free fatty acids in African and Caucasian hair	Ji et al (2013)
Hair mechanical properties and resilience to damage					
Examination of fibre knotting and breakage	Light microscopy of fibres collected - natural shedding after 4 consecutive shampooing sessions; SEM	African (South African), Caucasian (northern Europe) and Asian (Indian and Chinese) donors	Sample numbers varied from donors	Average length of collected fibres: Caucasian=219mm; Asian=250mm; African=54mm; African hair had higher number of knots and broken hair; Caucasian and Asian hair = shredded, Caucasian hair =highest degree of cuticle wear	Khumalo et al, 2000

Comparisons of hair morphology, hardness and elasticity	Fibre surface SEM; nano indentation for hardness, elastic and creep behaviour of surface and cross section of hair	Caucasian, Asian (East) and African hair in three conditions: virgin, chemical/mechanically damages, and conditioned after damage	Virgin hair tresses from each group, number not specified	Cuticle hardness and elastic modulus are the lowest in African hair and the highest in Asian hair ; damage and conditioning caused an uniform changes to the surface hardness and elasticity	Wei et al (2004)
Comparisons of hair surface roughness and friction coefficient	Atomic Force Microscopy (AFM); surface topography - hight and friction	Caucasian, Asian (East) and African hair in three conditions: virgin, chemical/mechanically damages, and conditioned after damage	Virgin hair tresses from each group, number not specified	For all types of hair, friction coefficient increases with damage and is decreases to virgin state after conditioning, surface roughness is lowest in Asian hair and similar for the others	LaTorre and Bhushan (2005)
Comparisons of tensile responses of fibres	AFM applied to fibres under tensile tension	Caucasian, Asian (East) and African hair - virgin, also comparisons of damaged and conditioned Caucasian hair	not reported	Tensile force and strain at failure lowest for African and highest for Asian hair, elastic modulus decreases in the same order	Seshadri and Bhushan (2008)

Comparison of cuticle layer, thickness, elasticity and break pattern under deformation	SEM, Goniophotometer, AFM	Caucasian and Asian hair	Participants' hair Japanese=89 and Chinese=114; German=160; Caucasian American=50	Number of cuticle layers: A=7.13; C=6/55; Thickens of cuticle A=0.45, C=0.43; Interval between cuticle edges A=6.61, C=6.98, Inclination angle A=3.34 C=2.78, harder Asian cuticle and different breakage pattern upon tensile tress	Takahashi et al, 2006
Comparison of hair damage after straightening and colouring	TEM and lipid TEM image analysis and grading, after hair damage	Asian, African and Caucasian hair	One donor from each type	Asian hair showed the highest resistance to damage, however overall results are inconsistent	Lee et all (2014)
Defining fine Caucasian hair	Hair diameter, density, tensile break and bending forces, self perception and expert evaluation	Caucasian women	151 participants	Hair fibre size is responsible for tensile stress and bending resistance, fine hair parameters defined, low variability of data for Caucasian hair	Bouabbache (2015)
Tensile measurements vs self reported hair problems	Tensile measurements, laser scan and questionnaire	Caucasian, Mexican, African American and Chinese participants	1500 fibres from 300 participants	Break stress : Caucasian>African American and Jamaican>Ghanian hair	Byant et al (2008)

Comparison of hair damage after bleaching, dyeing, solar radiation exposure and heat styling	Dry combing, tensile strength, protein loss, colour change	African and Caucasian hair (straight and curly, light and dark)	not reported	Bleaching caused the highest protein loss for all types of hair, combing work increased most for African hair	Bloch et al (2019)
Hair lustre/gloss					
Lustre of hair from different origin	Goniophotometer	Fibres from Blond Piedmont, light and dark brown European, black Indian and Japanese and black African-American hair	Hair pools from swatches, plus hair from a single Chinese donor	New method for hair lustre evaluation, taking into account the effect of colour, ellipticity, curvature, cross sectional size and surface roughness.	Keis et al (2004)
Abreviations used in the table. *IFs*: Intermediate Fillaments; *KAPs*: Keratin Associated Proteins, *OCs*: Orthocortex cells, *PCs:* Paracortex cells, *SEM:* Scan electron microscopy; *TEM:* Transmission Electron Microscopy; *FT-IR:* Fouria-transform Infra Red (spectroscopy); *LC/MS:* Liquid chromatography/mass spectroscopy; *AFM:* Atomic Force Miscroscopy; *ET:*Electron Tomography; *SAXS:* small angle x-ray scaterring; *DSC:* Differential Scanning Calourimetry; *DVS:* Dynamic Vapor Sorbtion.					



Reported variations of fibre characteristics and properties

straight (types 1 and 2)	wavy	wavy to curly	curly	very curly/kinky (types 7 and 8)
low ellipticity		moderate ellipticity		high ellipticity
diameter varies from <70µm to >80µm				major diameter ca 60-80µm
black colour		dark brown to blond and red		black colour
cuticle thickness=8-10 layers				cuticle thickness 5-8 layers
ortho and para-cortex cells homogenous distribution				ortho and para-cortex cells bilateral distribution
lower lipid content				high lipid content
eumelanin		eumelanin and pheomelanin in variable ratios		eumelanin
break stress and survival probability=high				break stress and survival probability=low
water content=varied				water content=low
lustre=high		lustre=medium and colour dependent		lustre=low

Figure 1. Reported variations of fibre characteristics and properties

209x297mm (300 x 300 DPI)