

# Countering Racial Bias in Computer Graphics Research (Supplement)

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## 1 SKIN PAPERS

### 1.1 White Skin Papers

Many of the works on subsurface scattering focus on fair, white skin, but refer to it solely as “skin” [22, 39, 52, 68], “human skin” [20, 38, 61, 62], or a “human face” [16, 37]. The final showcase renderings solely feature images of white skin. In those works, it is unclear if the same algorithms are applicable to all types of skin, or whether the phenomena being captured by the algorithms are equally relevant to other skin types. While some papers also feature images of East Asians, the skin tones involved can be the fairest of all the examples [17], so the question of generality remains.

Other papers do attempt to build more complete models of human skin, incorporate different Fitzpatrick types into their studies, and render skin patches in a wide range of shades, but again the final showcase images are solely of white skin [23]. Others have a narrow range of test subjects, e.g. Jimenez et al. [41] reports collecting data from “one Caucasian female, 33 years old; three Caucasian males, 26, 33, and 35 years old”, or see Figures 1 and 19 in Beeler et al. [2]. In other works [24], skin variations are presented, but only deal with sweat, oil, ink, blood, and dirt. Both the final renderings and reference images are all of white skin.

The scan of Lee Perry-Smith’s head is often used as the sole skin benchmark in papers [26, 29, 46, 63], which suggests that the development of other benchmarks would help diversify research practices. Other works include more than one head example, e.g. [42] appears to contain four, but they are all of white humans.

In all, we found 19 rendering papers that solely featured white skin. We also found 4 instances where this bias is inherited by commercial software [55, 58–60], where their demos and documentation feature solely renderings of white humans. These lists are almost certainly incomplete.

### 1.2 Skin Papers with More Diversity

Some skin papers explore the appearance space more broadly. For example, both Hanrahan and Krueger [32] and Krishnaswamy and Baranoski [48] modulate the level of melanin, and Marschner et al. [50] captures data from “a 43-year-old Caucasian male and a 23-year-old male from India.” Donner and Jensen [21] present a spectral model for skin that also attempts to capture “Asian” and “African” skin, though the final showcase renders are again only of white skin. In one of the largest-scale studies to date, over 100 subjects of various skin phototypes, as classified by Fitzpatrick scale, were recruited for Weyrich et al. [67], and ten different skin shades appear in the illustrations for that paper. Finally, three subjects of Mediterranean, South and East Asian descent were recently used to illustrate the method in Gitlina et al. [27].

Some works are notable in the striking diversity of their generated avatars [34, 70]. A recent facial capture paper includes a variety of subjects [28], but notably does not attempt to capture subsurface scattering parameters. Instead, it sets them uniformly across all subjects, with the subsurface scattering color varying according to the subject’s surface albedo. (Note that “albedo” is Latin for “whiteness”.) The relative importance of the phenomenon in darker skin is still unclear.

## 2 HAIR PAPERS

### 2.1 Hair Simulations

Some of the earliest work in hair simulation deals exclusively with straight hair [1, 12]. This straightness assumption then leads to approximations using sheets [47], extruded sheets [69, 73], or clusters [8] instead of individual strands. Subsequently, simulations of straight or wavy hair are usually referred to simply as “hair” or “human hair” [3, 4, 6, 7, 9, 11, 13, 14, 19, 25, 30, 31, 33, 40, 44, 64–66].

In at least one instance [51], the fact that the algorithm excels explicitly at *straight* hair is mentioned in the title. In another [35], the shortcomings of existing straight-hair models are foregrounded by the need to develop a *curly* hair model. The definition of *curly* remains ambiguous, as other works [74] contain much straighter hair that is still characterized as “curly”.

In all, we found 27 papers dealing with the simulation of straight-to-curly hair. In contrast, we only found one paper that deals with simulating kinky,  $(0 + 1i)$  hair. A Cosserat model is used to model a variety of hair styles [5], including kinky, high-curvature strands. Patrick et al. [57] also modeled long, braided  $(0 + 1i)$  hair, as well as short  $(0 + 1i)$  hair, but did not attempt any simulations. Bertails et al. [4] mentions the non-zero natural twist in “African” hair, but does not attempt to simulate it.

### 2.2 Hair Rendering

Hair rendering algorithms focus exclusively on straight-to-curly hair. Kajiya and Kay [43] formulated a hair rendering model specifically for fur, and approximated the fibers as straight cylinders. The model of Marschner et al. [49] modified this cylinder to include cuticle scales, and subsequently demonstrated the secondary highlights that appear. Extremely straight  $(1 + 0i)$  hair is used to showcase this feature (see its Figs. 12–15). It remains unclear how prominent this feature is in  $(0 + 1i)$  hair. Other works test their algorithms on straight ponytails [36, 53], a single curly lock [18], or head models covered in straight or wavy hair [15, 56]. The model of Khungurn and Marschner [45] incorporates the measured elliptical cross-sections of several different types of hair, but the final renders are all of straight or curly blonde hairs (see its Fig. 21).

Several works specifically focus on the subsurface scattering phenomena characteristic of light, blonde hair. The model of Moon et al. [54] deals with “multiply scattered light [that] predominates in blond and other light colored hair”, and Zinke et al. [75] first observe that “particularly in dense, light-colored hair, multiple scattering provides a critical component of the hair color,” before proceeding to develop a model for that case.

Recent work has revisited the problem of animal fur [10], and in particular modified the model of Marschner et al. [49] to include the medulla characteristic of animal fur [72]. The fur models have then been unified with “human hair” [71] (see its Fig. 18), and the “human hair” presented is consistently straight.

In all, we found 14 hair rendering papers featuring straight-to-curly hair. This list is almost certainly incomplete. The only paper we found for rendering  $(0 + 1i)$  hair was the previously mentioned Patrick et al. [57], which proposes a modified Kajiya-Kay model for dense, braided, and short, unbraided  $(0 + 1i)$  hair.

## REFERENCES

- [1] Ken-ichi Anjyo, Yoshiaki Usami, and Tsuneya Kurihara. 1992. A simple method for extracting the natural beauty of hair. In *Proceedings of SIGGRAPH*. 111–120.
- [2] Thabo Beeler, Bernd Bickel, Gioacchino Noris, Paul Beardsley, Steve Marschner, Robert W Sumner, and Markus Gross. 2012. Coupled 3D reconstruction of sparse facial hair and skin. *ACM Trans. Graph.* 31, 4 (2012), 1–10.
- [3] Miklós Bergou, Basile Audoly, Etienne Vouga, Max Wardetzky, and Eitan Grinspun. 2010. Discrete viscous threads. *ACM Trans. Graph.* 29, 4 (2010), 1–10.
- [4] Florence Bertails, Basile Audoly, Marie-Paule Cani, Bernard Querleux, Frédéric Leroy, and Jean-Luc Lévêque. 2006. Super-helices for predicting the dynamics of natural hair. *ACM Trans. Graph.* 25, 3 (2006), 1180–1187.
- [5] F. Bertails, B. Audoly, B. Querleux, F. Leroy, J.-L. Lévêque, and M.-P. Cani. 2005. Predicting Natural Hair Shapes by Solving the Statics of Flexible Rods. In *Eurographics Short Papers*. Eurographics.
- [6] Florence Bertails, Tae-Yong Kim, Marie-Paule Cani, and Ulrich Neumann. 2003. Adaptive wisp tree—a multiresolution control structure for simulating dynamic clustering in hair motion. In *Proceedings of the ACM SIGGRAPH/Eurographics Symposium on Computer animation*.
- [7] Florence Bertails-Descoubes, Florent Cadoux, Gilles Daviet, and Vincent Acary. 2011. A nonsmooth Newton solver for capturing exact Coulomb friction in fiber assemblies. *ACM Trans. Graph.* 30, 1 (2011), 1–14.
- [8] Menglei Chai, Changxi Zheng, and Kun Zhou. 2014. A reduced model for interactive hairs. *ACM Trans. Graph.* 33, 4 (2014), 1–11.
- [9] Johnny T Chang, Jingyi Jin, and Yizhou Yu. 2002. A practical model for hair mutual interactions. In *Proceedings of the ACM SIGGRAPH/Eurographics Symposium on Computer animation*. 73–80.
- [10] Matt Jen-Yuan Chiang, Benedikt Bitterli, Chuck Tappan, and Brent Burley. 2016. A Practical and Controllable Hair and Fur Model for Production Path Tracing. *Computer Graphics Forum* 35, 2 (2016), 275–283.
- [11] Byoungwon Choe, Min Gyu Choi, and Hyeong-Seok Ko. 2005. Simulating complex hair with robust collision handling. In *Proceedings of the ACM SIGGRAPH/Eurographics Symposium on Computer animation*. 153–160.
- [12] Agnes Daldegan, Nadia Magnenat Thalmann, Tsuneya Kurihara, and Daniel Thalmann. 1993. An integrated system for modeling, animating and rendering hair. In *Computer Graphics Forum*, Vol. 12. 211–221.
- [13] Gilles Daviet. 2020. Simple and scalable frictional contacts for thin nodal objects. *ACM Trans. Graph.* 39, 4 (2020), 61–1.
- [14] Gilles Daviet, Florence Bertails-Descoubes, and Laurence Boissieux. 2011. A Hybrid Iterative Solver for Robustly Capturing Coulomb Friction in Hair Dynamics. *ACM Trans. Graph.* 30, 6 (2011), 139–1.
- [15] Eugene d’Eon, Guillaume Francois, Martin Hill, Joe Letteri, and Jean-Marie Aubry. 2011. An energy-conserving hair reflectance model. In *Computer Graphics Forum*, Vol. 30. Wiley Online Library, 1181–1187. Issue 4.
- [16] Eugene d’Eon and Geoffrey Irving. 2011. A quantized-diffusion model for rendering translucent materials. *ACM Trans. Graph.* 30 (2011), 1–14. Issue 4.
- [17] Eugene d’Eon, David Luebke, and Eric Enderton. 2007. Efficient rendering of human skin. In *Eurographics Workshop on Rendering Techniques*. 147–157.
- [18] Eugene d’Eon, Steve Marschner, and Johannes Hanika. 2013. Importance sampling for physically-based hair fiber models. In *SIGGRAPH Asia Technical Briefs*. 1–4.
- [19] Alexandre Derouet-Jourdan, Florence Bertails-Descoubes, Gilles Daviet, and Joëlle Thollot. 2013. Inverse dynamic hair modeling with frictional contact. *ACM Trans. Graph.* 32, 6 (2013), 1–10.
- [20] Craig Donner and Henrik Wann Jensen. 2005. Light diffusion in multi-layered translucent materials. *ACM Trans. Graph.* 24, 3 (2005), 1032–1039.
- [21] Craig Donner and Henrik Wann Jensen. 2006. A spectral BSSRDF for shading human skin. In *Proceedings of the Eurographics Workshop on Rendering*.
- [22] Craig Donner and Henrik Wann Jensen. 2007. Rendering translucent materials using photon diffusion. In *Eurographics Workshop on Rendering Techniques*. 243–251.
- [23] C. Donner, T. Weyrich, E. d’Eon, R. Ramamoorthi, and S. Rusinkiewicz. 2008. A layered, heterogeneous reflectance model for acquiring and rendering human skin. *ACM Trans. Graph.* 27, 5 (2008), 1–12.
- [24] Luca Fascione, Johannes Hanika, Rob Pieké, Wenzel Jakob, Andrea Weidlich, and Hanzhi Tang. 2019. Path tracing in production-part 2: making movies. In *ACM SIGGRAPH Courses*. 1–32.
- [25] Yun Fei, Henrique Teles Maia, Christopher Batty, Changxi Zheng, and Eitan Grinspun. 2017. A multi-scale model for simulating liquid-hair interactions. *ACM Transactions on Graphics (TOG)* 36, 4 (2017), 1–17.
- [26] Roald Frederickx and Philip Dutré. 2017. A forward scattering dipole model from a functional integral approximation. *ACM Trans. Graph.* 36, 4 (2017), 1–13.
- [27] Yuliya Gitlina, Giuseppe Claudio Guarnera, Daljit Singh Dhillon, Jan Hansen, Alexandros Lattas, Dinesh Pai, and Abhijeet Ghosh. 2020. Practical measurement and reconstruction of spectral skin reflectance. In *Computer Graphics Forum*, Vol. 39. Wiley Online Library, 75–89. Issue 4.
- [28] Paulo Gotardo, Jérémy Riviere, Derek Bradley, Abhijeet Ghosh, and Thabo Beeler. 2018. Practical dynamic facial appearance modeling and acquisition. *ACM Trans. Graph.* 37, 6 (2018), 1–13.
- [29] Ralf Habel, Per H Christensen, and Wojciech Jarosz. 2013. Photon beam diffusion: a hybrid Monte Carlo method for subsurface scattering. In *Proceedings of the Eurographics Symposium on Rendering*. 27–37.
- [30] Sunil Hadap and Nadia Magnenat-Thalmann. 2001. Modeling dynamic hair as a continuum. In *Proceedings of Eurographics*, Vol. 20. Wiley Online Library, 329–338. Issue 3.
- [31] Xuchen Han, Theodore F Gast, Qi Guo, Stephanie Wang, Chenfanfu Jiang, and Joseph Teran. 2019. A hybrid material point method for frictional contact with diverse materials. *Proceedings of the ACM on Computer Graphics and Interactive Techniques* 2, 2 (2019), 1–24.
- [32] Pat Hanrahan and Wolfgang Krueger. 1993. Reflection from Layered Surfaces Due to Subsurface Scattering. In *Proceedings of SIGGRAPH*. 165–174.
- [33] Liwen Hu, Derek Bradley, Hao Li, and Thabo Beeler. 2017. Simulation-ready hair capture. In *Computer Graphics Forum*, Vol. 36. Wiley Online Library, 281–294. Issue 2.
- [34] Liwen Hu, Shunsuke Saito, Lingyu Wei, Koki Nagano, Jaewoo Seo, Jens Fursund, Iman Sadeghi, Carrie Sun, Yen-Chun Chen, and Hao Li. 2017. Avatar Digitization from a Single Image for Real-Time Rendering. *ACM Trans. Graph.* 36, 6, Article 195 (Nov. 2017), 14 pages.
- [35] Hayley Iben, Mark Meyer, Lena Petrovic, Olivier Soares, John Anderson, and Andrew Witkin. 2013. Artistic simulation of curly hair. In *Proceedings of the ACM SIGGRAPH/Eurographics Symposium on Computer Animation*. 63–71.
- [36] Wenzel Jakob, Jonathan T Moon, and Steve Marschner. 2009. Capturing hair assemblies fiber by fiber. *ACM Transactions on Graphics (TOG)* 28, 5 (2009), 1–9.
- [37] Henrik Wann Jensen. 2002. Digital face cloning. In *ACM SIGGRAPH Courses*. 1.
- [38] Henrik Wann Jensen and Juan Buhler. 2002. A rapid hierarchical rendering technique for translucent materials. In *Proceedings of SIGGRAPH*. 576–581.
- [39] Henrik Wann Jensen, Stephen R Marschner, Marc Levoy, and Pat Hanrahan. 2001. A practical model for subsurface light transport. In *Proceedings of SIGGRAPH*. 511–518.
- [40] Chenfanfu Jiang, Theodore Gast, and Joseph Teran. 2017. Anisotropic elastoplasticity for cloth, knit and hair frictional contact. *ACM Trans. Graph.* 36, 4 (2017), 1–14.
- [41] Jorge Jimenez, Timothy Scully, Nuno Barbosa, Craig Donner, Xenxo Alvarez, Teresa Vieira, Paul Matts, Verónica Orvalho, Diego Gutierrez, and Tim Weyrich. 2010. A practical appearance model for dynamic facial color. *ACM Trans. Graph.* 29 (2010), 1–10. Issue 6.
- [42] Jorge Jimenez, Károly Zsolnai, Adrian Jarabo, Christian Freude, Thomas Auzinger, Xian-Chun Wu, Javier von der Pahlen, Michael Wimmer, and Diego Gutierrez. 2015. Separable subsurface scattering. In *Computer Graphics Forum*, Vol. 34. Wiley Online Library, 188–197. Issue 6.
- [43] JT Kajiya and TL Kay. 1989. Rendering fur with three dimensional textures. In *Proceedings of SIGGRAPH*. 271–280.
- [44] Danny M Kaufman, Rasmus Tamstorf, Breannan Smith, Jean-Marie Aubry, and Eitan Grinspun. 2014. Adaptive nonlinearity for collisions in complex rod assemblies. *ACM Trans. Graph.* 33, 4 (2014), 1–12.
- [45] Pramook Khungurn and Steve Marschner. 2017. Azimuthal scattering from elliptical hair fibers. *ACM Transactions on Graphics (TOG)* 36, 2 (2017), 1–23.
- [46] Alan King, Christopher Kulla, Alejandro Conty, and Marcos Fajardo. 2013. BSSRDF importance sampling. In *ACM SIGGRAPH Talks*. 1–1.
- [47] Chuan Koon Koh and Zhiyong Huang. 2001. A simple physics model to animate human hair modeled in 2D strips in real time. In *Computer Animation and Simulation*. Springer, 127–138.

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- [48] Aravind Krishnaswamy and Gladimir VG Baranoski. 2004. A biophysically-based spectral model of light interaction with human skin. In *Computer graphics forum*, Vol. 23. 331–340. Issue 3.
- [49] Stephen R Marschner, Henrik Wann Jensen, Mike Cammarano, Steve Worley, and Pat Hanrahan. 2003. Light scattering from human hair fibers. *ACM Trans. Graph.* 22, 3 (2003), 780–791.
- [50] Stephen R Marschner, Stephen H Westin, Eric PF Lafortune, Kenneth E Torrance, and Donald P Greenberg. 1999. Image-based BRDF measurement including human skin. In *Eurographics Workshop on Rendering Techniques*. Springer, 131–144.
- [51] Aleka McAdams, Andrew Selle, Kelly Ward, Eftychios Sifakis, and Joseph Teran. 2009. Detail preserving continuum simulation of straight hair. *ACM Trans. Graph.* 28, 3 (2009), 1–6.
- [52] Johannes Meng, Johannes Hanika, and Carsten Dachsbacher. 2016. Improving the Dwivedi sampling scheme. In *Proceedings of the Eurographics Symposium on Rendering*. Wiley Online Library, 37–44.
- [53] Jonathan T Moon and Stephen R Marschner. 2006. Simulating multiple scattering in hair using a photon mapping approach. *ACM Trans. Graph.* 25, 3 (2006), 1067–1074.
- [54] Jonathan T Moon, Bruce Walter, and Steve Marschner. 2008. Efficient multiple scattering in hair using spherical harmonics. *ACM Transactions on Graphics (TOG)* 27, 3 (2008), 1–7.
- [55] NVIDIA. 2021. Faceworks. <https://developer.nvidia.com/faceworks>
- [56] Jiawei Ou, Feng Xie, Parashar Krishnamachari, and Fabio Pellacini. 2012. ISHair: importance sampling for hair scattering. In *Computer Graphics Forum*, Vol. 31. Wiley Online Library, 1537–1545.
- [57] D. Patrick, S. Bangay, and A. Lobb. 2004. Modelling and Rendering Techniques for African Hairstyles. In *Proceedings of AFRIGRAPH*. 115–124.
- [58] Redshift. 2021. Skin. <https://docs.redshift3d.com/display/RSDOCS/Skin>
- [59] Arnold Renderer. 2021. Skin. <https://docs.arnoldrenderer.com/display/A5AFMUG/Skin>
- [60] Renderman. 2021. PxrSkin. [https://renderman.pixar.com/resources/RenderMan\\_20/PxrSkin.html](https://renderman.pixar.com/resources/RenderMan_20/PxrSkin.html)
- [61] Jos Stam. 2001. An illumination model for a skin layer bounded by rough surfaces. In *Eurographics Workshop on Rendering Techniques*. Springer, 39–52.
- [62] Florian Struck, Christian-A Bohn, Sebastian Schmidt, and Volker Helzle. 2004. Realistic shading of human skin in real time. In *Proceedings of AFRIGRAPH*. 93–97.
- [63] Delio Vicini, Vladlen Koltun, and Wenzel Jakob. 2019. A learned shape-adaptive subsurface scattering model. *ACM Trans. Graph.* 38, 4 (2019), 1–15.
- [64] Kelly Ward, Nico Galoppo, , and Ming C Lin. 2004. Modeling hair influenced by water and styling products. In *International Conference on Computer Animation and Social Agents*. Citeseer.
- [65] Kelly Ward and Ming C Lin. 2003. Adaptive grouping and subdivision for simulating hair dynamics. In *Proceedings of Pacific Graphics*. IEEE, 234–243.
- [66] Kelly Ward, Ming C Lin, Joohi Lee, Susan Fisher, and Dean Macri. 2003. Modeling Hair Using Level-of-Detail Representations. In *Computer Animation and Social Agents, International Conference on*. IEEE Computer Society, 41–41.
- [67] T. Weyrich, W. Matusik, H. Pfister, B. Bickel, C. Donner, C. Tu, J. McAndless, J. Lee, A. Ngan, H.W. Jensen, and M. Gross. 2006. Analysis of Human Faces Using a Measurement-Based Skin Reflectance Model. *ACM Trans. Graph.* 25, 3 (July 2006), 1013–1024.
- [68] A Wilkie, S Nawaz, M Droske, A Weidlich, and J Hanika. 2014. Hero wavelength spectral sampling. In *Proceedings of the Eurographics Symposium on Rendering*. 123–131.
- [69] Kui Wu and Cem Yuksel. 2016. Real-time hair mesh simulation. In *Proceedings of the ACM SIGGRAPH Symposium on Interactive 3D Graphics and Games*. 59–64.
- [70] Shugo Yamaguchi, Shunsuke Saito, Koki Nagano, Yajie Zhao, Weikai Chen, Kyle Olszewski, Shigeo Morishima, and Hao Li. 2018. High-fidelity facial reflectance and geometry inference from an unconstrained image. *ACM Trans. Graph.* 37, 4 (2018), 1–14.
- [71] Ling-Qi Yan, Weilun Sun, Henrik Wann Jensen, and Ravi Ramamoorthi. 2017. A BSSRDF model for efficient rendering of fur with global illumination. *ACM Transactions on Graphics (TOG)* 36, 6 (2017), 1–13.
- [72] Ling-Qi Yan, Chi-Wei Tseng, Henrik Wann Jensen, and Ravi Ramamoorthi. 2015. Physically-accurate fur reflectance: Modeling, measurement and rendering. *ACM Trans. Graph.* 34, 6 (2015), 1–13.
- [73] Cem Yuksel, Scott Schaefer, and John Keyser. 2009. Hair meshes. *ACM Trans. Graph.* 28, 5 (2009), 1–7.
- [74] Qing Zhang, Jing Tong, Huamin Wang, Zhigeng Pan, and Ruigang Yang. 2012. Simulation guided hair dynamics modeling from video. In *Computer Graphics Forum*, Vol. 31. Wiley Online Library, 2003–2010. Issue 7.
- [75] Arno Zinke, Cem Yuksel, Andreas Weber, and John Keyser. 2008. Dual scattering approximation for fast multiple scattering in hair. *ACM Transactions on Graphics (TOG)* 27, 3 (2008), 1–10.