谷物可溶性(1→3)(1→4)-β-D-葡聚糖结构与生理活性的研究进展

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摘要：谷物 β-葡聚糖是 β-D-吡喃型葡萄糖基单元通过(1→4)-β-键重复连接并被单一(1→3)-β-D-键分离而形成的一种线性同聚多糖，同时也是谷物水溶性膳食纤维的主要成分，主要存在于大麦、燕麦、青稞、小麦和黑麦中。谷物可溶性 β-葡聚糖的生理效应与其独特的结构具有密切关系，本文注重于谷物 β-葡聚糖的分子结构特征与其在胃肠道中的生理活性的关系，总结了谷物可溶性 β-葡聚糖在降低胆固醇、餐后血糖指数与胰岛素水平上等生理活性的研究，探讨了谷物 β-葡聚糖对肠道菌群与免疫作用的新机制。对几种 β-葡聚糖生理活性机理的研究进行了描述：增加小肠黏度水平因此延缓胃排空、消化和分子吸收，包括葡萄糖、膳食胆固醇和胆汁酸；于小肠中与胆汁酸相结合降低胆汁酸重吸收，进而促进利用胆固醇的胆汁酸合成；降低餐后血糖指数与胰岛素水平改善胰岛素敏感性；于盲肠、结肠中发酵改善肠道健康。

关键词：谷物；β-葡聚糖；结构；生理活性
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Research Progress in the Structure and Physiological Activity of Soluble (1→3)(1→4)-β-D-glucan from Cereal

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Abstract: Cereal β-glucans are a type of linear homopolysaccharides formed by the linkage of β-D- glucopyranosyl units via (1→4)-β-linkage and separated by single (1→3)-β-linkages. They are the main component of water-soluble dietary fibers from cereals and are mainly found in barley, oat, hull-less barley, wheat, and rye. The physiological activity of soluble β-glucan from cereal is closely related to its unique structure of (1→3)(1→4)-β-D-glucan. This paper focused on the relationship between the characteristics of the molecular structure of cereal β-glucans and their physiological activity in the gastrointestinal tract. The physiological activities of cereal soluble β-glucans in reducing cholesterol, postprandial glycemic index, and insulin levels are summarized and new mechanisms underlying the effect of β-glucans on the intestinal flora and immune function are discussed. Studies on several mechanisms underlying the physiological activities of β-glucan are described. The viscosity level in the small intestine was increased, delaying the gastric emptying, digestion, and absorption of molecules, including glucose, dietary cholesterol, and bile acids. β-glucans bound with bile acid in the intestine to decrease the bile acid reabsorption, thus promoting the synthesis of bile acids from cholesterol. β-glucans improved insulin sensitivity by reducing postprandial glycemic index and insulin level and underwent colonic fermentation to improve intestinal health.

Key words: cereal; β-glucan; structure; physiological activity

膳食纤维（DF, Dietary fibre）是人类饮食的重要组成部分，早在上世纪七十年代，膳食纤维通常被认为是难以被人体消化吸收的植物营养素[1]，大多存在于植物细胞壁中[2]，是一类无法被人体消化酶水解但却可能受到肠道微生物降解的多糖和木质素的总称[2~3]。早期研究证明膳食纤维具有与多种流行病学的潜在关联[4]，甚至人体卡路里的摄取、食糜在肠道中滞留时间、结肠压力、人体粪便菌群、血清胆固醇及胆汁酸代谢等的变化与膳食纤维有密切的关系[4]。随着肥胖、心脑血管疾等代谢综合征的日益普遍，谷物

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(1→3)(1→4)-β-D-葡聚糖，这类难以被人体上消化道消化降解的膳食纤维开始受到研究者的广泛关注[5]。时至今日，研究发现膳食纤维的摄入大多通过其特有属性来影响人体胃肠道功能（黏度，吸水性，溶胀率，可发酵性及其结合胆汁酸的能力等），例如改变人体对营养物质的消化吸收速率[6]，促进人体肠道菌群的繁殖和润肠通便[7]，降低体内碳水化合物的转化速率进而减少对胰岛素的需求[8]，促进胆汁酸的排放和改变大肠中短链脂肪酸组成[9]。

谷物(1→3)(1→4)-β-D-葡聚糖（β-葡聚糖）存在于大麦、燕麦、青稞、黑麦与小麦中，其含量分别为3-11%[10]，3-7%[10]，5-10%[11]，1-3.4%[12]。和0.2-1.2%[13]。临床研究发现[9]，燕麦 β-葡聚糖具有降低血胆固醇水平、餐后血糖指数与胰岛素反应的活性，且与其结构、分子质量与物理特性有关[14]。大麦 β-葡聚糖因其在啤酒行业的负面作用而开始受到广泛研究，随后人体与动物试验发现其具有与燕麦 β-葡聚糖相类似的生理活性[15]。小麦中 β-葡聚糖的含量相对燕麦与大麦较低，主要位于糊粉层和胚乳组织的细胞壁中[16~17]，糊粉层中含有 25%的 β-葡聚糖[18]，且其结构与燕麦大麦 β-葡聚糖结构类似，并具有相似的物化特性[19~20]。黑麦中的 β-葡聚糖含量相对高于小麦，其结构同为通过(1→3)-β-键连接不同聚合度纤维寡糖的无支链线性多糖[21]，具有与燕麦相类似的生理活性[22]。青稞，与燕麦和大麦一同被认为是富含 β-葡聚糖的谷物[23]，具有与其余谷物 β-葡聚糖相似的结构与生理活性[23~25]，且因其成熟期比小麦短、较耐旱耐盐、对土地肥沃程度要求不高，而成为藏人之所以能够在高海拔地区定居的基础[26]。

谷物种属、基因及生长环境影响着谷物中 β-葡聚糖的含量[27]，而提取方式的不同不仅影响着谷物 β-葡聚糖的提取率，且影响谷物 β-葡聚糖的精细结构，从而影响 β-葡聚糖的物化特性[28~29]。谷物 β-葡聚糖大多基于利用水[28]、碱液[30]及酶液[31]从谷物中提取可溶性(1→3)(1→4)-β-D-葡聚糖进行研究，因此本论文主要目的在于总结谷物可溶性 β-葡聚糖的结构特征，其生理活性研究进展，及与此相关的研究前景。

1 结构特征

谷物可溶性 β-葡聚糖是一种仅由 β-D-吡喃型葡萄糖基单元构成的线性多糖。这些单元分别通过(1→4)-或(1→3)-β-D-键相连接，故因此又被成为混合线性(1→3)(1→4)-β-D-葡聚糖。(1→4)-或(1→3)-β-D-键的分布并不随意，但也不具有稳定的规律。1960 年 Parrish[32]发现在 β-葡聚糖中(1→4)-β-键大多在连续连接两到三个葡萄糖基单元后被(1→3)-β-键分割，1983 年 Woodward[33]发现 β-葡聚糖中存在类似纤维素的连续结构，随后相关结构报道再次验证 β-葡聚糖中特殊的链结构[34~36]。β-葡聚糖组成的基础是由 β-D-吡喃型葡萄糖基单元通过(1→4)-β-键重复连接形成纤维三糖或四糖为主的纤维寡聚物，再通过单一的(1→3)-β-D-键连接组合形成的一种线性同聚多糖（图 1）。大多数的纤维链段为三聚体和四聚体，但聚合度更高的的纤维单元也同样存在于 β-葡聚糖链中[29, 37, 38]。试验证明大多数不同谷物的 β-葡聚糖具有相同的甲基化分析结果和核磁谱图，但不同谷物的 β-葡聚糖的结构仍然具有较大的差异，例如纤维三糖和四糖的比例、聚合度更高的纤维寡聚物的含量、和(1→4)-β-键和(1→3)-β-键的比例[37~39]。而这种精细结构特征又决定了他们的物化理特性[40~44]和胃肠道的生理作用[45]，例如溶解度，黏度和凝胶行为等。在 β-葡聚糖键类型中，(1→3)-β-D-键可以防止分子间紧密堆积和提高溶解度，这一特性导致谷物 β-葡聚糖结构与纤维素中 D-吡喃型葡萄糖基单元完全通过(1→4)-β-键连连接形成紧密堆积的晶体结构完全不同[33, 41]。

研究谷物 β-葡聚糖结构特点时大多采用酶法水解 β-葡聚糖。地衣聚糖酶，又被称为(1→3)(1→4)-β-D-葡聚糖-4-葡聚糖水解酶（EC3.2.1.73），可以切断 β-葡聚糖中三取代葡萄糖基上的(1→4)-糖苷键，从而得到不同聚合程度的纤维链段（DP）（图 1）。谷物 β-葡聚糖的主要水解产物为 3-O-纤维素二糖-D-葡萄糖（DP3）和 3-O-纤维素三糖-D-葡萄糖（DP4），它们以随机的形式分布在 β-葡聚糖的直链中[35]。然而 β-葡聚糖水解产物中还具有少量更高聚合度的纤维素寡聚物（5~15%），聚合程度为 5~20 个葡萄糖基，其中以 DP5，DP6 和 DP9 占多数[29, 39, 46]。

同一种属的谷物 β-葡聚糖具有相似的寡糖分布，而不同植物来源的 β-葡聚糖通常具有较大区别[38, 43]。小麦、大麦和燕麦 β-葡聚糖里纤维三糖的相对比例分别为 67~72%，52~69%和 53~61%，纤维四糖在三者中的相对比例则为 21~24%，25~33%，34~41%。由于纤维三糖和四糖在不同谷物 β 葡聚糖中相对比例不同，因此可以通过它们两者的摩尔百分数之比来表示种间差异。小麦、大麦、黑麦和燕麦的 DP3：DP4 比例分别为 3.0~4.5、1.8~3.5、1.9~3.0、1.5~2.3，这一比例通常也被称为是谷物 β-葡聚糖的结构指纹。然而研究发现同种谷物的 DP3:DP4 比例也具有差异性，这一发现归因于他们的基因的差异与生长的环境的不同[47~50]。糯大麦品种中的 β-葡聚糖相比非蜡质大麦品种中的 β 葡聚糖具有更高的 DP3:DP4 比例，而大麦糊粉

组织中的 DP3:DP4 比例比淀粉质胚乳组织中更高[51]。

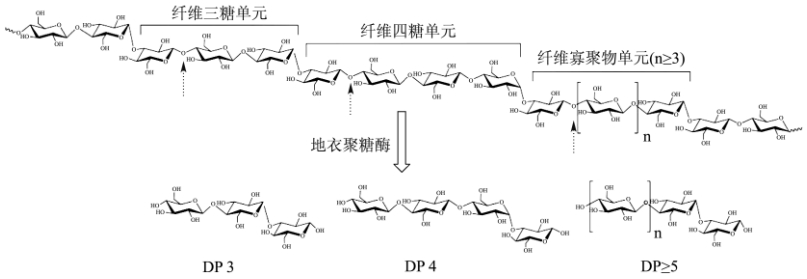

图 1 谷物 β-葡聚糖结构与地衣聚糖酶水解

Fig.1 Structure of cereal β-glucans and their debranching by lichenase

2 生理活性

2.1 胆固醇

1978 年，燕麦制品被发现具有降胆固醇的作用[52]，高胆固醇血症患者摄入定量的燕麦麸能降低 19%血清总胆固醇浓度及 23%的低密度脂蛋白胆固醇浓度。随着对燕麦麸的研究发现，燕麦麸中富含 β-葡聚糖[53, 54]，及粘性多糖与降胆固醇相关性得到陆续报道[55]，致使具有粘性的 β-葡聚糖被认为是燕麦麸起到降低胆固醇作用的的活性成分。1997 年[56]，在 FDA 公布的关于降低饱和脂肪和胆固醇摄入的健康声明中，指出全燕麦中可溶性膳食纤维具有降低心脑血管疾病风险的可能。FDA 总结以往报道，确认燕麦可溶性膳食纤维的降低胆固醇作用，且声明中提到 β-葡聚糖是燕麦健康作用的主要生物活性组分。而大麦[57~59]、小麦[60]、黑麦[61]和青稞[62]β-葡聚糖同样被发现具有与燕麦 β-葡聚糖类似的降胆固醇功效。

FDA 推荐 β-葡聚糖每日摄取剂量为 3 g，但因群体多样性及饮食习惯等因素的影响，并未对该剂量的有效性进行更多的报道。Davidson 等人[63]研究不同剂量的燕麦膳食与燕麦麸对轻度高胆固醇血症患者的影响，发现 88 g 的燕麦膳食、56 g 的燕麦麸和 86 g 的燕麦麸（相当于 3.6 g、4.0 g 和 6.0 g 的 β-葡聚糖）具有显著降低总胆固醇和低密度胆固醇水平的效果，但在另外的研究中 β-葡聚糖含量的改变并未产生显著性的影响[64]。因此 FDA 推荐的 β-葡聚糖摄入量是根据不同研究中每日谷物摄入水平进行关联。Ripsin 等人[65]利用 Meta 分析研究了富含 β-葡聚糖的燕麦膳食摄入对血液中胆固醇水平减少的影响，结果认为每日 3 g 燕麦可溶性膳食纤维摄入能减少胆固醇 0.13-0.16 mmol/L，且至少 3 g 的 β-葡聚糖摄入量才能产生显著性影响，而对于高血脂患者则效果更为明显。

人体获取胆固醇仅有两种途径，体内肝脏合成（700-900 mg/d）与膳食摄入（300-500 mg/d）[66]。而人体同样在消耗与利用胆固醇，例如转化为胆汁酸/盐（大约 400 mg/d），死去皮肤与黏膜细胞（大约 100mg/d），及类固醇激素合成的损失（大约 50mg/d）[67]。肝脏负责维持人体胆固醇平衡，其细胞负责将胆固醇转化为胆汁酸/盐和类固醇激素，进而将其转移至胆囊作为胆汁、细胞膜中使用或作为胆固醇酯进行储存。肝脏中胆固醇的消耗主要途径是胆汁酸的合成，胆汁酸合成需要经过 14 种酶活反应并受 7α-羟化酶进行调速[68]。而胆固醇的体内平衡也通过羟甲戊二酰辅酶 A 还原酶(3-羟基-3-甲基戊二酰辅酶 A 还原酶，HMG-CoA)进行调控，其作为胆固醇合成的限速性酶和胆固醇运载中低密度脂蛋白胆固醇的受体[67]。

早期研究发现，燕麦等谷物可溶性膳食纤维的黏度与胆固醇的减少具有相关性，并推测膳食纤维中的 β-葡聚糖为主要影响组分[69, 70]。随着谷物 β-葡聚糖人体临床试验的开展[71~72]，血清总胆固醇的降低被发现与粪便中胆汁酸含量的增高具有关联，富含 β-葡聚糖膳食纤维的摄入不仅促进了血清总胆固醇的降低，而且通过粪便检测发现其促进了胆汁酸的排泄，最终促进了人体胆汁酸的合成[73]。然而 Keogh 等人[74]通过人体试验发现，β-葡聚糖降胆固醇生理活性影响并不稳定，并推测其影响因素为：1.商业纯化工艺破坏了原有结构；2.过于温和的萃取条件未灭活内源性 β-葡聚糖酶进而导致 β-葡聚糖过度水解；3.烹饪过程或提取工艺改变其分子量；4.冻干或储存过程影响其生物利用率。同时并总结概括了可溶性膳食纤维对心脑血管疾病影响的可能机理：1.增加胃肠道黏度从而降低胆固醇吸收和阻碍胆汁酸的重吸收，进而促进体内胆固醇转化为胆汁酸的消耗；2.通过产生短链脂肪酸酶来抑制胆固醇；3.使肠道内腔搅动层增厚，产生一系列免疫反应从而促进糖胺聚糖、蛋白多糖和糖蛋白等黏膜粘液的分泌。同年，Yang 等人[75]试验发现大麦可溶性 β-葡聚糖的摄入显著上调了大鼠体内胆固醇 7α-羟化酶的表达，并推测是由于 β-葡聚糖促进胆汁酸排泄所引起。随后，不同试验的开展使谷物可溶性 β-葡聚

糖降低胆固醇的机理推测开始形成：β-葡聚糖降低血清总胆固醇与低密度胆固醇最有可能的方式是通过降低胆汁酸的重吸收，促进肝胆固醇转化为胆汁酸而促进其消耗，增加肝脏对低密度胆固醇的摄取从而同时减少人体低密度胆固醇含量[9, 14]。此外还发现 β-葡聚糖具有减少肠道炎症标志物，增加 eNOS（表达内皮型一氧化氮合酶）表达和抑制动脉粥样硬化病变[76]。2011 年[77]与 2012 年[78]通过动物试验分别发现 β-葡聚糖的摄入一方面显著影响 HMG-CoA 还原酶的表达，另一方面却增加了肝中低密度胆固醇受体的基因表达水平，这两者的影响共同促进了肝脏胆固醇转化胆汁酸的速率。因此 β-葡聚糖降胆固醇机理逐渐得到认可[79]：β-葡聚糖增加肠道食糜黏度，一方面减少了对膳食中胆固醇的吸收，另一方面阻碍了胆汁酸的重吸收、从而促进肝脏中胆固醇转化成胆汁酸，最终起到降低体内胆固醇浓度的作用。随后该机理受到支持，燕麦 β-葡聚糖的摄入显著上调胆汁酸限速酶 CYP7A1 和 CYP7B1 的表达[78, 80]，并推测 β-葡聚糖的摄入促进胆固醇通过经典途径转化为胆汁酸。

膳食纤维的生理活性往往归结于其理化性质的影响：持水能力、膨胀、扩散抑制能力（通过增粘和凝胶），结合性，和敏感性或抗细菌发酵降解[81]。尽管 β-葡聚糖降胆固醇作用的机理仍有争议，但大多数动物与人体试验已经证明可溶性 β-葡聚糖在降低血清总胆固醇和低密度胆固醇水平的同时增加了粪便中胆汁酸的排泄。β-葡聚糖通过增加肠道内容物的黏度来阻碍胆固醇的吸收与胆汁酸的重吸收，进而促进胆汁酸排泄，这一过程增大了体内胆固醇消耗，进而降低人体血清总胆固醇水平与低密度胆固醇水平。

2.2 餐后血糖与胰岛素反应

不同组成的膳食摄入对餐后血糖指数与胰岛素反应具有不同影响，较低的餐后血糖指数与胰岛素反应被认为是有益于人体健康，特别对于糖尿病患者。血糖指数（GI, Glycemic Index），也被称为血糖生成指数，其表示 50 g 的碳水化合物的食物与相当量的葡萄糖相比，在一定时间内（一般为餐后 2 小时）引起体内血糖应答水平的百分比值。早期研究中，市售商业麦片（4%β-葡聚糖含量）被发现并不具有降低血糖的效果[82]。然而，富含 β-葡聚糖的燕麦麸或其他谷物可溶性膳食纤维被发现具有降低血糖反应的作用[83~85]。利用多种谷物可溶性膳食纤维对健康人群与二型糖尿病患者进行膳食干预[85~87]，试验发现富含 β-葡聚糖的谷物可溶性膳食纤维能显著抑制餐后血糖指数与胰岛素水平的上升，这一结果与 β-葡聚糖的含量呈正相关趋势[83]。然而利用富含 β-葡聚糖（19%）的燕麦麸制得的意大利面条作为膳食，提供了 5.2 g 的 β-葡聚糖摄入量，并未显著降低健康受试者餐后血糖指数，但却降低了胰岛素反应[88]。因此推测食物的物理性状和烹调工艺对 β-葡聚糖生理活性具有显著影响。

早期研究发现，燕麦或大麦等谷物膳食纤维降低餐后血糖指数与胰岛素反应是通过 β-葡聚糖的黏度[89~90]。β-葡聚糖黏度是由 β-葡聚糖在溶液中的浓度和分子量控制，因此餐后血糖指数与胰岛素反应受 β-葡聚糖的浓度与分子量影响[91]。在 β-葡聚糖分子量的研究中发现，饮入含有 5 g 分子量 70000 的燕麦麸 β-葡聚糖提取物可以显著降低餐后血糖指数与胰岛素水平，但分子量为 40000 的大麦 β-葡聚糖却并未具有类似的效果[92]。尽管研究中提到这一显著区别与大麦 β-葡聚糖低分子量相关，但在另一组的研究中 5.8 g 分子量为 100000 的 β-葡聚糖同样未显著降低餐后血糖指数[90]。这些差异的原因在于 β-葡聚糖提取物纯度的不足[90]，或者因为提取方式对溶解度的影响所致。当黏度是决定 β-葡聚糖生理活性关键要素时，烹饪烘焙等食品加过程与贮藏过程对 β-葡聚糖溶解度与分子量的影响需要加以考虑。研究表明，烘焙会造成面包中 β-葡聚糖的解聚[93]。造成这一影响主要由于小麦粉中 β-葡聚糖酶[94~95]。然而含有小麦面粉和燕麦或大麦 β-葡聚糖的面包等烘焙食品已发现具有显著降低餐后血糖和胰岛素的效果[84, 87, 96]。贮藏过程研究发现[97]，冷冻贮藏燕麦麸饼干显著降低 β-葡聚糖的溶解性，且冻融循环会使燕麦麸中 β-葡聚糖的溶解能力下降 9-55%。

燕麦、大麦等天然谷物加工制品相对于葡萄糖和白面包具有降低餐后血糖指数与胰岛素反应的作用，这一生理活性不仅受 β-葡聚糖剂量的影响，同时 β-葡聚糖的溶解度与分子量也对其产生影响。

2.3 肠道菌群与免疫

传统研究中关于谷物可溶性 β-葡聚糖的生理活性大多集中在上、中消化道（口腔至回盲瓣），主要因为人体上、中消化道以上缺乏 β-葡聚糖的消化酶因此其保持完整的结构。然而当其进入下消化道（盲肠、结肠、直肠）时，β-葡聚糖被大量的肠道菌群通过发酵利用，这一过程对下消化道中肠道菌群的组成与功能产生影响[98~99]。肠道菌群通过发酵产生短链脂肪酸、氨基酸与维生素从而有利于人体宿主营养与能量代谢[100]，由微生物发酵产生的代谢产物不仅影响人体胃肠道而且影响宿主生理健康，其通过复杂的微生物组成形成网络从而作为一个人体虚拟的内分泌器官，因此肠道菌群在人体健康与疾病状态中起到重要作用

[101~102]。通过改变肠道菌群进而对肥胖[103-105]、糖尿病[105~106]和心脑血管疾病[107~109]等代谢紊乱进行干预的研究已经展开。当前研究表明，操控肠道菌群进而提高菌群中益生菌组成的比例有利于代谢性疾病的预防与治疗[101, 106, 110]。谷物中可溶性 *β*-葡聚糖作为可发酵的膳食纤维[111]，在体外发酵与体内干预试验中发现，*β*-葡聚糖对肠道菌群具有积极的影响作用[112~114]。*β*-葡聚糖的摄入促进盲肠中产生更多的短链脂肪酸及降低盲肠与结肠 pH[115]，且其发酵产生的大量短链脂肪酸有利于预防炎症性肠道疾病[116]。富含 *β*-葡聚糖的燕麦膳食能显著促进双歧杆菌、乳杆菌的增殖和抑制大肠杆菌与拟杆菌，降低小肠结肠内容物 pH，及增大盲肠短链脂肪酸含量[117, 118]，且 *β*-葡聚糖相比其他可溶性膳食纤维能产生更高浓度的丁酸[119]。甚至发现，*β*-葡聚糖促进肠道微生物增殖的同时导致大量共轭胆酸转化为游离胆酸[80]，进而减少其主动吸收。2016 年，Wang 等人[120]通过 *β*-葡聚糖对轻度高胆固醇血症患者肠道菌群组成与功能的影响研究研究发现，高分子量 *β*-葡聚糖有利于改变肠道菌群组成及减少心脑血管危险标志物，推测 *β*-葡聚糖对道肠道菌群的影响依赖于分子量，而高分子量 *β*-葡聚糖的摄入同时也有利于增加拟杆菌属和降低厚壁菌门数量。

肠道健康依赖于肠道菌群的丰富性、多样性与稳定性。肥胖、胰岛素抵抗和血脂异常等代谢紊乱患者的肠道菌群同样发生紊乱。尽管研究已经发现，*β*-葡聚糖有利于增加短链脂肪酸、促进肠道益生菌繁殖及抑制有害菌的数量，*β*-葡聚糖对于人体肠道菌群的影响由于研究设计、试验模型及其菌群菌落分析方法的不一致导致“*β*-葡聚糖—人体肠道菌群—宿主健康”这一影响机制不够清晰，仍待揭示。

在多糖免疫的研究中已经发现，酵母、真菌 *β*-葡聚糖因其分子键以(1→3)-*β*-键和(1→6)-*β*-键为主，赋予了其免疫活性[121]。由(1→3)-*β*-键和(1→4)-*β*-键组成的线性 *β*-葡聚糖被赋予了降低代谢综合征的患病率的生理活性。谷物可溶性 *β*-葡聚糖对于免疫的影响主要通过其发酵产物短链脂肪酸，起到预防炎症性肠道疾病的作用[116]，但这一机制仍不清楚。然而，近期研究发现，许多膳食纤维可以激活肠道免疫细胞上的模式识别受体（PRRs）[122]，并调节肠道免疫应答与肠道屏障功能[123]。Paul de Vos 课题组[124]针对“*β*-葡聚糖—肠道上皮细胞—树突状细胞—T 细胞”这一免疫途径，研究了谷物可溶性 *β*-葡聚糖的免疫作用，试验证明 *β*-葡聚糖等可溶性膳食纤维可以通过对人体黏膜的刺激进而影响人体的免疫系统。次年该课题组[125]将燕麦 *β*-葡聚糖进行水解，发现其相比未水解的 *β*-葡聚糖更容易激发人体树突状细胞的 Dectin-1 受体，部分水解的燕麦 *β*-葡聚糖增加免疫活性可能可以归因于 *β*-葡聚糖长链的断裂，从而暴露更多的(1→3)-*β*-键，及 *β*-葡聚糖分子因水解而粒径减少。尽管体外细胞试验表面燕麦等谷物可溶性 *β*-葡聚糖能刺激小鼠腹腔巨噬细胞等免疫细胞产生更多的类似 IL-1 和 TNF-*α* 等免疫因子[126]，但关于“谷物 *β*-葡聚糖—肠道黏膜—人体免疫系统”这一影响机制仍不够清晰，有待揭示。

近年来，肠道菌群代谢产物和营养物质调节宿主免疫系统这一新兴领域逐渐受到关注[127]。根据 *β*-葡聚糖降胆固醇的机理可知，*β*-葡聚糖阻碍了胆汁酸的重吸收促使其随着粪便排出。然而在下消化道中，*β*-葡聚糖在结肠中高度发酵被降解成不同类型的短链脂肪酸，同时更多的胆汁酸也随之进入结肠。*β*-葡聚糖与胆汁酸的进入改变了“肠道菌群-宿主代谢-宿主免疫”这一稳态。肠道菌群有利于将胆汁酸去缀合化，并将初级胆酸转化为次级胆酸[80]。然而 *β*-葡聚糖对肠道菌群的影响降低了盲肠 pH 从且抑制了肠道菌群 7-*α*-脱羟激酶活性，因此减少了次级胆酸的比例[128]。而利用 *β*-葡聚糖增殖的益生菌则有利于将共轭胆酸转化为游离胆酸[129]。随着胆汁酸作为信号因子的发现[130]，更多被 *β*-葡聚糖阻碍吸收的胆汁酸进入下消化道，通过更为丰富多样的肠道菌群修饰后[131]，这些胆汁酸通过刺激肠道黏膜细胞上的核激素受体法尼酯 X 受体（FXR）和膜受体 G 蛋白偶联胆汁酸受体（TGR5）等，影响人体代谢与免疫[127, 132~134]。

3 总结

过去研究表面，谷物可溶性 β-葡聚糖生理活性对人体健康影响机制大多通过几个方面（见图 2）：1.β-葡聚糖增加小肠食糜黏度从而降低对葡萄糖[89~90]、膳食胆固醇[14]、脂肪酸[135]等小分子的吸收，同时于回肠末端阻碍了胆汁酸的主动吸收、于其余肠道下阻碍胆汁酸的被动吸收[74]；2.胆汁酸重吸收的阻碍促使肝脏利用更多体内胆固醇合成胆汁酸，进而降低人体总血清胆固醇水平与低密度胆固醇水平[79]；3.葡萄糖吸收的阻碍延缓了餐后血糖指数与胰岛素水平的上升[90]，精氨酸与赖氨酸等小分子吸收被阻碍减少了胰岛素分泌[136]；4.*β*-葡聚糖于盲肠和结肠中的高度发酵，促进益生菌增殖与抑制有害菌[137]，同时产生大量的短链脂肪酸（特别是丁酸），与降低盲肠和结肠 pH[115]；5.短链脂肪酸的增多有利于预防炎症性肠道疾病[76, 116]；6.结肠菌群的增殖、餐后血糖指数与胰岛素水平的延缓有利于提高胰岛素敏感性[138]。

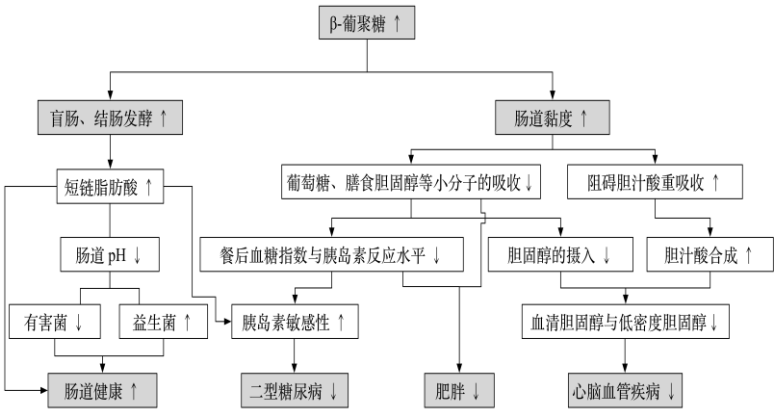

图 2 目前研究表明谷物 β-葡聚糖预防慢性疾病的机制

Fig.2 Accepted mechanisms underlying the protective effect of cereal β-glucans on chronic diseases

随着代谢组学研究的发展，胆汁酸被发现不只在肠道中促进脂质的吸收，而且作为信号因子在人体代谢等多个方面产生重要影响[127, 130~133, 139]，β-葡聚糖与胆汁酸间相互作用产生的影响将远大于β-葡聚糖黏度起到的阻隔效应[140]。不同结构的谷物可溶性 β-葡聚糖与不同种类胆酸、及不同胆酸比例的胆汁酸相互作用的不同，将改变进入盲肠、结肠的胆汁酸的数量与种类。而 β-葡聚糖发酵降解对盲肠、结肠环境的显著性改变同样影响着不同类型胆酸数量与比例，从而影响人体胆汁酸肝肠循环与胆汁酸合成。被阻碍或束缚进入下消化道的胆汁酸与核激素受体法尼酯 X 受体（FXR）和膜受体 G 蛋白偶联胆汁酸受体（TGR5）的相互作用，对人体脂质、葡萄糖的代谢平衡与胆汁酸合成起到关键调节作用[130, 141, 142]，其还可以调节人体促胰岛素分泌激素水平[143]、碱性成纤维细胞生长因子 19（FGF19）[143]、胆固醇代谢[144]、肠道菌群组成[131]与人体能量消耗[144]。因此谷物可溶性 β-葡聚糖生理活性机理及其结构与生理活性的相互关系需要更进一步的研究。

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